John S Gero *Editor*

Design Computing and Cognition'22

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Preface

Designers are fundamentally optimists, since designing is about improving the world from what it was when designing commenced. However, times do not always provide a foundation for optimism. Today, we are still in the COVID-19 pandemic, which has caused so much pain and suffering at multiple levels as well as social and economic disruption. The scale and effects of this disruption continue to be played out. Then there is the Russian invasion of Ukraine. An event that was deemed unthinkable before it occurred. This has disrupted the rule-based order of Europe and inadvertently caused economic and food challenges in the rest of the world. Finally, the combination of the COVID-19 pandemic and the Russian invasion of Ukraine has produced an economic effect that yet may result in a global recession.

Notwithstanding the challenges as a result of these events, design researchers met for one of the first fully in-person conferences in the previous two years and re-discovered the value of face-to-face contact with other researchers both in terms of their research and in terms of social interactions with other humans. The Design Computing and Cognition conference series is not simply a forum to present research, it is a place of community activity and community building. The conference program provided considerable time for both research discussion and social interactions.

Design research presents unique research challenges. Unlike many other kinds of research, the results of designing are unique to each designer or design team and therefore cannot be directly compared but need to be re-represented to be commensurable. Designing involves framing and re-framing, which themselves are not adequately understood. Designing is non-monotonic, so many models are not applicable. Designing is situated, so the situation matters. Designing makes use of a large panoply of cognitive processes that can be difficult to untangle. The neurocognition of designing is largely unknown. This makes design research a difficult but fruitful research area as many discoveries have yet to be made.

The papers in this volume are from the *Tenth International Conference on Design Computing and Cognition (DCC'22)* held in person at the University of Strathclyde, Glasgow, Scotland. They represent the state of the art of research and development in design computing and design cognition including the increasingly active area of design neurocognition. They are of particular interest to design researchers, developers and users of advanced computation in designing as well as to design educators. This volume contains knowledge about the cognitive and neurocognitive behavior of designers, which is valuable for those who need to gain a better understanding of designing.

In these proceedings the papers are grouped under the following nine headings, describing both advances in theory and application and demonstrating the depth and breadth of design computing, design cognition and design neurocognition:

Natural Language Processing and Design
Design Cognition—1
Design Neurocognition
Learning and Design
Creative Design and Co-design
Design Cognition—2
Shape Grammars and Design Knowledge
Design Generation and Quantum Computing
Human Behavior

A total of 115 papers were submitted to the conference, from which 48 were accepted and appear in these proceedings. Each paper was extensively reviewed by at least three reviewers drawn from the international panel of reviewers listed on the following pages. The reviewers' recommendations were then assessed before the final decision on each paper was taken. The authors improved their contributions based on the advice of this community of reviewers prior to submitting the final manuscript for publication. Thanks go to the reviewers, for the quality of these papers depends on their efforts. Thanks are due to Julie Milovanovic who put the papers together to form the conference proceedings.

Charlotte, USA John S Gero

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Natural Language Processing and Design

Extracting Information for Creating SAPPhIRE Model of Causality from Natural Language Descriptions

Kausik Bhattacharya, Apoorv Naresh Bhatt, B. S. C. Ranjan, Sonal Keshwani, V. Srinivasan, and Amaresh Chakrabarti

Structured representations from natural language descriptions of biological and engineered systems are a good source of inspiration in analogical design. Researchers proposed methods for developing knowledge representations from such documents, to make them conducive for use as a source of analogy. Ontology-based representations, such as FBS, SBF, SAPPhIRE, etc. are effective in analogical design, but manually creating accurate descriptions using these models is both time- and resource-intensive. Hence, methods to automatically create ontology-based representations are useful for developing a repository of biological and engineered systems. However, such methods are partially automated, with major human decision-making touchpoints. Before standardizing and automating the process, it is important to understand it end-to-end for accuracy and variability. This paper reports results from a detailed study on manual information extraction from systems description texts, using the SAPPhIRE model. A new process is proposed that aims to reduce variability in the extracted information across subjects, with preliminary results that show significant promise.

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Introduction

This paper presents a study on the process for extracting information that is relevant for creating causality descriptions using the SAPPhIRE model from natural language descriptions of biological and engineered systems. Understanding such a process is essential to choose right automation strategy for creating an ontology-based representation from descriptions in natural language for analogical design. The goals of this research are: (1) to understand the process of creating causality descriptions using the SAPPhIRE model from descriptions in natural language and (2) to develop a new, generalized process of extracting information of entities of the SAPPhIRE model from descriptions in natural language. The paper starts with a brief introduction that explains the design-by-analogy as an essential method for design creativity and gives a quick overview of its various support. It explains the importance of converting a natural language description of a system into a ontology-based data representation, reports research on method for this conversion and presents new research opportunities. The paper then presents the research questions, work done and the results. The paper ends with a conclusion which includes an outline of the next step in this research.

Design Creativity and Design by Analogy

A design is a means for changing existing situations into preferred ones [1]. Creativity in design is often characterized as a process by which an agent uses its ability to generate something that is novel and useful [2]. Researchers also studied the influence of different design methods on creative design outcomes [6] and developed methods for enhancing creative ideation in design. Literature provides evidence that the presence of a stimulus can lead to the generation of more ideas [4]. Systematic use of knowledge from both artificial and natural domains helps designers generate a variety of solutions and develop them into realizable and practical prototypes [7]. "Design-by-Analogy is the process of developing solutions through mapping of attributes, relations, and purposes that a source problem or situation may share (or at least partially share) with an existing target solution or situation" [8]. Many empirical studies were conducted to understand the process and factors influencing the effectiveness of Design-by-Analogy [3, 4, 9–12]. Representation of stimulus plays an important role in Design-by-Analogy [15, 16] and it can reduce fixation and enhance designers' creativity during idea generation [13, 14, 17, 18].

Support for Design by Analogy

Search for Analogue(s) is a key step in the Design-by-Analogy process [19], and finding relevant and good analogues directly influences the design outcome. Many pieces of support are developed to facilitate Design-by-Analogy, including with the recently developed powerful techniques of AI and Data Sciences [20, 21]. In this paper, an outline of the commonly cited Design-by-Analogy support from literature is provided.

Support like Functional Model database [22] and AskNature [23] use a function-based approach to identify analogues from a database. The Functional Model database has an engineering-to-biology thesaurus that maps biological terms to the functional basis of technical systems. AskNature categorizes the information of the biological functions according to the four layers of Biomimicry Taxonomy (Group, Sub-group, Function, Strategy). Biological models are mapped into different engineering fields using "strategy". Analogy Retriever [24] uses 16 ontological relationships to describe the connections between various system entities. This supports analogical reasoning for creative idea generation by solving proportional analogy problems.

On the other hand, support like Functional Vector [25] and SEABIRD [26] use vector space method to find analogue based on semantic similarity of words. In the Functional Vector model, a query vector of functions is generated. A relevancy score of the query with a functional vocabulary is calculated using a patent database. SEABIRD method generates the Product Aspects (PA) and Organism Aspects (OA) matrices from a database of technical system documents and biological functions. Mapping between two domains is then quantified based on the values from the mathematical product of the PA and OA matrices.

There is a third category of support, like DANE [27] and IDEA-INSPIRE [28], which use ontology-based data models. DANE uses data query at multiple levels of abstractions in a controlled database comprising structured data models of SBF (i.e., Structure-Behavior-Function) [29]. In SBF, 'Structures' are the constituent components and substances and relations among them; 'Behavior' is the series of state changes from an input to an output state, and the transition from one state to another happens through functions. 'Function', therefore, is used as a behavioral abstraction. In IDEA-INSPIRE, the search strategy uses single or multiple levels of abstraction of the SAPPhIRE model [28]. The SAPPhIRE model has seven layers of abstraction, namely, State Changes, Actions, Parts, Phenomena, Inputs, oRgans, and Effects. They cover the physical components of the system and interface and their interactions, along with the structural context and the scientific law that governs them. The SAPPhIRE model with an example (heat transfer from a hot body to cool surrounding air) is shown in Fig. 1.

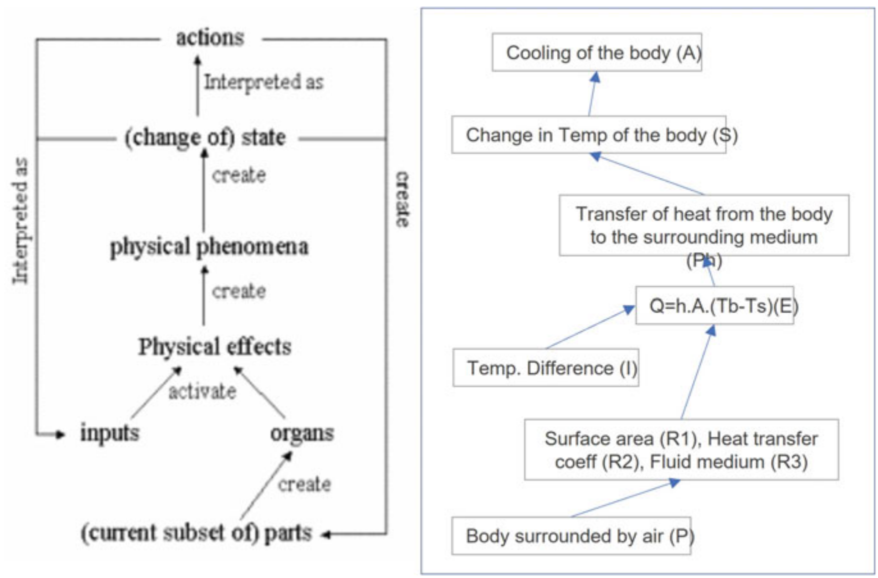

Fig. 1 SAPPhIRE model of causality with an example of heat transfer from a hot body to cool surrounding air [28]

Structured Representation from a Natural Language Description

Generating large number of stimuli and maintaining diversity and variety of content, are important requirements along with 'Abstraction', 'Mode of representation', and 'Open-endedness' of the cases in any Design-by-Analogy database [35, 37]. Though ontology-based models are very effective, they are hand crafted and limited in number. On the other hand, there is an abundant source of knowledge of biological and technical systems, available in the form of technical documents and many websites. However, such information or data are unstructured because they are not associated with any specific format or data model. Structured data has a schema or model that defines how the data is organized [43]. Since structured data are preferred in Design-by-Analogy because of computational advantages, researchers proposed methods using the numerical techniques of AI and Data Sciences that can generate structured data or knowledge representation from information given in natural language descriptions [20]. Semantic networks are considered as effective for knowledge representation from vast data sources and hence many such networks were developed [38]. While working with Engineering examples, TechNet could be better than other common sense semantic networks such as WordNet or ConceptNet [39]. However, all the literature pointed out that more study is needed with TechNet or any similar networks. Despite huge potential of knowledge graph as knowledge representation from vast NLP data, they are limited by construction effort, evolvement, and portability [41]. Another knowledge graph-based representation was developed using a rule-based approach for engineering examples which was found to be large and scalable compared to publicly available Knowledge graphs [40].

However, these knowledge graph or Semantic networks do not provide any abstraction levels as such and can't explain the system causality. Ontology models have many advantages in analogical reasoning. They can provide multiple level of abstractions of a system and can be used to explain the system functions [44]. Results show that ontology-based models, such as SAPPhIRE or SBF, are very effective in design ideation [7, 36]. So, numerous techniques were developed to automatically create ontology-based representation of texts. One such Natural Language Programming (NLP) based technique was developed to find causal relations between biological functions using a linguistic pattern of biologically meaningful keywords [31]. It progressively refines search keywords until a suitable match is found. A simple template is used to capture causal relations of biological functions from a sentence in natural language [45]. Another support called IBID (Intelligent Bio-Inspired Design), was developed for the conversion of natural language description into SBF [32]. IBID uses a combination of a knowledge-based and machine learning-based approach to extract and represent the knowledge using the SBF model. This work on IBID reported a detailed comparative study of multiple machine learning algorithms used to classify knowledge using Structure, Behavior and Function tags. In another research, a four-step process for converting natural language description into descriptions using SAPPhIRE model was reported [12, 33]. In this work, all the sentences with potential SAPPhIRE constructs are extracted and then split into words or collections of words. A Support Vector Machine based classifier is used to classify the SAPPhIRE label of each word or collection of words.

Research Questions and Research Methodology

Opportunities for Research

All these different kinds of support proposed in literature for creating an ontology-based data model from natural language text, uses supervised learning with hand-annotated data for training and validation. However, none of these explain how the hand-annotated data were created. These support are semi-automated with many major decision-making touchpoints. The end-to-end process for creating such structured data model from a natural language description and its overall accuracy have not been reported. Therefore, the main factors that influence creation of ontology-based models and how to validate them, are not adequately researched. An empirical study, comparing three approaches, namely keyword search using Ask Nature (handcrafted database), NLP-based approach (unstructured corpus) and one where Biologists manually perform the search in literature, reports that though NLP-based technique is very promising, it is currently error prone [34].

Research Questions

Therefore, the main question posed in this research is 'How can we create an accurate and repeatable ontology-based data model from a natural language description?' The assumption is that without the conversion process being accurate and repeatable, the process cannot be automated. We divided this research question into two sub-questions for the first part of this research:

1. What is the current process of developing a structured data model from a given natural language document, and what are the issues?
2. What should be a process for creating a structured data model based on the information given in a natural language document that overcomes these issues?

In this research, we used the SAPPhIRE model to represent the causality of the final outcome. The SAPPhIRE model captures the details of a system through its seven levels of abstraction, namely, State Changes, Actions, Parts, Phenomena, Inputs, oRgans, and Effects, and the causal relations between these entities. The SAPPhIRE model can describe the working of both natural and engineered systems, scalable for complex systems through multi-instance modelling and can help produce rich, comprehensive descriptions [30]. It can be used in both Analysis and Synthesis of Design, including for novel ideation [30, 35] and for transfer in Biomimetics [19].

Research Methodology

To answer the first sub-question, an Intercoder Reliability (also known as Inter-Encoder Reliability) study was carried out to create descriptions of systems using the SAPPhIRE model from their descriptions in natural language. To build a description of a system using the SAPPhIRE model from its natural language description, the main step is to extract the SAPPhIRE construct-specific information from the description in natural language. Hence in the second sub-question, a major focus has been on the process for this information extraction. Based on the lessons from the Intercoder Reliability study, we proposed a generalized process for extracting SAPPhIRE information from a description in natural language, with an aim to at least reduce, if not eliminate, the variability in the interpretation of the information given in a natural language description. Before continuing further, user trials were conducted for validation of the process. The results of these user trials should help understand whether the new process is in the right direction of addressing current issues and which areas need to be worked on further.

Intercoder Reliability Study

Goals of the Study

The goals of this Intercoder Reliability study were the following:

- What was the degree of agreement between two or more researchers creating descriptions of systems with the SAPPhIRE model from the given descriptions in natural language?
- What were the issues that researchers faced while creating descriptions of systems with the SAPPhIRE model from the given descriptions in natural language?

Study Procedure

For the first research question, a study was conducted with four researchers, each having a minimum of 4 years of experience in using the SAPPhIRE model for their own research. Each researcher was given the description in natural language for 4 systems (we call each description 'a sample') and was asked to create a description using the SAPPhIRE model for each system. Intercoder Reliability score was then calculated based on the word/group of words identified for each SAPPhIRE construct in each sample. We calculated the Intercoder Reliability Score for a given sentence and aggregated score for all the sentences in each sample. The '*% Intercoder Reliability*' score of a sentence is calculated as:

$$\frac{Total\ number\ of\ SAPPhIRE\ clauses\ agreed\ at\ (a)\ 75\%\ and\ (b)\ 50\%\ levels}{Total\ number\ of\ ALL\ SAPPhIRE\ clauses\ identified\ by\ all\ researchers} \times 100$$

We calculated the score at the following two levels:

(a) 75% level: here, we consider those words for which three or more out of 4 researchers agreed with the words and their labels
(b) 50% level: here, we consider those words for which two or more out of 4 researchers agreed with the words and their labels

The above calculation is illustrated here with this sentence—"Respiration can be a significant cause of water loss". This sentence was part of one of the four samples. The four researchers together identified the SAPPhIRE words as given in Table 1:

From Table 1, we can observe that:

- Three or more researchers agreed with only one word (i.e., 'Respiration as a Phenomenon)
- Two or more researchers agreed with both words (i.e., 'Respiration' & 'water loss' as Phenomenon and State Change respectively)

Hence, we can compute the score as follows in Table 2:

Table 1 SAPPhIRE constructs identified by researchers in a sentence, "Respiration can be a significant cause of water loss"

Word(s)	SAPPhIRE constructs (identified by four researchers)			
	Action	Phenomenon	State change	Explanation
Respiration	1	3		3 out of 4 agreed that 'Respiration' is a Phenomenon and 1 felt it is an Action
Water loss	1		2	2 out of 4 agreed that 'Water loss' is a State Change and 1 felt it is an Action and 1 didn't assign any label

Table 2 Intercoder-reliability score of a sentence, "Respiration can be a significant cause of water loss"

Total # of Words	3 or more of 4 researchers agreed		2 or more of 4 researchers agreed	
	Count	%	Count	%
2 (Respiration, Water loss)	1 (Respiration)	50%	2 (Respiration, Water loss)	100%

Samples Used in the Intercoder Reliability Study and Results

Designers typically look at large number of short descriptions of biological or engineered systems and hand pick the relevant ones for which later they seek more details. Such short descriptions are usually about 'how a system works' and therefore has causal information. Four samples (natural language descriptions of four systems) used in the study are 'Elephant Turbinate', 'Bombardier Beetle', 'Thermal Wheel' and 'Electric Horn' and represented by the sample ID 'EG1', 'EG2', 'EG3' and 'EG4' respectively. The contents of these samples were hand curated with information taken from the commonly available websites such as howstuffworks.com, asknature.org or Wikipedia etc. The details of these samples are available at https://github.com/kausikbh/DCC22_SAPPhIRE_Data. The final summary of the Intercoder Reliability score of all four samples is given in Table 3.

Table 3 Intercoder Reliability score of all 4 samples

Sample ID	Total # of words	3 or more out of 4 researchers agreed		2 or more out of 4 researchers agreed	
		Count	%	Count	%
EG1	71	6	8	21	30
EG2	69	2	3	8	12
EG3	68	1	1	6	9
EG4	221	2	1	22	10
Overall	429	11	3	57	13

The results above indicated disagreement among the researchers on deciding about the SAPPhIRE information in each sample. Hence workshops were conducted with the 4 researchers to collect feedback and identify the root causes for the differences. Based on the workshop, the following key root causes were identified:

- Differences in natural language interpretation among the researchers, leading to multiple representations of the same information given in a natural language text.
- Often natural language text does not have enough information to complete the model, but there is no standard way of assessing the information gaps and how to fill the gaps.
- The definition of the SAPPhIRE constructs is not applied consistently due to perceptual differences among humans. This leads to interpretational differences of the same definition.
- The text in natural language often describes the technical process at a high level and does not mention the underlying physical principles. As a result, different technical or scientific terminologies were used to represent the same physical behavior by the researchers.

For the final root cause, an observational study was conducted to share the benefits of using a catalogue of physical laws and effects [5]. It was found that the use of standard terminologies reduced the total number of SAPPhIRE words to describe a model by 28% by increasing the use of common words to represent the same physical behavior. Please note that while low Intercoder Reliability does not necessarily indicate lack of accuracy but lack of consistency. For instance, 'how a pendulum works' can be written in different physics books in different details; while all may be accurate descriptions, not all may be consistent with one another.

Proposed Process

We developed a new process for extracting the SAPPhIRE construct-specific information from a natural language description. In this new process, we propose the following:

1. Knowledge graphs are found to be very powerful for knowledge representation from large natural language documents [38]. Hence Knowledge graphs is used in this process as a standard way of representing the information extracted from a natural language text to reduce any interpretational differences of natural language document.
2. Rule-based reasoning applied to a knowledge graph simulates human reasoning ability and allows incorporating prior knowledge to assist in reasoning [42]. Hence a set of SAPPhIRE construct-specific standard rules is developed to identify candidate words for each SAPPhIRE construct. This will help in applying the definition of the SAPPhIRE constructs consistently.

3. Use of a standard vocabulary of physical laws is proposed in the new process, to avoid use of different words or terminologies that represent the same physical behavior. However, more work is needed to implement this.

Process Descriptions

The process flow diagram of the new generalized process is shown in Fig. 2. Though the process flow diagram has the provision for all the features mentioned above, the first version of the process implemented only the first two features (i.e., Knowledge Graph and rules). Here, we first convert all compound sentences into simple ones by splitting them into independent sentences. Then we identify the Parts-of-Speech (POS) tag of every word. Once pre-processing is completed, a knowledge graph is generated using the POS tags of the words and their syntactic relationships. The objective of the knowledge graph is to represent the information given in the natural language description in a common format so that extracting information later, relevant for a particular SAPPhIRE construct, becomes easy. POS tags that are used in building the knowledge graph are (a) Nouns, (b) Verbs (we distinguish transitive and intransitive verbs), (c) Adjectives, (d) Adverbs, (e) Prepositions, and (f) Conjunctions. POS tagging is done in the following sequence. For each sentence, first the verb(s), subject(s) and object(s) are identified. Then other relations between the words (e.g., Nouns connected through prepositions, Adjectives with Nouns and Adverbs with Verbs) are identified. Then any Conjunction, Adverb or Preposition that connect two independent clauses (a sentence or a group of words that has its own meaning) are identified, and finally, the sequence of actions (transitive verbs) as given in the natural language description are identified.

Through the steps explained above, we capture the following three types of information in the knowledge graph,

(a) Relation between two entities: This is done by identifying: (i) two nouns which are connected by a verb, (ii) a noun and an adjective or adverb connected by a verb and (iii) two nouns connected by a preposition.
(b) Conditions between two events: Here, events are represented by transitive verbs, and we capture whether two transitive verbs are connected using a conjunction or an adverb.
(c) The sequence of events: This is essentially a sequence of transitive verbs, representing a description of a technical process.

While building the Knowledge Graph and identifying candidate words, the meaning of the words should not be considered standalone or isolated. It is to be understood as to what information is conveyed and a single word or a group of words that convey a specific meaning in the context of the paragraph or document is to be picked up.

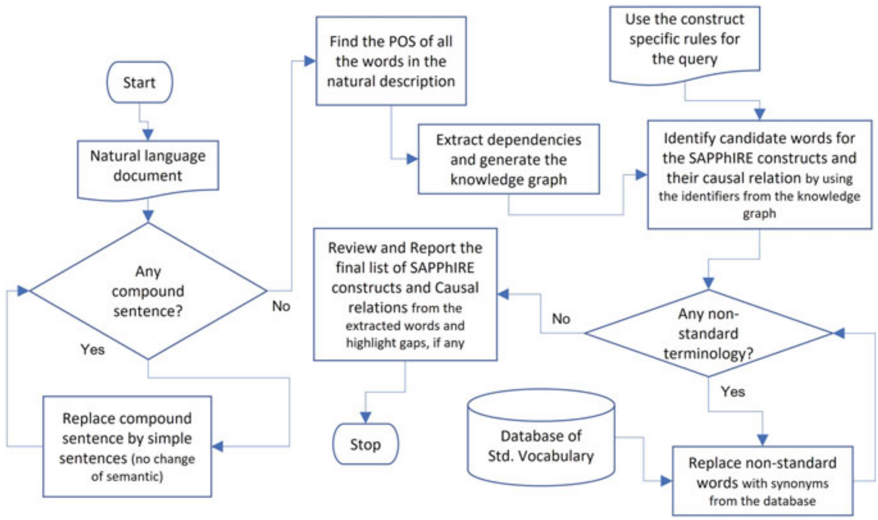

Fig. 2 Process for extracting information from a natural language description

After this step, the construct-specific rules will be used to identify, from the knowledge graph, the candidate words for each SAPPhIRE construct and the causal relationships among them. For extracting the candidate words, the following sequence should be followed,

- First, work on all the nouns and identify those which could be the 'Parts'. Then rest of the nouns should be considered for the 'Inputs' and the 'State Change'. 'State Change' nouns will be associated with verbs that imply a meaning of a change in the noun.
- Then look for all the transitive verbs. Most of the natural language text describes a technical process comprising a sequence of action verbs. Once we identify the action verbs representing a technical process, we identify 'Actions' and 'Phenomena'.
- Then work on the rest of the POS tags, like, Adjectives, Adverbs, Prepositions, Conjunctions etc., to identify Organs.

It should be noted that a particular word should be used in only one construct.[1] The candidate words identified using the construct-specific rules are the potential SAPPhIRE constructs given in the natural language text to build the model. However, these words might not be the true SAPPhIRE constructs conforming to the definition given for the construct. Hence at this stage a review would be necessary to determine the appropriateness of the candidate words for each SAPPhIRE construct. A set of interpretation guidelines are created to assist this review process.

[1] In the multi-instance cases, this may not be true. For example, change in parts can become the input.

This review will also determine any missing SAPPhIRE construct. A reviewer will require (some/necessary) domain knowledge to perform the review task effectively.

Process Validation

A thorough developer testing was done first, before taking up user validation of the newly developed process.

Developer Testing

Developer testing was done using eight different sample cases where each sample has the natural language description of a system and its physical process. Samples used in the developer testing included all the four samples used during the Intercoder Reliability study before the new process was developed, as well as fresh samples. Old samples were used to compare the results obtained using with and without the new process. New samples were used as additional tests to verify whether the process is consistently working outside of the known examples. In all these samples (old and new ones), it was observed that the process was consistently able to extract candidate words for the SAPPhIRE constructs and their causal relations. Following this process, it was also possible to identify any missing information related to any SAPPhIRE construct. It was also observed that (some) domain knowledge was necessary to review the information extracted using the process and make a final choice of words for the SAPPhIRE constructs.

Figures 3 shows a comparison of the total number of words for each SAPPhIRE construct, generated without and with the process, in the two sample cases (a) Thermal Wheel and (b) Elephant Turbinate. The words generated without the process are the ones identified by the researchers during the Intercoder Reliability study at the beginning. In both these samples, the distribution of total number of words for the SAPPhIRE constructs were similar for without and with the process. We also observed that many common words used by the researchers for different SAPPhIRE constructs matched with the candidate words generated by the process. We therefore see that the new process can capture the common thinking of the test participants.

User Validation of the New Process

User validation was conducted after verification of the new process through developer testing. User validation was done with the same four researchers who participated in the previous study before process development. There were four new sample cases namely, electric battery, a solar water heater, a mechanical lock and visualizing

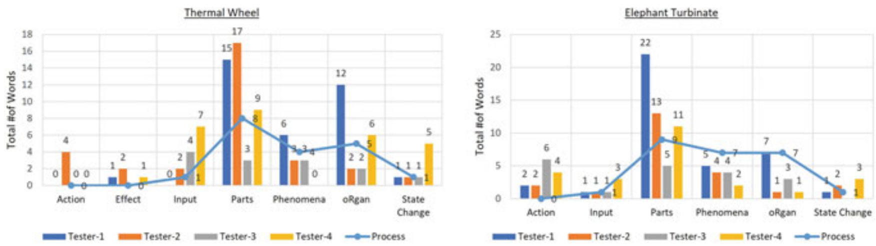

Fig. 3 Comparison of the total number of SAPPhIRE words generated without and with process for the **a** 'Thermal Wheel', **b** 'Elephant Turbinate'

infrared rays by fish. We took new samples to ensure, testers are not producing the outputs out of their memory of the previous study. Like in the previous study, these samples are brief description of how a system, biological or engineered, works and are hand curated with information taken from the commonly available websites such as howstuffworks.com, asknature.org or Wikipedia. Each researcher first created the knowledge graph-based representation of the natural language description. Then they used the construct specific rules to select a list of candidate words for each SAPPhIRE construct. Since all the candidate words may not be a valid SAPPhIRE construct, interpretation guidelines were applied to arrive at the final list of words. The details of these four samples as well as some example of the deliverables created by the testers during the study (knowledge graph and the SAPPhIRE labels that coders used to encode words from the sample texts), are available at https://github.com/kausikbh/DCC22_SAPPhIRE_Data.

With the final list of SAPPhIRE words, we computed the Intercoder Reliability score to find out the level of agreement. Table 4 shows the Intercoder Reliability score for the final choice of words list. Table 5 summarizes the Intercoder Reliability score without and with the new process in one place, for comparison.

From Table 5, we can see that in both scenarios, namely, (a) A: 3 or more out of 4 researchers agreed, and (b) B: 2 or more out of 4 researchers agreed, there is an improvement in the overall level of agreement when the new process is used. This was confirmed by a one-way within-subjects ANOVA given in Table 6 for the above

Table 4 Intercoder reliability score in user validation

	Total # of words	3 or more out of 4 researchers agreed		2 or more out of 4 researchers agreed	
		Count	%	Count	%
EG5 (electric battery)	21	12	57	16	81
EG6 (solar heater)	15	13	87	13	87
EG7 (mechanical lock)	35	23	66	28	80
EG8 (visualizing infrared rays by fish)	51	26	51	38	75

Table 5 Intercoder reliability scores WITHOUT and WITH new process

		Total # of words	3 or more out of 4 researchers agreed		2 or more out of 4 researchers agreed	
			Count	%	Count	%
Without New process	EG1	71	6	8	21	30
	EG2	69	2	3	8	12
	EG3	68	1	1	6	9
	EG4	221	2	1	22	10
	Overall	429	11	3	57	13
With New process	EG5	21	12	57	16	81
	EG6	15	13	87	13	87
	EG7	35	23	66	28	80
	EG8	51	26	51	38	75
	Overall	122	74	61	95	78

Table 6 One-way within-subjects ANOVA Test Results

Scenarios	Groups with intercoder reliability score	Test statistics
A: 3 or more out of 4 researchers agreed	Without process [$M = 0.032$, $SD = 0.029$] and with process [$M = 0.653$, $SD = 0.136$]	$F(1, 6) = 59.32$, $p < 0.05$, $\eta^2 = 0.91$
B: 2 or more out of 4 researchers agreed	Without process [$M = 0.153$, $SD = 0.086$] and with process [$M = 0.808$, $SD = 0.043$]	$F(1, 6) = 140.1$, $p < 0.05$, $\eta^2 = 0.95$

two scenarios (‘A’ and ‘B’). In both these scenarios at $p < 0.05$ level, we reject the null hypothesis that both groups (‘without’ and ‘with’ new process) are the same. In other words, when the process is used result is significantly different from those which did not use it.

Discussion

The new process, based on rules involving the parts of speech of English grammar and their syntactic dependencies, acts as a guard rail, making everyone look at a common list of possible words or clauses for a given construct (we call them candidate words in the process). Results obtained from user validation confirm that the new process can help reduce the variability in the extracted SAPPhIRE information by different users. Though the results are encouraging, it has room for further improvements. A detailed analysis of the results indicated that the Parts and the Actions-Phenomena have the maximum agreement. It is so because Parts are mainly those Nouns that represent a material entity, and Action/Phenomenon are mainly the Transitive Verbs denoting an action. We however see need for a better interpretation guideline to differentiate a Phenomenon (which represents an interaction of a system entity with its surrounding) from Action (which is the interpretation of the state change resulting from the same interaction). Often natural language text will have either of this two information (Phenomena and Action), hence in our study we tried to ensure we are able to capture the system interaction from the text, irrespective of its label (Phenomena or Action). Other constructs, Input, Organ, Effect and State Change, do not have the same degree of straightforwardness. do not have the same degree of straightforwardness. Most of the time, a natural language description would not explicitly call out what are the inputs for an interaction, the conditions or structural context for a physical law (or effect) to trigger interactions and the resulting state changes. These must be derived from the given information using the interpretation guidelines. In the absence of a known physical law, this decision becomes subjective. Hence, we see opportunities for extending the rules beyond grammar to make appropriate choices and a guideline around dealing with any missing information. We continue to see people using different words to express the same physical interactions in absence of a common catalogue. Although the new process calls for a common catalogue, it was not used in this study.

Our main research question was to know how to create accurate and repeatable ontology-based data models from natural language descriptions. Answer to this question will help to design suitable automation strategy for extracting SBF or SAPPhIRE information from natural language documents, as researchers did in the past. The process will also help in producing necessary accurate data to validate such automation scheme without the constraints of specialists' availability. An actual quantitative cost–benefit of any automation and what are any limitations, will be known once an accurate and repeatable end to end process with automation is created.

Conclusions

Design thinking needs exploration of design space repeatedly. A large Design-by-Analogy database with systems models, like SAPPhIRE, will help having more (count) inspirations or stimuli in the conceptual phase of design and therefore can have a strong positive influence on creativity. Hence a process that can generate the descriptions of the SAPPhIRE model from the information in natural language documents, which are available in plenty, will be very useful in design. To understand the current process of creating descriptions of the SAPPhIRE model from a natural language text, an Intercoder Reliability study was conducted. This study revealed the challenges with the current process which we attempted to address through a new, generalized process of extracting SAPPhIRE information from natural language descriptions. From the validation of the new process, we see that the new process helps identifying candidate words for the various SAPPhIRE constructs and revealing gaps in the SAPPhIRE information in the same natural language description. Through the user validation of the new process, we also identified areas in which the rules need to improve. So far, our research has been limited to natural language understanding and extracting information relevant for a given abstraction level. We saw evidence that documents in natural language often do not have information related to all the seven abstraction levels of the SAPPhIRE model. Hence, we need to expand the approach so that will also help accurately fill in any missing information. It might be noted that the designers may choose to represent the same information in many ways. Hence, we need a method that can compare different SAPPhIRE representations of the same system and assess their similarities and dissimilarities. Our future research intends to investigate these opportunities. Due to the diverse nature of technical documents in natural language, there are complexities with natural language understanding of these. We therefore approached in an iterative way, where we first learn and then improve. Our results showed us a path to proceed with further refining the process by addressing the observations from user validation as well as by incorporating more complex scenarios and variability of natural language descriptions. A detailed process validation via lab experiments, and further process optimization and automation after the validation are also planned.

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Recognizing the Structure of Biological Designs in Text Documents

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Biologically inspired design entails analogical transfer of design knowledge from natural systems to technological systems. The goal of the Intelligent Biologically Inspired Design (IBID) project is to help engineers build a precise understanding of a biological system described in a text document and thereby acquire biological cases needed for biologically inspired design. In this paper, we describe a novel technique for recognizing the structural elements of a biological system in a text document. IBID's structure recognition technique allows the structural elements in a biological process to be mapped to domain-independent equivalent concepts useful for cross-domain analogical transfer. In a pilot study, we compare the performance of IBID's structure recognition technique with that of human subjects. Our findings suggest that IBID may be able to help non-experts in biology in recognizing structure.

Introduction

Biologically inspired design involves the translation of knowledge about the natural world into new technological innovations [1–3]. The field looks to combine biology and technology to develop innovations that take advantage of biological structures, functions, processes, and systems [4–6]. While the Biomimicry Global Design Challenge [7] shows that biologically inspired design can solve large scale problems, the knowledge gap between the source of ideas in biology and its implementation in design and engineering remains an issue [8, 9]. Engineers may be adept at creating solutions but are unlikely to be experts at biological terms and concepts, impeding their ability to abstract relevant concepts from biological articles [10].

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Given the propensity of publications in modern science and volume of data being analyzed to solve potential design challenges, a tool that can serve as an efficient intermediary to bridge the design inspiration and implementation phases is needed. The quality of the design process itself may heavily depend on the ability of the designers to manage enormous amounts of information [11], requiring that any algorithm that attempts to convey biologically inspired design be scalable [12].

IBID is a tool for assisting engineers and designers in finding solutions to design problems via biological processes. The goal of IBID is to translate domain-dependent biological terminology into terms more accessible to non-experts in biology [13, 14]. IBID tries to identify the structures, behaviors, and functions involved in biological processes and find their closest domain independent equivalent concepts that are understandable by engineers and designers. Structures, behaviors, and functions are the components of Structure-Behavior-Function (SBF) models of technological and natural systems [15, 16] and SBF modeling is a way of representing systems with concepts and the relationships among them.

IBID leverages AI techniques to aid scientific document understanding [17]. For example, IBID uses graph search algorithms to translate biological concepts into "common concepts" more understandable by non-experts. IBID indexes biological processes with these "common concepts" and supports search queries allowing the user to quickly find the relevant biological processes from the biological articles stored in the repository. Previous work on IBID has enabled it to translate biological function and behavior concepts into their domain independent "common concepts."

Structure recognition is a new subsystem in IBID that is responsible for identifying the structural elements in biological processes and translating them into domain independent concepts. Our research introduces a computational technique for IBID's structure recognition and tests its effectiveness by extracting structure concepts using the technique. In this paper, we also compare IBID's structure recognition and biology non-experts' structure recognition to discover differences.

Related Research

Despite the enormous potential of biologically inspired design, engineers face many challenges when trying to employ it. Chen and Zhang [18] note that if engineers were able to mimic the ability to harvest water from thin air like the Namib Desert Beetle, many of the water challenges that exist globally could be solved. However, three major challenges exist for engineers [8, 9]:

- *Findability*—finding the relevant articles that address their design issues;
- *Recognizability*—engineers are not necessarily biology experts, and thus have difficultly recognizing that an article is relevant to their design problems.
- *Understandability*—even if engineers find and recognize a biological system in an article, understanding it can still be difficult.

To address these challenges, others have explored methods that take advantage of natural language processing. For example, Nagel et al. [19] designed a system to translate engineering design queries to biology equivalents using an engineering to biology thesaurus that mapped biological terms to engineering function terms.

Shu and Cheong [20] mapped engineering keywords into biological meaningful keywords to retrieve cross-domain information. Helfman Cohen and Reich [10] used engineering functions to describe biological systems. Krupier et al. [21] proposed a system in which relations between individual parts of a system are used in analogical problem solving supporting the notion of taking context into account when analyzing biological systems for design ideas. Their system used certain trade-offs to overcome the inherent limitations of using functions as the starting point of biological abstraction—evolution and environmental shifts have made it difficult to understand why biological systems are organized the way they are [22].

Previous work on IBID involved construction of partial SBF models of biological systems described in biological articles. IBID's domain-specific structure ontology was borrowed from Vincent's ontology [6] of biological systems. The behavior ontology extended Khoo et al.'s cause and effect patterns [23]. The function ontology was developed internally in our laboratory [14].

Rugaber et al. [14] used a passage from Norgaard and Dacke [24] to show how IBID can identify structure, behavior and function in a passage based on the ontologies:

> The mechanism by which fog water forms into large droplets on a beaded surface has been described from the study of the elytra of beetles from the genus Stenocara. The structures behind this process are believed to be hydrophilic peaks surrounded by hydrophobic areas; water carried by the fog settles on the hydrophilic peaks of the smooth bumps on the elytra of the beetle and form fast-growing droplets that - once large enough to move against the wind - roll down towards the head.

The structure identified by IBID is *elytra*, the behavioral cause is droplets *grow* and effect is *roll down towards the head* and the function is *move*.

In our current research, we have developed and used a new domain independent structure ontology. While certain research in the field of biological inspired design incorporates structure in complimentary forms, our system uses structure recognition as a primary conveyance mechanism with a domain-independent ontology that eliminates the difficulty of understandability with using the previous domain-dependent ontology in IBID. The structure recognizer enables biological processes to be found via domain-independent structures in comparison to previous work that focuses on finding biological processes via functions. Designers and engineers are thus provided with the components, elements, and substances of a biological system in a domain independent manner which they can translate into their own field of expertise. They can also use the facet search functionality to find biological processes involving the structures of interest and thereby solve the problem of findability and recognizability.

Intelligent Biologically Inspired Design

IBID is a tool for assisting non-experts in finding design solutions via biological processes. IBID seeks solutions to problems via the implementation of SBF models of technological and natural systems [15, 16]. The SBF modeling scheme is like Gero's FBS scheme in some ways. While FBS originates from early work in the domain of architecture, SBF derives from early AI research on device comprehension called Functional Representation [25]; Goel [15] sketches the evolution of SBF modeling from the Functional Representation scheme. And while FBS is a more informal account of the process of conceptual design, SBF has a syntax and semantics defined well enough to enable qualitative simulation [26].

A specified ontology allows us to define the specification of concepts and relations to other concepts [27].

- Structure Ontology: The components, elements, or substances in a biological process and the connections between them.
- Behavior Ontology: The causal mechanisms by which a biological system realizes its functions.
- Function Ontology: The outcomes and results of a biological system.

Inherently, both the behavior and function parts contain structure concepts, leading to the need to detect and translate structure terms prior to behavior and function terms. IBID operates in a logical manner that is conducive to this ordering by extracting structure terms first.

There are three use cases for IBID as shown in Fig. 1. The first case shows the process of engineers and designers searching for biology articles relevant to their design decisions. The second case shows how knowledge engineers can update ontologies used in IBID and the third case shows how the repository of biology articles is updated by system administrators.

Structure Recognition in IBID

IBID's structure recognition subsystem is responsible for identifying structures that are potentially involved in the SBF representation of a biological process and extracting domain independent concepts from the structures. This approach differs from previous approaches taken [19, 20, 28, 29] that focus on mapping engineering and biology terms as well as more recent approaches taken by Helfman et al. [10] and Krupier et al. [21] that focus on function. Analyzing structure allows IBID to help engineers understand the components of a biological system without having to know specific biological terms and having to use analogous transformations to engineering systems to aid in the design process.

IBID's structure recognition involves three steps: filtering, WSD and cost-first search. IBID filters out verbs, adjectives, pronouns and stop words leaving only

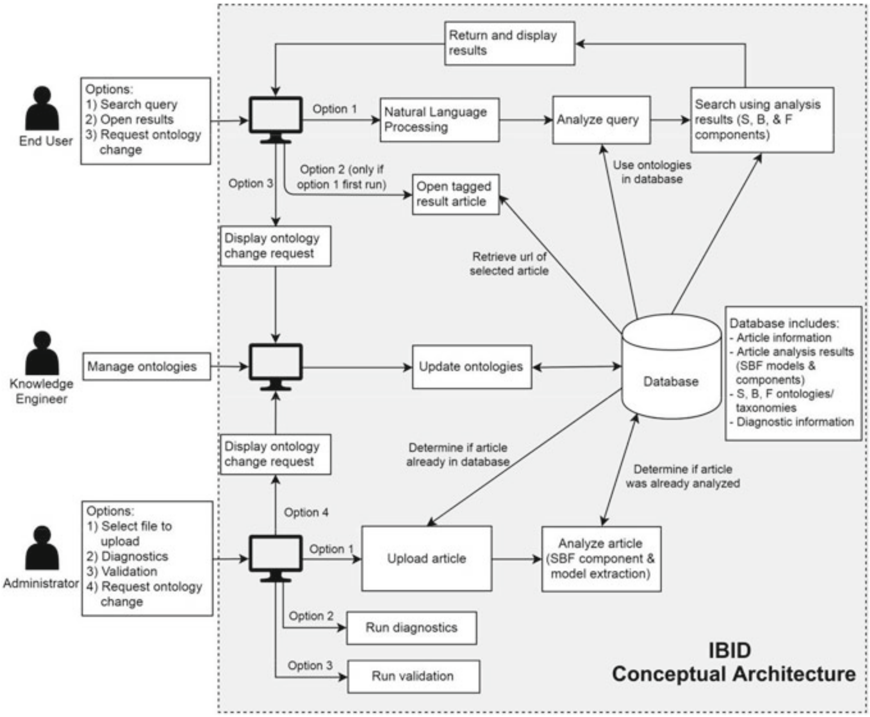

Fig. 1 IBID conceptual architecture (adapted from Goel et al. [13])

relevant nouns that are potential structures in the SBF model. WSD seeks to eliminate two issues noted by Hacco and Shu [30]—1. differences in sense or meaning, and 2. differences in a match relating to abstract versus physical objects. IBID does WSD using the Lesk Algorithm in which the most probable sense of the input word is determined based on the amount of overlap between the context surrounding the word and the dictionary definition and example usages of each of the word's senses [31]. When given a paragraph and a target word whose sense is to be determined as input, IBID's WSD service takes a window of ±2 non-stop words surrounding the target word as the context. IBID then queries WordNet—an electronic lexical database—for the definition and example usages for each of the target word's senses [32]. The most probable sense is the sense with the largest number of overlaps between the set of words in its example usages and definition and the set of words in the target word's context. All the relevant nouns after the filtering step pass through the WSD step as target words. Once the most probable sense is determined for each target word, IBID finds its closest domain independent concept in the domain independent structure ontology using a cost-first search algorithm.

The cost-first search algorithm treats synsets in WordNet [32] as nodes and traverses WordNet by going from a synset to its hyponym synset or to its hypernym synset. A synset is a set of synonyms denoting the same concept. Since synonyms denote the same concept, they are treated as the same node in the cost-first search algorithm. A hyponym synset is a set of synonyms denoting a sub-concept, whereas a hypernym synset is a set of synonyms denoting a super-concept.

Figure 2 shows the pseudocode of the cost-first search algorithm and Fig. 3 illustrates the cost-first search algorithm with an example. Given the input concept synset "paramecium—any member of the genus Paramecium," the algorithm searches its neighboring nodes in WordNet to look for a path that goes from the input concept to any concept listed in the ontology. A neighboring node is either a super-concept or a sub-concept. When conducting the search, the algorithm prioritizes super-concepts over sub-concepts since concepts in the ontology tend to be more general than the biology-specific concepts in paragraphs describing biological processes. In the example shown, the algorithm successfully finds a path between the input concept *paramecium* and the concept *animate thing* in the domain independent structure ontology. This path consists of paramecium (input), ciliate (super-concept of paramecium), protozoan (super-concept of ciliate), protoctist (super-concept of protozoan), microorganism (super-concept of protoctist), organism (super-concept of microorganism), and animate thing (super-concept of organism).

Figure 4 shows some of the concepts that are in the domain independent structure ontology. The ontology was developed in several iterations using the hyponym-hypernym relationships in the WordNet taxonomy. We started with a subset of structural concepts [33] used in our earlier work on creative problem solving in science [34]. We added concepts and generalized sub-concepts into their super-concepts. For an input concept, the algorithm finds the path with the shortest length among the multiple potential paths into the ontology. As demonstrated in Fig. 3, the nodes denote concepts, and the edges denote the relationships among them. We have arbitrarily defined the edge between a concept and its super-concept to have a cost of 1.5 and the edge between a concept and its sub-concept to have a cost of 2 so that a super-concept is considered closer than a sub-concept. Distance between two concepts is the total length (cost) of the edges between them. The algorithm first searches in the vicinity of the input concept i.e., its neighbors and then the neighbors of each neighbor, to see if a visited node is a concept in the ontology; the algorithm expands its search area until it finds a concept in the ontology or reaches the maximum search distance of 20. In the example illustrated in Fig. 2, *animate thing* is the closest domain independent ontology concept the algorithm finds when given the input concept *paramecium.*

Positive Example of IBID's Structure Recognition

Figure 5 below illustrates the flow of IBID's structure recognition with an example. The structure recognition subsystem takes a paragraph describing a biological process as the input:

> Two types of genes normally control the cell cycle: proto-oncogenes, which start cell division and tumor-suppressor genes which turn off cell division…

```
Procedure CostFirstSearch(startConcept)
        Input
                startConcept: start concept
        output
                path from the start concept to a concept in the domain independent structure
        ontology or None if there are no solution paths shorter than the length limit
        local
                Frontier: a Priority Queue of PathNodes ordered by cost
                Explored: set of nodes that have been expanded

        Frontier ← Empty Stack
        Frontier.add(PathNode(startConcept, None, 0))
        Explored ← { }
        largestDistance ← 0
        while (Frontier is not empty and largestDistance <= DISTANCE_CAP)
                pop currentNode from Frontier
                currentConcept ← currentNode.concept
                path ← currentNode.path
                cost ← currentNode.cost
                Explored ← Explored Union {currentConcept}
                if (currentConcept in domain independent structure ontology) then
                        return path
                For all {hypernym concepts}
                        path ← path + hypernymConcept
                        cost ← cost + cost(<currentConcept, hypernymConcept>)
                        if ((hypernymConcept not in Explored AND hypernymConcept not in
Frontier) OR cost < cost of hypernymConcept in Frontier) then
                        Frontier.add(PathNode(hypernymConcept, path, cost))
                For all {hyponym concepts}
                        path ← path + hyponymConcept
                        cost ← cost + cost(<currentConcept, hyponymConcept>)
                        if ((hyponymConcept not in Explored AND hyponymConcept not in
Frontier) OR cost < cost of hyponymConcept in Frontier) then
                        Frontier.add(PathNode(hyponymConcept, path, cost))
        return None
```

Fig. 2 Cost-first search pseudocode

After filtering, the relevant nouns in the order of their occurrences in the paragraph are types, genes, cell, cycle, proto-oncogenes, cell, division, genes, cell, division…These nouns are sent to the WSD module along with their contexts. WSD infers the intended sense for the input nouns based on their contexts and glosses (synset, definitions and example usages) stored in WordNet. For example, when inferring the intended sense for the word cell, it queries WordNet for a list of senses and their glosses:

0. Cell: (any small compartment) "the cells of a honey-comb"

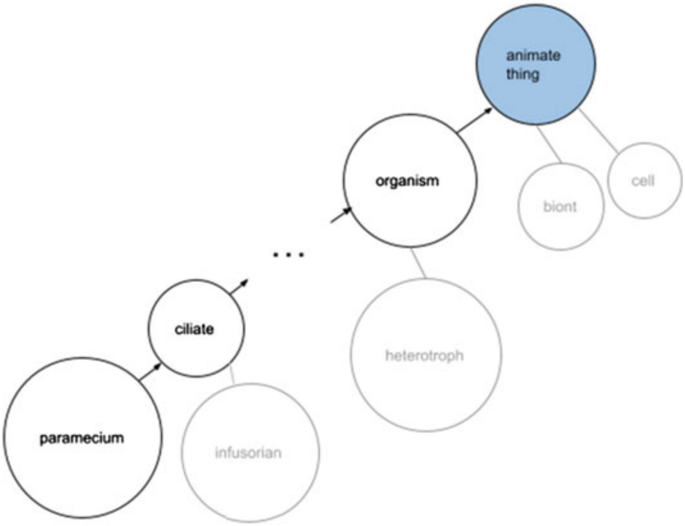

Fig. 3 Cost-first search example

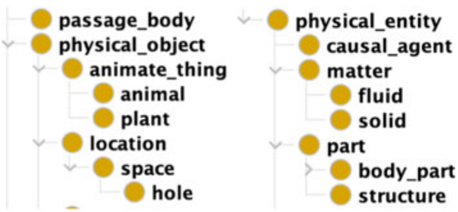

Fig. 4 Two small excerpts of IBID's domain independent structure ontology

1. cell: (biology) the basic structural and functional unit of all organisms; they may exist as independent units of life (as in monads) or may form colonies or tissues as in higher plants and animals) …

The context for a word is the ±2 window of non-stop words surrounding it. In the case of the word cell, the context is the words normally, control, cell, cycle, proto-oncogenes. The WSD module infers that the intended sense for the word cell by calculating the overlap between its context and each of its glosses and decides that the most probable sense is its second sense indicated by the index 1—(biology) the basic structural and functional unit of all organisms; they may exist as independent units of life (as in monads) or may form colonies or tissues as in higher plants and animals—in its list of senses.

The cost-first search algorithm receives the word-index tuple *cell, 1* as the input concept and tries to find a path that leads to a concept in the domain independent structure ontology. In this case, it finds the path *cell, animate thing*.

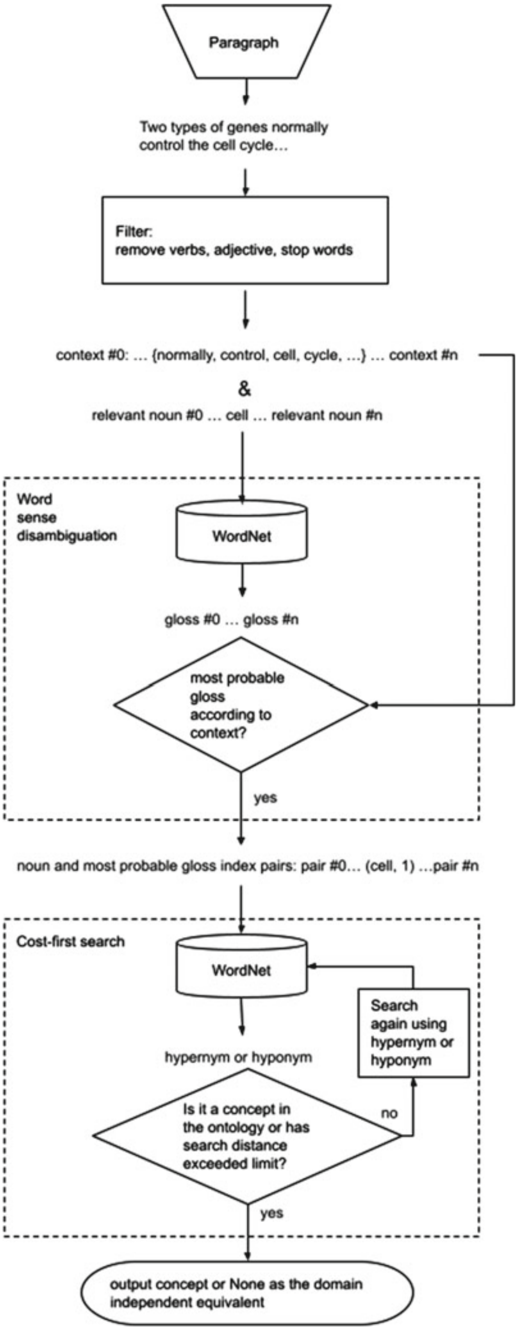

Fig. 5 Structure recognition in IBID

Negative Examples of IBID's Structure Recognition

We recognize that there are two main factors influencing the accuracy of structure recognition: the filter may eliminate words that are relevant or fail to eliminate words that are irrelevant, and the WSD module may fail to infer the correct sense for the input word. For example, IBID failed to eliminate words that were irrelevant in the paragraph that describes genes controlling cell cycles given above. When processing the *genes* paragraph, IBID's filter determined the word *types* as relevant.

IBID may also fail to infer the correct sense of a target word. For example, IBID failed to infer the correct sense of the target word *root* in the paragraph that started with "roots commonly pass-through dry soil layers to layers that contain more moisture." Instead of the first sense—"root:(botany) the usually underground organ that lacks buds or leaves or nodes; absorbs water and mineral salts; usually it anchors the plant to the ground," IBID inferred that the intended sense was the second—"beginning, origin, root, rootage, source: the place where something begins, where it springs into being."

Experimentation and Results

To test the effectiveness of IBID's structure recognition subsystem, we used it to detect structural elements from four paragraphs describing different biological processes and conducted a pilot study in which we compared IBID's structure recognition to that of a group of biology non-experts who undertook the same structure recognition task as IBID did.

In total, twelve participants completed the experiment. The participants had taken 1.9 college level biology classes on average. Before the task, the participants were educated about the SBF model technique. Their understanding of the structures in the SBF model was assessed using a quiz question. They then read four paragraphs, each describing a biological process: *eels catching prey, roots transporting water, paramecium eating food, and genes controlling cell division.* The participants were asked to highlight relevant words in the paragraphs they thought were biological structure terms. They were provided with the domain independent structure ontology that IBID used and asked to select the concept that best classified each word they highlighted or write down *other*.

Comparing IBID's Results and the Humans' Results

We compared the relevant terms identified by IBID with those identified by the participants, as well as the domain independent structure IBID extracted with those the participants selected for each relevant term. The criterion for determining whether the participants as a group thought of a word as relevant was at least a 50% highlight rate. Table 2 shows a sample of the fourteen relevant nouns the participants agreed on across the four paragraphs.

Figure 6 shows the criteria for determining a match when comparing IBID's extracted concepts and the participants' extracted concepts. Circle 1 represents all the words in the input paragraph excluding the stop words. Circle 2, 3 represent the words highlighted by at least one participant and the words identified as relevant by IBID respectively. Circle 4 represents the words highlighted by at least 50% of participants and is shown as a subset of circle 3 given IBID's high recall. The domain independent concept for a word in circle 4 was the most frequently selected concept for that word (circle 6). Circle 5 represents the domain independent concepts IBID extracted from the set of words represented by circle 4. The overlap between circle 5 and circle 6 represents the set of matching domain independent concepts between IBID and the participants.

Table 1 shows the Cohens Kappa metric for IBID and for the participants who incorrectly answered the quiz question when treating the set of relevant words produced by the correct quiz group as "ground truth." Each row of Table 2 contains a relevant noun, its IBID concept, its IBID concept after adjustments, the equivalent concepts selected by the participants and the type of mismatch between IBID and the participants. For a relevant noun, the number in the parenthesis following a human concept denotes the number of participants who selected this concept, the IBID concept column contains the domain independent concept IBID recognized, and the IBID concept-adjusted column contains the IBID concept after the ontology adjustment and criteria relaxation. The type of mismatch column contains the classification of the mismatch between the IBID and the human concepts.

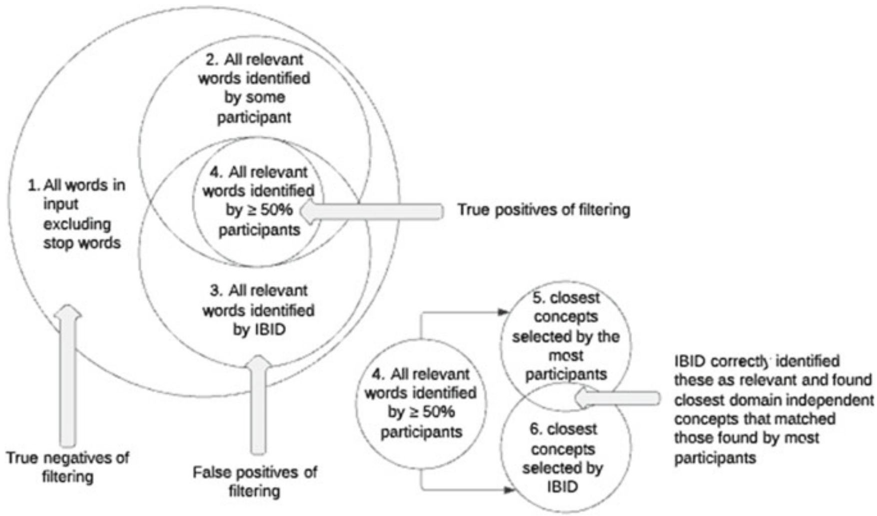

Fig. 6 Metrics for the filtering step

Table 1 Cohen's Kappa using the correct quiz group as "ground truth"

	IBID versus correct quiz group (%)	Incorrect quiz group versus correct quiz group (%)
Eels	35	10
Roots	28	13
Paramecium	65	15
Genes	35	4

Table 2 IBID's mapped concepts vs human selected concepts (truncated)

Relevant noun	IBID concept	IBID concept adjusted	Human concept	Type of mismatch
Eels	Solid	Matter	Agent (6) Animal Physical entity	WSD
Prey	Agent	Agent	Agent (4) Animal Animate thing Physical entity Physical object	Match
Volleys	Activity	Activity	Agent Matter (2) Part Physical object Process (2) Substance	Human disagreement
Genes	Grouping	Grouping	Agent (4) Component Part Physical entity Substance	Function/context

Out of the fourteen domain independent concepts for these words, there was one match between IBID's extracted concepts and those of the participants. After the adjustment and criteria relaxation, the number of matches increased from one to six.

Adjusting for Sources of Discrepancies via Adjusting the Ontology and Relaxation of Matching Criteria

We identified four factors contributing to the discrepancies between the participants' results and IBID's results:

1. The average level from which the participants selected the domain independent concepts was only 1.07, whereas the average level from which IBID found

concepts was 1.45. The ontology has a hierarchical structure. The higher the level number, the deeper down the hierarchy a concept is.

2. There was a high likelihood of disagreement among the participants in selecting the closest domain independent concept for a relevant word as shown in Table 2.
3. The participants selected domain independent structure concepts whose definitions implied their involvement in functions, indicating that the participants were able to take the function of the biological process into account.
4. IBID sometimes made WSD mistakes.

To adjust for the participants' tendency to select more abstract concepts and their high likelihood of disagreement, we removed level 2 and below of the ontology and relaxed the criteria for determining whether there's a match between IBID's and the participants' domain independent concepts. We required only that IBID's extracted concept matched any of the participants' concepts.

We generated an extra set of IBID domain independent concepts for the relevant words using the adjusted ontology. We decided that there was a match if either of the IBID concepts extracted using the adjusted ontology or one using the complete ontology matched any of the participants' selected concepts. This increased the number of matches. The remaining mismatches could be attributed to WSD mistakes and the participants' ability to take the function of a biological process into account when extracting structures.

Discussion

While previous work on IBID [14] has focused on extracting functions and behaviors, our current research aims to develop and test a computational technique for extracting structures. We discovered a few differences between IBID and the participants. Biology non-experts could be imprecise when extracting domain independent concepts from biological processes and there was a high rate of disagreement among them. Their tendency to choose more abstract concepts indicated that they preferred a top-down approach in which they stopped searching down the ontology as soon as they encountered difficulty in deciding which sub-concept to select. On the contrary, IBID usually took the bottom-up approach since the relevant nouns in the biological processes were usually more specific than the concepts in the ontology. However, our sample size of twelve was small and more data should be collected. Nevertheless, we were able to observe discrepancies between the participants' results and IBID's results and plan to recruit many more participants for future studies.

Regardless of the small sample size, the imprecision of biology non-experts shows the need for a tool such as IBID. While the non-experts chose a variety of domain independent concepts for the same word, IBID's cost-first search algorithm always found the same concept for the same word sense given its deterministic nature. Therefore, IBID may help non-experts understand biological systems more precisely by eliminating the need for them to determine structural elements using limited domain knowledge. The similarity between IBID's set of relevant nouns and the relevant nouns produced by the correct quiz group is higher than the similarity between the relevant nouns of the correct quiz group and that of the incorrect group according to the Cohen's Kappa scores.

The concept agent—any entity that produces an effect or is responsible for events or results—was frequently selected by participants as the domain independent concept. This caused function/context mismatches sometimes as the concept of agent implied its role in a function. A function/context mismatch happened when the participants took the function of the biological system into account when deciding the structure concept. This violated the "no-function-in-structure" principle described in De Kleer and Brown [35], as the selection of structure concepts that involved functions indicated that non-experts preferred "function-in-structure". However, there is inherent difficulty in eliminating context from structure, as how a component functions in a certain situation is apt to have a subtle influence on the way it is perceived [36].

As mentioned, given that there was a high rate of disagreement among the participants and that they tended to choose more abstract concepts than IBID did, IBID has the potential of helping non-experts understand the structures of biological systems more precisely after improvements that remove the identified sources of mismatches. Regardless of the imprecision, the benefits of IBID are illuminated by this finding: IBID is more precise and does context-free structure extraction and has a vast vocabulary of biological terms to draw from, enabling the potential of helping non-experts in biology understand biological systems more precisely by removing the inherent difficultly in cognitively separating a structure from its isolated and contextual forms. In fact, results after the adjustments show that the difficulty in separating structures from their contextual forms accounted for 4 out of 7 mismatches between the participants' and IBID's structure recognition results after adjusting for participants' tendency to disagree and prefer more abstract structure concepts. Our structure recognition circumvents the difficulties of starting biologically inspired design with function that Kruiper et al. [21] sought to address by separating structure and function.

Cheong and Shu [28] note that designers tended to rely on non-analogous associations rather than analogical reasoning. Our structure recognition approach provides a way for designers to engage with a tool that performs part of the analogical reasoning—cross-domain "bridging"—for them by extracting the domain independent structures from biological processes. A future functionality we want to support is the tunability of IBID's filter so that the user can adjust the number of relevant nouns IBID identifies. A potential future experiment would be to allow human subjects to select the structures from paragraphs without categorizing them and instead see if they agree with IBID's classifications.

Conclusions

While other research in the field of biological inspired design focuses on directly translating engineering keywords into biological keywords, on using functions as the starting point of biological abstraction, and on extracting domain-specific structures, our research's focus is on structure extraction using a domain independent ontology that acts as the bridge between the biology domain and the engineering domain. In the experiment described above, IBID's structure recognition technique successfully extracted domain independent structure concepts from various biological processes despite some discrepancies between IBID's and the participants' structure recognition.

Acknowledgements We thank the members of the Georgia Tech's Design & Intelligence Laboratory for their assistance with the IBID experiment. We are grateful to Julian Vincent for sharing his ontology of biological systems [6]: while we built the domain-independent ontology of structure from our earlier work, IBID uses his domain-specific structure ontology. This research was supported by internal seed grants from Georgia Tech.

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Generative Design Ideation: A Natural Language Generation Approach

Qihao Zhu and Jianxi Luo

This paper aims to explore a generative approach for knowledge-based design ideation by applying the latest pre-trained language models in artificial intelligence (AI). Specifically, a method of fine-tuning the generative pre-trained transformer using the USPTO patent database is proposed. The AI-generated ideas are not only in concise and understandable language but also able to synthesize the target design with external knowledge sources with controllable knowledge distance. The method is tested in a case study of rolling toy design and the results show good performance in generating ideas of varied novelty with near-field and far-field source knowledge.

Background

The performance of human design ideation is often limited by the designers' knowledge scope, which hinders them from exploring external inspiration and opportunities to be applied in the domain of interest. In this section, we discuss the need of generative and knowledge-based AI tools for design ideation process and introduce the recent advance of pre-trained language model that we use in this study to develop such a tool.

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Computer-Aided Design Ideation

"What to design?" is a common question for designers and companies when developing innovative products. At the early design stages, the quantity and diversity of conceptual design ideas are essential for designers to explore new design opportunities departing away from existing designs. However, the well-recognized features in existing designs can continuously fixate designers' thinking and limit their capability of generating novel ideas [1]. Traditional approaches to overcome design fixation include brainstorming and design heuristics [2, 3], which have been proven effective to improve creative thinking and help designers to think out-of-the-box. However, apart from design thinking, the limitation of designers' knowledge base is also an important source of design fixation.

In recent years, knowledge-based methods and tools have been developed for computer-aided ideation. For example, AskNature is a web-based tool that provides a large variety of biomimicry knowledge and strategies for designers to draw inspiration from nature [4]. Luo et al. introduced InnoGPS to guide the provision of design stimuli from the patent database by their knowledge distance to the design problem or interest [5]. Sarica et al. developed the technology semantic network for identifying technical white space according to the semantic distance between the design target and the stimuli [6, 7]. These approaches are design stimulators that systematically provide knowledge-based inspirational stimuli to provoke designers during ideation.

On the other hand, researchers have also been exploring generative approaches that automate the early phase design process. For example, generative grammars are used to encode design knowledge computationally, which can be used to rapidly generate design alternatives [8]. However, the graphical design representation from this approach can be too abstract for designers to articulate, and therefore further inference is needed to generate useful design ideas. Moreover, the recent advance of AI has led to deep generative models, such as Generative Adversarial Networks (GAN) and Variational Autoencoders (VAE), which have been increasingly popular in design automation [9]. These models learn from the visual design knowledge like images or meshes and generate design concepts also in visual representation. This makes them more suitable for embodiment and detailed design rather than the early-stage design process of ideation. Therefore, the knowledge-based and generative ideation method is still an open arena in design research.

Figure 1 shows different computer-aided ideation modes in terms of human–computer collaboration. Figure 1 (a) is the most common scenario where humans generate ideas, and record, analyze and improve them with the aid of computers. In scenario (b), computers provide stimuli to inspire human designers to generate ideas. Many existing computer tools, such as InnoGPS, can facilitate such a process. In scenario (c), computer-based tools generate the ideas for human designers to evaluate, select and improve. The computer-generated ideas could also provoke designers to be more creative with the extended knowledge that comes with the generated ideas. Scenario (c) is of the central interest of the present study.

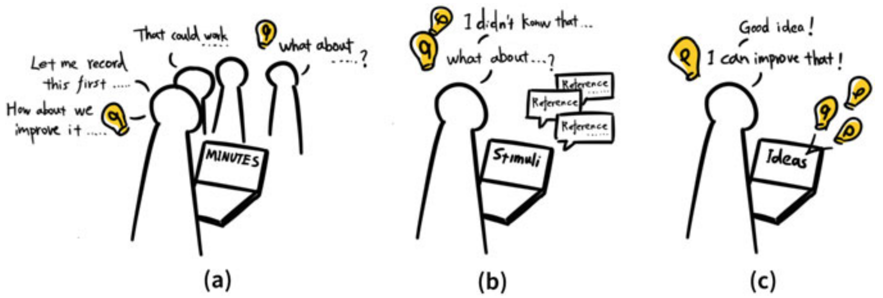

Fig. 1 Human–computer collaboration in different ideation approaches: **a** brainstorming, **b** stimuli-based approach, **c** generative approach

Pre-trained Language Model

Pre-Trained Language Model (PLMs) are language models that have been trained with a large textual dataset collected from varied sources including Wiki, books, and web data, and can be applied to deal with specific language-related tasks [10]. In recent years, transformer-based language models have been achieving state-of-the-art performance on many tasks. For example, the generative pre-trained transformer (GPT) [11, 12] is one of the most popular series of PLMs. GPT-2 [11] is trained on 8 million documents of web data and can perform different downstream language-related tasks after fine-tuning. Fine-tuning is a training technique that uses a relatively small dataset of the task of interest to retrain a large pre-trained model. Since being released, GPT-2 has achieved dramatic improvement on natural language generation (NLG) tasks like natural language inference and question-answering. GPT-3 [12] is the largest PLM nowadays and was trained on a 500 billion tokens dataset. This powerful model is designed for prompt-based learning that requires only a few examples of the specific task to achieve outstanding performance.

Another important transformer-based PLM is the Bidirectional Encoder Representations from Transformers (BERT) [13], which was trained with Wiki and books data that contains over 3.3 billion tokens. BERT is commonly used in natural language understanding (NLU) tasks such as text classification and keyword extraction. However, as a masked language model, BERT is generally weak at NLG, because it can only learn the contextual representation of words [10].

The state-of-the-art network architecture of transformers, as well as the huge pre-training datasets, offer PLMs not only the capability of learning human language, but also the knowledge and logic that come with it. By applying PLMs, knowledge-based systems could leverage a wide range of knowledge without the need for manual formulation and inference.

Aim

Existing computer-aided ideation methods can retrieve external knowledge as stimuli but lack the ability to generate and represent ideas in understandable forms. Therefore, experiences and skills are still required for designers to generate and articulate creative ideas when using these methods, and the quality and quantity of the alternatives for the convergence of ideation are dependent on the designers. Moreover, when using external knowledge as stimuli during ideation, far-field stimuli tend to yield more novel but less feasible ideas comparing to near-field stimuli [5]. The present research aims to quickly generate ideas in a given domain of interest that take near-field or far-field external knowledge as inspiration, and at the same time, in the understandable representation of natural language.

Furthermore, we aim to explore the use of generative pre-trained language models in developing an effective knowledge-based expert system for conceptual design and fill in the gap that transformer-based AI models have yet to be seen utilized in the design community [8].

Significance

This research will leverage the recent progress of natural language processing (NLP) to creative design ideation tasks and provide new insights into computer-aided design ideation. For novice designers, engineers, or students, this approach can help them think out of the box. It can also help experienced designers ideate with an extended knowledge base. Moreover, the generated ideas in human language could provoke the designers for even more ideas, like the inspirational human-to-human interactions in the brainstorming process, just this time the brainstorming will be happening between humans and computers (Fig. 1c). This will not only boost the diversity and speed of the generation of initial ideas but also potentially change the human–computer interaction during ideation.

Method

Luo et al. [5] introduced InnoGPS (http://www.innogps.com/), a knowledge-based design expert system based on all USTPO patents from 1974 to 2020 that guides the retrieval of near-domain and far-domain stimuli by knowledge distance to aid creative design ideation. In this work, we employ InnoGPS to gather patent data and assess knowledge distance.

Figure 2 shows the dataset preparation, fine-tuning, and idea generation processes in our method. For a specific domain as the knowledge source, we gather the titles of the patents in this domain from InnoGPS and extract a keyword for each title using

KeyBERT. KeyBERT [14] leverages BERT embeddings to extract keywords and key phrases that best represent a document. The prepared dataset containing keyword-title pairs in the selected domain is then used to fine-tune the base model of GPT-2. Finally, given any target keyword representing the home design, the fine-tuned model will generate ideas for the target design based on external knowledge learned from the selected domain. The example in Fig. 2 shows how the model can learn from an external domain and generate rolling toy ideas based on it.

In this way, thanks to the knowledge learned from both the commonsense pre-training and domain-specific fine-tuning data, the model can leverage the source knowledge in a way that is potentially applicable to the target, and thus generate novel and useful ideas.

In a practical design ideation scenario, the proposed method can be used with InnoGPS to explore external knowledge domains before generating ideas. Figure 3 depicts the workflow. After inputting a keyword of the target domain of interest in InnoGPS, the user will be directed to a list of nearby domains in the order of

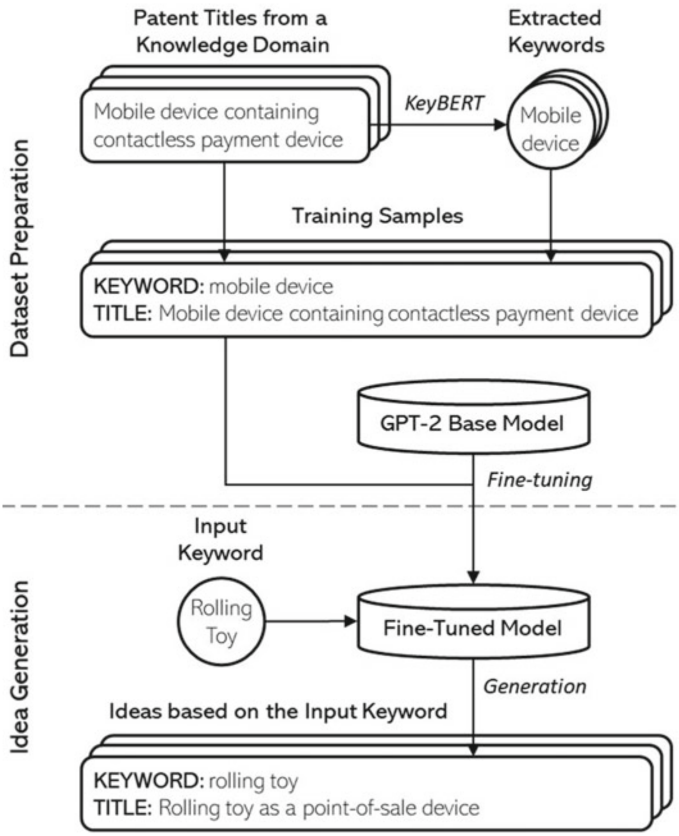

Fig. 2 GPT-2-based idea generation workflow

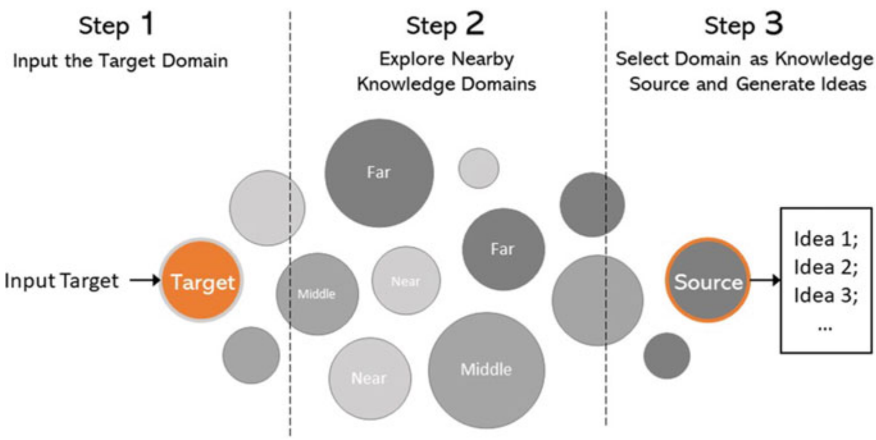

Fig. 3 Workflow of using the proposed method with InnoGPS

their knowledge distance proximity (as quantified in InnoGPS) to the target domain. Selecting a domain as knowledge source will generate ideas based on both the target and source domains. Each knowledge domain in the expert system, e.g., InnoGPS in this case, can have a fine-tuned GPT-2 model to generate ideas as the user may request, just like a virtual domain expert that can ideate for the user. Different virtual experts whose knowledge with varied knowledge distance to the target design may help generate new ideas with varied novelty and feasibility.

Case Study and Results

Consistent with the case study conducted by Luo et al. [5], this experiment focuses on the design ideation of rolling toys and retrieving design stimuli from near-domain and far-domain knowledge. Six domains are picked as references according to their rank order by knowledge proximity to rolling toys: (1) Weapons, (2) Agriculture, (3) Lighting, (4) Drilling & Mining, (5) Grinding & Polishing, and (6) Fuels & Lubricants. Regarding knowledge distance calculation, please refer to Luo et al. [5]. The first three domains are relatively near-field (13th, 17th, 28th nearest, respectively) while the other ones are considered far-field (64th, 68th, 100th nearest, respectively). These domains vary a lot regarding the number of patents they hold. To control variables and test for performance, we picked the latest 20,000 patents from each domain to form our fine-tuning dataset. Moreover, the titles of the chosen patents all have more than three words because we want the model to learn to generate ideas that contain more information. Otherwise, the model will be more likely to simply repeat the keyword without adding any useful insights.

For this study, we use the 355 M base model of GPT-2, and each model is fine-tuned for 20,000 steps with a batch size of 1. Figure 4 shows the fine-tuning loss of each

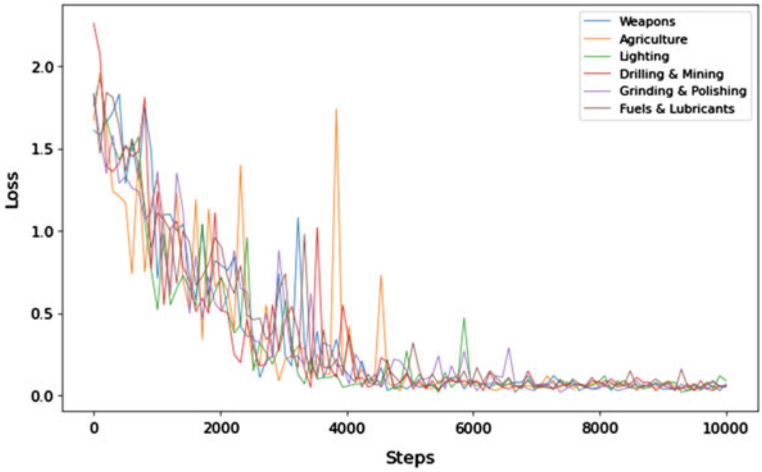

Fig. 4 Training loss during the fine-tuning of the models

model during the first 10,000 steps. The loss is stabled afterward. The fine-tuning loss is plotted every 100 steps.

For idea generation, we use the parameters of 'temperature = 0.9; top-k = 50' to enable a more randomized generation for more creative ideas. 500 rolling toy ideas are generated by the virtual domain expert (i.e., fine-tuned GPT-2 based on each domain's knowledge) and the unique ones are selected for further analysis. Table 1 reports the percentage of unique ideas from each domain and some examples of generated rolling toy ideas.

In general, the proposed method can generate understandable and concise ideas in natural language that take advantage of external knowledge. This can be potentially valuable for the ideation with both near-field and far-field knowledge sources. For example, given near-field stimuli of weapons, rolling toy designers may quickly come to the idea of "adding a gun or other shooting mechanism to the rolling toy" and then fixate on it. Our model, in addition to that, suggests that the rolling toy can also be designed into a moving shooting target or dart board based on the domain of weapons. For far-field stimuli, the model can also provide ideas as inspiration when designers find it challenging to synthesize such knowledge.

Furthermore, as addressed by Luo et al. [5], when ideating with external knowledge, the design ideas that synthesize far-field source knowledge could be more novel compared to those utilizing near-field stimuli. Therefore, our hypothesis is that the ideas generated by GPT-2 may follow the same pattern, i.e., far-domain virtual expert models may generate ideas with overall more novelty than near-domain virtual expert models.

To test the hypothesis, we employ TechNet [6] as a tool to measure idea novelty. When measuring term-term relevancy in TechNet, the lower relevancy score means the given pair of terms are more semantically distant in the design context. Thus, by

Table 1 Results of rolling toy idea generation

Domain	% Unique ideas	Examples of generated ideas
Weapons (13th nearest)	35.8% (179/500)	• Rolling toy wheeled target • Rolling toy projectile launcher • Rolling toy dart board capable of making turns • Rolling toy air gun
Agriculture (17th nearest)	40.8% (204/500)	• Rolling toy bale wrapper apparatus • Rolling toy saddle with pressure adjustment • Rolling toy bump stop device • Rolling toy with liquid container
Lighting (28th nearest)	69.6% (348/500)	• Color changing LED roll toy • Musical spell-playing rolling toy • Rolling toy and cart with a plurality of removable LED-units • Lighting device for rolling and adjusting a light source
Drilling and mining (64th nearest)	69.8% (349/500)	• Rolling toy spindle drive system • Rolling toy deflector and method of use • Rolling toy anti-locking system and method • Rolling toy spinner reel
Grinding and polishing (68th nearest)	76.4% (382/500)	• Fixture for rolling toy sleeves • Deep rolling toy arm with interchangeable rolling force • Nozzle device for the rolling of a rolling toy • Children's rolling toy mill with disconnected work stations
Fuels and lubricants (100th nearest)	68.6% (343/500)	• Lubricant for rolling toy made from colored aluminum alloy and coated with an acetylene-based additive • Toy diesel fuel production system and rolling toy vehicle • Toy with rolling bearing and friction mechanism • Electrical tool and planer for use in a rolling toy

extracting all term pairs in a generated idea and calculating their semantic distances, the minimum value among them can be used to estimate the degree of novelty regarding the knowledge distance within the idea. The lower minimum score means a more novel idea. Figure 5a reports the results of such evaluation.

In TechNet, as reported by Sarica et al. [6], the estimated mean value of the term relevancy score is 0.133 (shown as the blue line). It means the ideation using either near-field or far-field models achieves an overall good novelty. Note that this

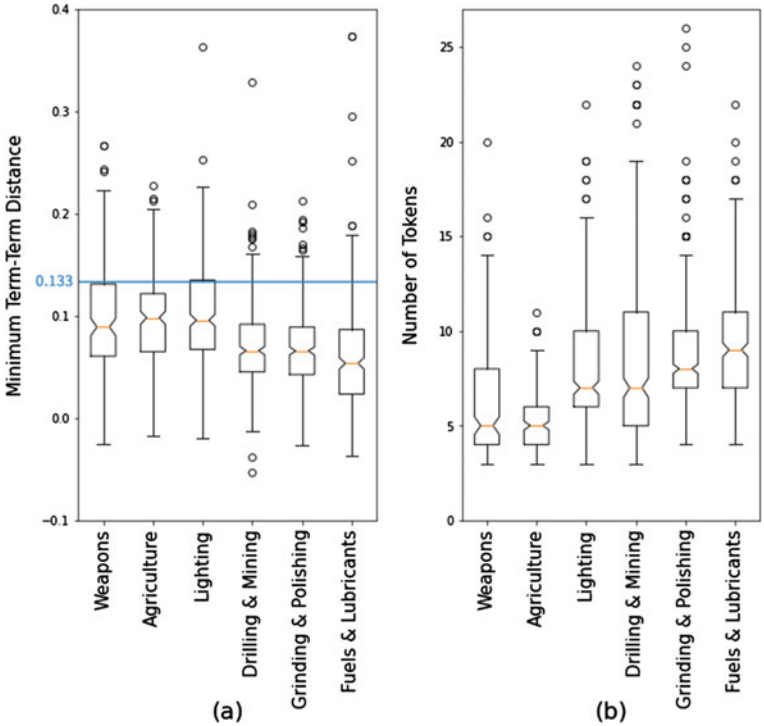

Fig. 5 Distribution of the minimum term-term semantic distance (**a**) and number of tokens (**b**) of the generated ideas

mean value was calculated using 10^8 different pairs of terms. In real contexts, the more relevant pairs will appear more commonly, thus making the mean value even higher. Moreover, according to Fig. 5a, ideas generated by the far-field domain expert models achieve generally lower relevancy scores than those by near-field models, thus verifying our hypothesis. However, as shown in Fig. 5b, far-field models tend to generate longer ideas which are likely to contain more details. The richer details could also be the source of the lower minimum relevancy because it could increase the probability of the co-occurrence of terms with low relevancy.

In Fig. 6, we present four sketches drawn by the first author that are derived from the ideas generated from our near-field and far-field expert models, representing the initial embodiment designs of the concepts.

Figure 6 (a) is a moving and rolling dartboard that provides a challenging game experience, it has two boards on the sides and can switch sides by turning around; (b) is a rolling light source that can move around with the target that it aims to lighten, and with a well-designed algorithm it will also be able to focus the light on the target while moving; (c) is a rolling reel robot that can lay cables or wires in any desired routes, which could be helpful to lay cables in narrow places that human cannot reach; (d) applies nozzles in rolling toys that could entirely change the way that they

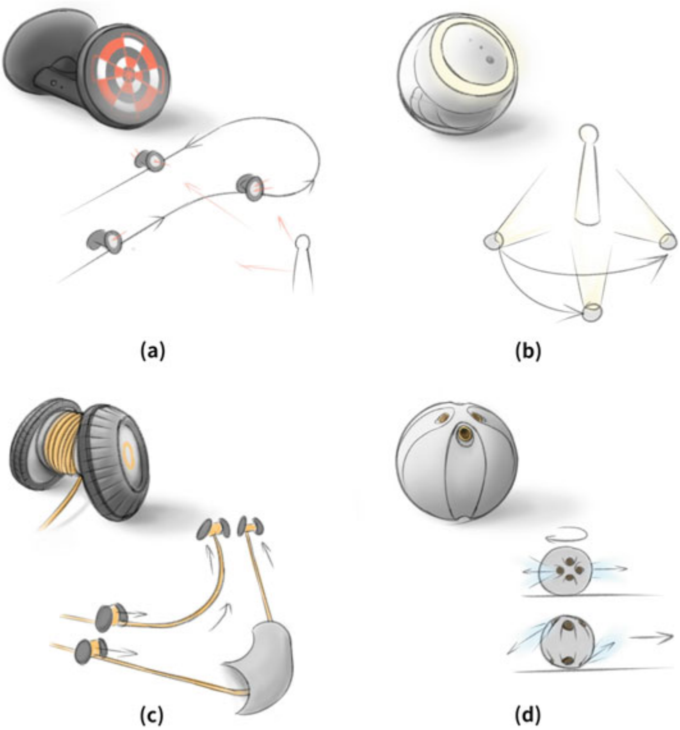

Fig. 6 Sketches based on the generated ideas: **a** Rolling toy dart board capable of making turns (weapons); **b** lighting device for rolling and adjusting a light source (lighting); **c** rolling toy spinner reel (drilling & mining); **d** nozzle device for the rolling of a rolling toy (grinding & polishing)

roll. This is done by using 8 nozzles that aim at different directions to create force in those directions, controlling the timing and strength of the nozzles will result in different movements. All the above concepts are selected and developed from the ideas generated by our method which are listed in Table 1. The initial generated ideas of the concepts are shown in the caption of Fig. 6.

Discussion and Future Work

The proposed study explores a novel generative approach to design ideation which utilizes the fine-tuning mechanism of GPT to leverage knowledge understanding and domain synthesis. The method's capability of generating novel and understandable ideas is verified in a rolling toy design project. We also show that the minimum term-term relevancy score can be used as an evaluation metric for idea novelty. In real ideation practice, not all output from our approach can be directly usable for progressing into the next stage of the design process. Designers may come across unfamiliar terms in the output that indicate unfamiliar knowledge, and therefore need further investigation to make sense of the ideas. The output may also vary in quality and some of the results could make less sense, especially for those generated with far-field knowledge. The proposed method is not expected to be a 'machine designer' that design concepts automatically, but a design assistant that ideate and brainstorm with human designers to boost their creativity. Thus, designers' efforts are still required to develop sketches as in Fig. 6 from generated ideas as in Table 1.

However, a statistical assessment approach regarding the performance of the idea generation and the quality of ideas is still a challenge in this context. Natural language understanding and sentence embedding techniques (e.g., BERT) could be an option for bridging this gap and will be explored in future works. Moreover, as an initial attempt at idea generation using natural language generation, this paper does not validate the choices for the subsystems and how they might affect the performance, e.g., what if we use GPT-3 to do few-shot learning for the generation of ideas? This will also be tested in the future with both machine and human calibration.

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The ABC (Affordance-Bias-Cognition) Reasoning of Product-Use Interaction: A Text Mining Approach

Nicola Melluso, Gualtiero Fantoni, and Antonella Martini

Abstract The main approaches to study the cognitive aspects of product-use interaction involve many theoretical models that map the match or mismatch among the users' and designers' knowledge, beliefs, and expectations into positive interactions (affordances, alternative uses) or negative interactions (misuse and failure). However, these assumptions have only been approached theoretically and hardly find empirical consensus in Engineering Design. For this reason, the aim of this paper is to show how it is possible to apply Text Mining to empirically demonstrate a theoretical model developed to interpret the cognitive aspects of product-use interaction. We approached this study by analyzing the textual content of patents to empirically demonstrate the reasoning of the following cognitive aspects: affordances, bad design, and bias. In particular, we developed a framework called Affordance-Bias-Cognition (ABC) reasoning that aims at demonstrating that when humans (designers or users) approach objects, they follow a well-defined pattern of cognitive activities (or phases): cause, perception, interpretation, manipulation, and check. Furthermore, we demonstrate that affordances, bad design, and bias follow the same cognitive processes, and that differs only because users and designers, acting like humans, have misconceptions that lead to positive and negative interactions.

Introduction

The latest design theory research has produced valuable works to aid engineers in approaching user- or human-centered design philosophies that focus on studying

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human perception and cognition [1]. This bridge between psychology and design mainly focuses on studying product-use interaction [2] with a particular focus on understanding how the human cognitive apparatus perceives the world [3]. As a result, the study of psychological dimensions is becoming highly relevant to design optimization and evaluation [4].

The most important consideration that has to be discussed regards the mental (or cognitive) processes that are involved in the human interaction with designed items. In particular, we need to consider that when a human (or user) interacts with objects, this interaction becomes a matter of subjective processing of information [1]. Under this assumption, when considering the design process, designers need to consider the cognitive processes of the potential user interacting with the designed items.

From the best of our knowledge, a product-use interaction can result in four outcomes: affordances, misuses, failure and alternative uses. This is well stated by Cascini et al. [3] that justified these outcomes of the interaction as a mismatch between the knowledge and experience of the designer and the user. When a designer designs a product, he uses his knowledge, experience and beliefs to simulate how the user approaches the product. The match or mismatch between the simulation of the designer and the actual interaction of the user generates affordances, misuses, failures or alternative uses.

In this paper we use patent data to study the mental processes that occur during product-use interaction. The reason why we believe patents are suitable for this study is that these documents always have a section (called "Background") in which is described the prior art of the invention. Typically, this background identifies the technical gaps of previous inventions providing textual description of some problems and of some use cases of product-use interaction. This document structure makes the patent suitable for the study of what designers write about product-use interaction. Moreover, given that a patent is written in plain text, we make use of a Text Mining approach to perform our experiments.

The research question of the paper can be framed as: what are the cognitive aspects of product-use interaction? To answer this question we approached methodologically with a novel approach: using Text Mining of patent data. Typically, the study of product-use interactions is approached with conjectural hypotheses that develop theoretical frameworks. None of these approaches use empirical studies that use large data repositories.

We formulate a theoretical framework, called Affordance-Bias-Cognition (ABC) reasoning and we demonstrate it empirically using Text Mining. The contribution of the paper is twofold: theoretically, (i) it supports the understanding of cognitive aspects of product interaction, practically, (ii) it improves the generalization and the extraction and automatic methods for detecting cognitive aspects from patent text.

Background

In this section we discuss the background of the present work. In particular we describe the theoretical foundations of interaction from a cognitive perspective and then we give an overview of the past works that used Natural Language Processing (NLP) and Text Mining (TM) in Engineering Design, with a particular focus on Design Cognition.

Product-Use Interaction from a Cognitive Perspective

Many authors have adopted the Function-Behavior-Structure (FBS) model as a reference to describe design processes and tasks, while others started a debate on the validity of this framework by underlining some ambiguities. In particular, the definition of Gero's model as "designer-centric" opened a line of research that aims to identify extensions of the base FBS model [3, 5, 6]. Some authors focused on defining extensions of the model, shifting the perspective from the designer towards the user.

The introduction of the user's perspective focuses on aspects of the product interaction regarding cognition. With his book Psychology of Everyday Things, Norman [7] first performed an analysis of the product's design employing some cognitive perspectives. His analysis was followed by the work of Maer and Fadel [5] that introduced the affordances into an extended theoretical model providing a series of instructive examples showing how users perceive a product's affordances and how designers could exploit this. These studies introduce the first cognitive aspects of perception in the study of product-use context.

Since then, the cognitive aspects of product interaction have been considered in comprehensive models capable of representing product affordances and their user's perception, knowledge, and relationships with the product itself. It has been observed that when a user designs how to approach an artifact for herself/himself, it uses them/themselves own perspective. In particular, Gero and Kannengiesser [2] define two scenarios that could occur at the moment of interaction: (i) the user correctly interacts with the product; (ii) the user wrongly interacts with the product.

In the first scenario, the user's perspective is aligned with the information coming from the product [8]. In the second scenario, a user can misunderstand the product behavior despite achieving a specific goal or even can consciously use the product incorrectly [3]. These two scenarios are called respectively "uses" and "misuses".

As we can see, the concepts of "uses" and "misuses" are strictly related to the user's perspective, namely the beliefs and expectations that he/she has about the product's behavior in a given environment [9]. Brown and Blessing [9] claims that these beliefs and expectations are parts of the user's cognition, represented by them/themselves knowledge. This is aligned with Norman's view of the user's knowledge, namely a filter (or interpretation) of the information coming from a product [7].

However, the main contribution about the user's perspective in product interaction is given by Cascini et al. [3]. Their extended FBS model, which can be recalled as cognitive-FBS, focused on providing a formal explanation of "uses" and "misuses" because the product interaction could be studied from two different perspectives: the user and the designer's perspective. The most important consequence of this novel theoretical model is that a good or a bad design depends on the match or mismatch users' and designers' expectations.

Text Mining Approaches to Analyze Design Artifacts

The use of Text Mining (TM), together with the development of Natural Language Processing (NLP) techniques, shows breakthrough results in their applications for Engineering Design purposes [10, 11]. However, there are still challenges and problems to overcome, such as the treatment of difficult concepts such as the one related to both design and cognition [10, 12]. This is because natural language is quite ambiguous and fuzzy in itself when describing objects of common life. Things may get even worse when it comes to technical phenomena, since natural language was not "designed" to describe technology [6].

However, some promising results, especially for what concerns design cognition, have been achieved. For example, Fantoni et al. [6] developed a NLP-based methodology to extract information about the functions, the physical behaviors and the states of the system directly from the text of a patent in an automatic way. Chiarello et al. [14] developed an automatic method that extracts users from patents, while Giordano et al. [15] designed a Named Entity Recognition (NER) system able to extract technologies from patents. All of these works laid the groundwork for exploiting Text Mining (or NLP) on patents to improve research and practice in Engineering Design [16, 17].

The main advantage of using TM and NLP for Engineering Design is the possibility of extracting relevant data for understanding theoretically and practically the complexity of the cognitive aspects involved in the interaction of users with products [13, 14]. The contribution of TM for Design Cognition could be twofold: on one hand, textual data, for example contained in patents, can help to demonstrate empirically some theoretical models that hardly find quantitative demonstrations [18, 19], on the other hand, TM techniques can help to improve design practices for practitioners [11].

The first work that shows an application of such techniques in Design Cognition is the one of Chiarello et al. [10] that extracts artifacts that are able to activate spontaneous and immediate users' reactions, such as affordances. They propose an NLP-based approach to extract affordances from patents using the combination of gazeetteers (or lexicon) and lexical and syntactic rules. A second work, by Melluso et al. [12] further explored the ability of an NLP-based system able to extract cognitive artifacts, in particular, focusing on bad design and bias.

Theoretical Framework

In the present study we focus on demonstrating empirically a theoretical model concerning the cognitive aspects of product-user interaction. In particular, we start from the assumptions provided by two pre-existent theoretical models: the 'Affordance based design' by Maier and Fadel [5] and the extended FBS framework by Cascini et al. [3]. These two models map the interaction between users and products from a cognitive perspective taking into consideration the users' and designers' knowledge, beliefs and expectations. However, the validity of these models has never been demonstrated empirically.

In order to find a validation of the theoretical implications introduced by Maier and Fadel [5] and Cascini et al. [3] we need to consider the type of experiment we want to conduct. In fact, given that we are approaching the experiment using Text Mining and analyzing the text of the patents, we need to wrap the two models and reformulate them in a way that is suitable for being experimented. If we consider that the unit of analysis is the text of the patents, we need to define a model that well-suits the way a product-use interaction is described in a patent. Given the two models, in the present study we want to focus on the following research question: what is the difference between the users' misconceptions and designers' misconceptions?

To answer this question we need to take into account the expression of positive and negative interactions occurring in a product-use context. In particular, we focus on the expressions of affordances, bad design and bias. As described by Cascini et al. [3], the match or mismatch among the users' and designers' knowledge, beliefs and expectations can lead to the following results of the interactions: affordances, alternative uses, misuse and failure. When it comes to analyzing text of the patents, these interactions have been mapped as affordances, bad design and bias. For this reason, there is a distinction between theory and practice: theoretically, the interactions can be mapped into affordances, alternative uses, misuse and failure, but practically, they can be mapped into affordances, bad design and bias [12].

In order to overcome this difference, we propose a theoretical framework, called Affordance-Bias-Cognition (ABC) reasoning model. The proposed model describes the cognitive processes occurring during the product-use interaction. The model is divided into different phases that are described as follows.

The user gathers information from the reality through them/themselves sensors and thus perceives the behaviors of the reality. Products are made of a series of components that, through their characteristics, show properties that can be measured by machines (via physical, optical, chemical sensors) or perceived by the 5 senses. Thus, we can distinguish two different phases: the phase called "Cause" and the phase called "Perception". The phase "Cause" is situated at the initial status t_0, where it is represented by a preliminary phase that anticipates the "Perception". Namely, we consider the "Cause" phase the cognitive process that creates the motivation to the user to start approaching the product. Cascini et al. [3] define this process as the "expected achievement of the user's goal".

Then, the user interprets physical behaviors by reasoning, a complex series of signal to signal transformations that can mainly be described as access to memory (previous experiences), analysis (processing), abstraction (clustering) and selection. In our ABC-reasoning model, we call this process "Interpretation". The main driver of them/themselves following actions is the goal the user wants to achieve. We can describe this goal in terms of the status he/she expects to reach through the product manipulation or series of manipulations (phase called "Manipulation") (Fig. 1).

The product response to manipulation corresponds to a new status induced by the physics the manipulation activated. The consequence of the manipulation is a new status that again is perceived by the user through them/themselves senses or measuring artifacts that interact with the user's senses.

If the final status is the desired one, the user's goal is achieved and the user is satisfied. Two cases are possible: the product has performed one of the functions it is designed for (teleologically) or it is used for another purpose than the one the

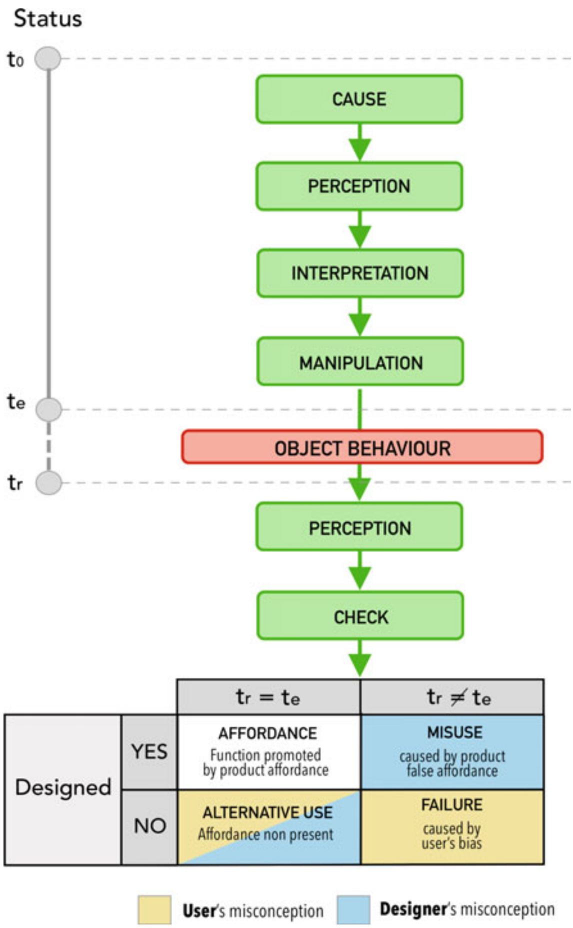

Fig. 1 ABC (Affordance-Bias-Cognition) reasoning model of Engineering Design. The model shows that cognitive tasks (represented as green blocks) occur sequentially starting from the initial status t_0. Each cognitive task corresponds to an ABC phase. Between the phases "Manipulation" and "Perception", the product (or object) behaves according to its properties and functions. The object behavior is delimited by two status: the expected status t_e and the realized status t_e. The match or mismatch between these two status generates four outcomes: affordance, misuses, alternative uses or failures

designer has supposed. However we have a satisfied user with a product alternative use.

When a product does not provide the right information to the user, thus preventing an immediate use, we can affirm the product affordance is wrong or missing. However users can figure out how to use the product correctly or conversely can try to use and fail. In both cases the missing affordance is ascribed to the designer and is commonly said it is due to bad design.

A false affordance is due to a structure that induces a certain use that is not the designed one, so users have expectations the designer has not intended and also in this case we define it as a result of bad design.

A particular class of bad design can be found in controls that often present conflicting feedback, show ambiguous or unintuitive labels, have unexpected mapping between functions and controls, too similar to each other. Such problems are due to hidden properties, but also to the conflict between what the user expects and what the designer designed.

Other cases of failures are instead originated by biases. Thinking a bit deeper we can affirm that biases are also induced by product appearance or behavior or are not prevented by an accurate design able to convey the user towards the right manipulation.

Other cases of wrong design are due to a simpler situation when the designer misses to analyze the use of a complex product in which parts are also going interacting together. The case of the center console in a car where the gear lever, the cup holder and the radio share almost the same area thus creating reciprocal issues.

In the following section we describe the experiment run to answer the research question.

Data and Methodology

In this section we describe the approach used to study the proposed theoretical model. The approach is mainly based on the application of NLP techniques [10, 12] to detect elements in the texts that suggest an explicit expression of the phase involved in the ABC model. In particular, the method could be divided into three main steps shown in Fig. 2: (i) Data Collection, (ii) Phases Extraction and (iii) Sentences Analysis.

First, we gathered the data collected in the previous works of Chiarello et al. [10] and Melluso et al. [12]. In particular, they built a dataset of sentences from patents containing affordances, bad design and bias. These sentences are extracted from the text patents.[1] After collecting the "Background" section of a sample of 5,000 patents belonging to the IPC class code G06F ("Electric digital data processing") and a sample of 5,000 belonging to the IPC class code H04L ("Transmission of digital Information"), they collected 11,385 sentences containing affordances,

[1] The patent dataset used in these works is the one developed by Erre Quadro S.r.l. that contains over 90 million patents from the DOCDB and European Patent Office (EPO) repositories [15].

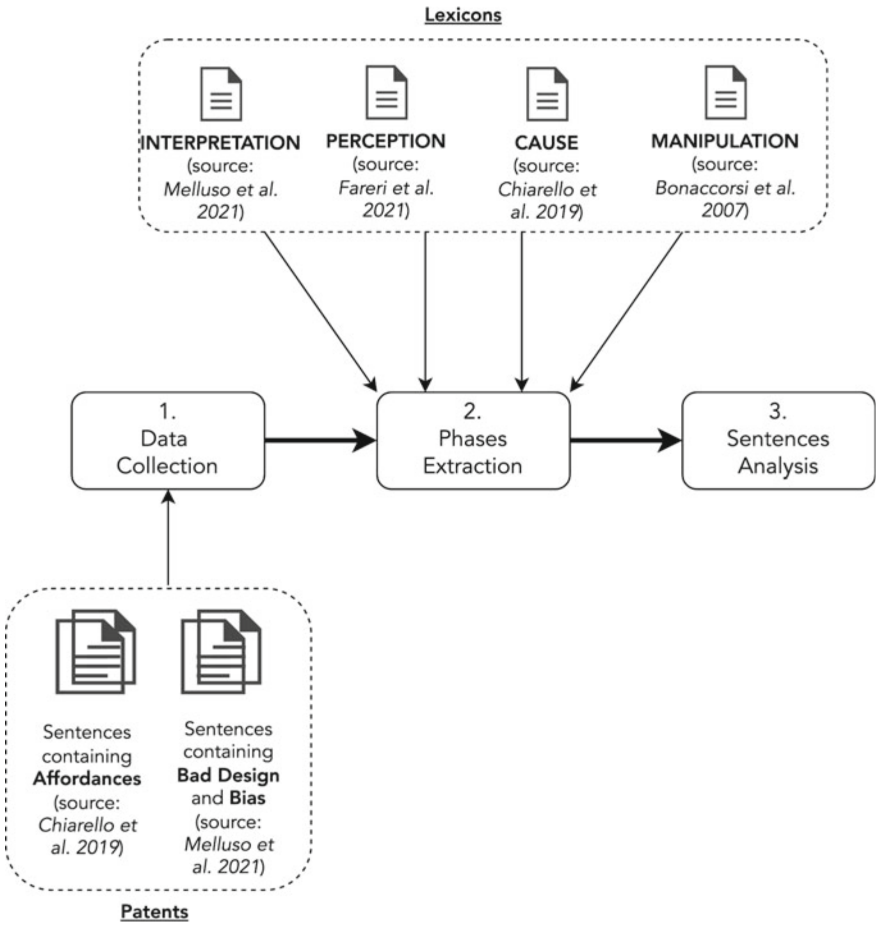

Fig. 2 Workflow of the methodology adopted in this study. The three phases are represented by square blocks. The inputs for each phase comes from lexicon developed in previous works

7,452 sentences containing bad design and 4,810 sentences containing bias. These sentences were extracted automatically and then validated manually.

Second, we analyze the sentences by automatically checking if they contain certain ABC phases. We approached this task by using a gazzeeter-based Named Entity Recognition (NER) system that searches manually collected list of words in the text [20]. We use a python library called *spacy*[2] [21], except for the "Check" phase that uses the pre-built sentiment analysis classifier developed by HuggingFace.[3] Table 1 shows for each phase a sample of the gazettes employed. For what concerns the extraction of the "Check" phase we assess if a sentence is positive according to

[2] https://spacy.io/.

[3] https://huggingface.co/nlptown/bert-base-multilingual-uncased-sentiment.

Table 1 Samples of gazettes used to detect the ABC-phases with the reference for the works that developed them

ABC phase	Description	Sample	Source
Cause	The sentence contains expressions that introduce a statement that refers, usually to contradict or agree, something that has been said previously	However, if, for example, when, although, …	Chiarello et al. [10]
Perception	The sentence contains verbs of perception, namely verbs that conveys the experience of one of the physical senses	See, watch, look, hear, listen, feel, taste…	Fareri et al. [22]
Interpretation	The sentence contains a cognitive related expression; a cognitive related expression is a term, usually a verb, that refers to an aspect of the intellectual functions and processes (such as attention, memory, judgment, evaluation, reasoning etc.…)	Believe, assume, conclude, think …	Melluso et al. [12]
Manipulation	The sentence contain verbs that express the fact that a user is approaching to the object	Move, arrange, operate, open, close, adapt…	Bonaccorsi and Fantoni et al. [23]

the polarity score given by sentiment analysis performed over the sentence. We define a threshold of 0.75 to classify a sentence as positive. In fact, given that the "Check" phase consists of a match between the user's expectations and the designer's expectations, we assume that if a match occurs then the sentence has a positive sentiment, else if a mismatch occurs then the sentence has a negative sentiment. Evaluating if the sentence is positive or negative is complementary. In fact, with our assumption, if we know that a sentence contains the "Check" phase, we know that a positive match occurred and, on the opposite, the absence of "Check" means that a mismatch did not occur.

Finally, in the last step, we analyzed the results of the phase extraction. In particular, we checked the existence of structural differences between the sentences containing affordance, bad design and bias. The analysis of this difference is conducted by comparing the proportions of the sentences containing each phase. In this case, we employed the Marascuilo procedure [24] in order to test whether three populations have the same proportions. The procedure was done based on the results of the chi-square tests at 10% significance levels for each phase. With this procedure we test the following null hypotheses:

H0: the proportions of sentences containing a phase are equal across the groups.

In practice, we are testing if the sentences containing affordance, bad design and bias have the same proportions of expressions referring to the ABC phases. If the null hypothesis is not rejected, this means that there is no statistically significant difference between sentences and consequently, that affordances, bad design and bias are expressed very similarly in patents.

Results

In this section we describe the results of the analysis performed in the present study. Given a total number of 23,647 sentences containing affordance (11,385) or bad design (7,452) or bias (4,810) we found the proportion of ABC phases shown in Table 2. These results lead us to advance the following considerations.

First, on average, a total number of 16,203 (proportion of 0.68) sentences contain at least one ABC phase. Among them, 12,580 (proportion of 0.77) sentences contain words referring to at least two phases, and 7,486 (proportion 0.46) contain at least three phases. These results show that the ABC phases appear in the majority of sentences containing affordance, bad design and bias. This is a preliminary confirmation that the proposed model actually appears in the patent text.

Second, Table 2 shows that the null hypothesis is rejected for all the ABC phases, except for the phase "Check". As we can see, there is no statistically significant difference between the proportions as resulted from the chi-quadro test (2 degrees of freedom, 0.01 of level of confidence alpha and 9.210 chi-squared degrees of freedom) following the Marascuilo procedure (1966). These results confirm that the occurrence of an affordance, bad design or bias does not differ for the phases proposed by the ABC model.

Third, the rejection of the null hypothesis for the phase "Check" gives a twofold confirmation on what is only theoretically expressed by Cascini et al. [3] and on what is proposed in our ABC model: a mismatch between the expected behavior of the designer and the expected behavior of the user lead to failures and misuses, that are typically expressed with negative connotations [12] (Chiarello et al., 2020). In fact, sentences containing bad design and bias contain a lower proportion of positive

Table 2 Results of the statistical analysis

Proportions	Affordance	Bad design	Bias	Test statistic	P-value
Cause	0.34	0.35	0.34	0.9501	0.6218
Perception	0.27	0.27	0.28	0.3428	0.8424
Interpretation	0.34	0.35	0.36	4.0284	0.1334
Manipulation	0.30	0.30	0.31	1.6934	0.4288
Check	0.51	0.16	0.16	1392.41408	<0.01 (***)

statements compared to the proportion of sentences containing affordances. This means that at the final stage of the ABC phases, when a mismatch between user's and designer's expectations occurs, negative expressions appear in the text.

Another detailed view of the results is given by the examples in Table 3, where a sample of 3 sentences containing all the ABC phases is shown respectively for affordance, bad design and bias.

Discussion

The experimental results find consensus with existing literature on design research. There exists a series of frequent patterns of cognitive actions in the product experience [25]. The importance of perception of both users and designers when approaching the product is well defined as one the most important cognitive actions [26]. Also, we are in line with the importance of studying affordances for understanding human interpretation of products [27]. The theoretical model of Cascini et al. [3] finds empirical consensus in this study. The match or mismatch between designer and user knowledge, experience and beliefs that lead to misuses, failures and alternative uses is now further explored.

Moreover, the analysis conducted on the sentences containing affordances, bad design, and bias shows that searching for textual units in patents can confirm what has been hypothetically modeled. Namely, we demonstrate the potential of using Text Mining over patent data to study some aspects of Design Cognition. What emerges from this study is that by analyzing the natural language, it is possible to observe novel things that could be difficult to be observed empirically.

Limitations and Future Developments

This study has several limitations that could be addressed in future developments.

First, the approach used to extract the phases of the ABC model from the sentences lacks validation. The extraction performance can be evaluated in terms of precision and recall. This evaluation will improve the reliability of the study.

Second, in the present study, we follow a top-down (deductive) approach that does not explain completely the composition of the sentences containing affordance, bad design and bias. A concurrent bottom-up (inductive) approach could be used to understand the composition of those sentences that do not contain any of the ABC phases. Furthermore, a combination of the two approaches would substantially clarify the whole process.

Finally, this study mainly relies on patent text. This is critical because it takes into consideration not the design process itself, but a description of the output of design. The analysis of patents suffers from this problem also because the text of patents follows a strict and controlled process of writing that implicitly hijacks the meaning

Table 3 Examples of sentences containing all of the ABC-phases

Sentence type	Sentence	Cause	Perception	Interpretation	Manipulation	Check
Affordance	Since the user can approach to the FET, given that it shows a small gate current, it can be easily manufactured or can be compared to a bipolar transistor	Since	Shows	Compared	Manufactured	Positive
Affordance	If the user is interested in detailed information on narrow search topi, users may be able to find what they want processing the query and searching for a specific data source	If	Find	Processing	Searching	Positive
Affordance	It would be desirable to develop techniques to allow user's to access to open rights to give the opportunity to check if the resources are secure when the user authenticate remotely server is unavailable while maintaining a high degree of trust	When	Access	Check	Authenticate	Positive

(continued)

of the design itself. Moreover, dealing with the fuzzy nature of natural language usually leads to misconceptions. The future development is to align this approach with novel approaches to study and analyze design cognition [19].

Table 3 (continued)

Sentence type	Sentence	Cause	Perception	Interpretation	Manipulation	Check
Bad design	While touch screens generally are adapted to detect input from a single finger or other instrument, they are often unable to be properly detect by the user and are unable to process simultaneous input from multiple such instruments	While	Detect	Adapted	Process	Negative
Bad design	However, in a case in which graphical icons are shown into one or more folders, a user may not be able to determine what graphical icons are included in each folder until opening each folder	However	Shown	Determine	Opening	Negative
Bad design	However, the disposition of the fusion keys observed by the user may cause some to them to easily confuse one which button to push	However	Observed	Confuse	Push	Negative

(continued)

Conclusions

This paper presents the theoretical model called Affordance-Bias-Cognition (ABC) reasoning. This model maps the cognitive aspects that occur during a product-use interaction. The model identifies 5 cognitive phases the both users and designers face when respectively approach and design a product. These phases are mapped into “Cause”, “Perception”, “Interpretation”, “Manipulation” and “Check”.

Table 3 (continued)

Sentence type	Sentence	Cause	Perception	Interpretation	Manipulation	Check
Bias	If the user sees that he has lost the storage medium, then he needs to check the changing or updating of the add-on module, which may be time consuming and inconvenient because it requires the reinstallation of the printer driver	If	Sees	Check	Changing, updating	Negative
Bias	However, after seeing the charger shape, many consumers may falsely believe that the charger will not consume power unless it is actually connected to the electrical device	However	Seeing	Believe	Consume	Negative
Bias	If the users have look the keyboard, they may improperly assume that they have entered improper data, improperly operated the application, and/or conclude the application is programmatically flawed	May improperly	Looks	Assume, conclude	Entered	Negative

Text mining is used to empirically demonstrate this model. The textual content of the patents is analyzed to test hypotheses on the existence of the cognitive phases as well as on their proportional presence in sentences containing product-use interaction such as sentences containing affordances, bad design and bias. We observed that when humans (designers or users) approach objects, they follow a well-defined pattern of cognitive activities (or phases). Deviations from this pattern result in well-known interactions such as alternative use, misuses and failure.

The study of the cognitive processes in Design Research occurs at the hands of qualitative research that focuses on theoretical modeling. Such modeling is possible through research studies that observe the behavior of designers and users in specific contexts. Although design research is moving toward new approaches [19, 20], what is lacking is a comprehensive study of how designers describe user-product interactions, mainly what psychological processes are being considered.

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Design Progress Dashboard: Visualising a Quantitative Divergent/Convergent Pattern of Design Team Progress Through Natural Language Processing

Matt Chiu, Arlindo Silva, and Siska Lim

Design as a process has mostly been studied from a qualitative perspective. This paper aims to contribute to a better quantitative and qualitative understanding of the design process. To do that, we introduce the Design Progress Dashboard (DPD) framework, a set of Natural Language Processing (NLP) assisted tools using the Word2Vec and t-SNE models to organically and quantifiably capture and visualise the design progress of a typical design class. We describe the methods used to gather data and perform analyses of student designers' mental thought processes through a periodic written assignment throughout the design class by converting text information into numerical data. Towards this end, we present a case study to dive into one of the design teams from the design class and propose a clear explanation on the usefulness of the research framework, its limitations and the potential future work.

Introduction

Design is a "purposeful human activity" and is often decision oriented [1]. Evaluation of a design project often investigates the measurable outcome at the end of the whole design process because the process of design itself is hard to quantify. The design process is often described in various frameworks such as the Double Diamond, OODA, Design Thinking and Lean UX [2]. Although the frameworks differ in their respective focus, the element of framing and reframing applies in many of these frameworks. The framing and reframing process constantly shifts the focus of difficult design problems as the project evolves, with new insights iteratively found.

It is also important for design managers such as the course instructors of a University design class or the entire team, in the case of a self-managing team [3], to be quantitatively informed on the progress made by the teams in order to react and

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intervene when necessary [4] to achieve better performance. The better the performance of the design team, the higher probability of success of the new product development when it comes to projects involving cross-disciplinary team dynamics [5–7]. In the context of this paper, a design class involving 26 students with diverse backgrounds to design an orange squeezer [8] from the Singapore University of Technology and Design (SUTD) was chosen. The class adopts the 4D double diamond design framework [9, 10].

Furthermore, with the advancement in Artificial Intelligence (AI) research, the Natural Language Processing (NLP) framework which specialises in textual analysis, becomes a possible approach to evaluate design work quantifiably. Textual interpretation methods such as the Latent Semantic Analysis (LSA) [11] and Sentence Similarity [12] are some of the current approaches which attempt to evaluate design. While there are attempts to apply NLP research to evaluate design projects, most evaluation often measures the project output to seek measurable success (such as novelty [13, 14]) instead of the process. To the best of the authors' knowledge, only a few of these studies look into the intermediate evaluation of design course progress [4] in attempt to provide timely feedback while the project is ongoing. The measuring of design outcome at the end of the project is often too late for any constructive interventions to be done within the timeframe of the project. In this paper, the application of NLP will be explored to sort captured textual information on a design project for a class of 26 students working in smaller groups.

Related Works

Reframing a Design Problem

Being the initial point of a design process, proper framing of the design brief influences the designer's response, and the overall direction of the project in an attempt to solve the problem statement [14, 15]. It has been observed that a designer's creative performance is highly dependent on the type of information that is provided in the brief, thus creating an impact on the design output as well [16]. Many design problems are deemed "wicked", where there is a lack of clarity in aim or the method of approach [17]. Such problems are generally difficult, where any attempts to solve them often require addressing many layers of complexity; and this creates a cluster of problems and is "problematique" [1]. While in the state of "problematique", it is hard to precisely isolate each problem while any attempts to solve one may interfere or even aggravate the others. The definition of frame was proposed initially in artificial intelligence domain [18], and can be defined as the sharing and clarification of viewpoint for all stakeholders [19]. On the other hand, reframing can be seen as the change of such viewpoints as a result of "social interaction" [20, 21]. With each reframing, the team improves their knowledge of the problem. This means that the act of reframing throughout the design process is crucial to designers in a classroom setting, thus a close monitoring is essential for the class instructors to better understand the progress of each individual or team as they reframe from the initial problem statement or brief. Overall, there lies a need for a system to allow class instructors to visualise real time progress, so that any timely interventions can be done when appropriate.

The Importance of Divergence and Convergence in Design

On the other hand, the Divergent Thinking (DT) process is best known for its ability to generate outcomes in terms of quantity and the diversification of ideas arising from an open-ended question [22]. Hence, this has been widely adopted for creative problem solving. The concept of DT is also widely popular due to the ability to produce novel ideas as opposed to convergent thinking, which narrows down to a single “correct” idea [23]. According to Runco and Acar [24], the critical component of DT is the “potential” of obtaining novel ideas as the outcome is always unknown. This suggests that indicators shown by the adoption of DT on a wicked problem can be used as a form of estimate on the potential of the project outcome. Therefore, for a creative process to happen, both divergent and convergent thinking components are essential [25] to generate enough possible ideas and be able to evaluate them based on their appropriateness and usefulness [26], which is largely similar to the definition of creativity by Amabile [27]. The interplay of divergence and convergence was also highlighted by Banathy [1] as a design dynamics framework that transforms existing systems and reimagines the future; where there is a constant exploration of a divergence process to understand the options available, followed by a convergence process to evaluate and down select the options as shown in Fig. 1. This divergence and convergence model was later adopted by the UK Design Council and rebranded into the 4D Double Diamond design methodology [9] which we will discuss next.

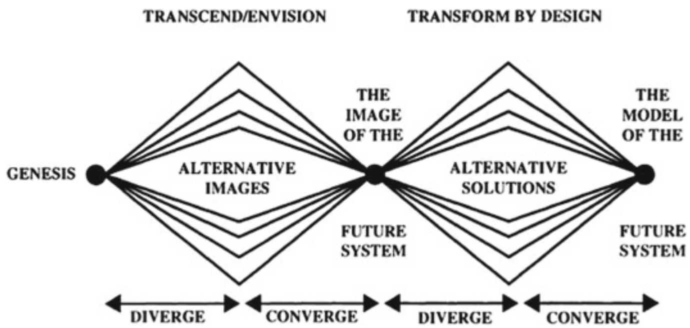

Fig. 1 The dynamics of divergence and convergence [1]

Design Process Across Products, Systems & Services

Adapting from the diagram in Fig. 1, the 4D Double Diamond framework (4D framework) by the UK Design Council consists of the 4 phases which are "Discover", "Define", "Develop" and "Deliver" respectively [9, 10]. In this 4D framework, the phase of divergence appears twice, first at the "alternative images" also known as the reframing process to draw the boundary of the problem and secondly at the "alternative solutions" to converge on the ideation and prototype for a solution. Such 4D framework was therefore widely adopted in the design industry as there are clear phases with tangible outputs for designers to follow. The 4D framework of design is diverse and applicable across multiple industrial contexts [28] and various design purposes such as product, service, or system development and even educational programs [15]. Although there are various design frameworks, the 4D framework was used as it is the basis for the syllabus adopted by SUTD, and inherently contains the divergence and convergence capability to hopefully be captured by this research.

Opportunity of Adopting NLP in Design Documentations

To be a successful team, constant communication and mutual understanding of the project amongst all members of the team during the design process is essential [29, 30]. To communicate within the team or for the purpose of facilitation by course instructors, written documents about the project progress are often created and exist in the form of design journals, blog posts and even diaries. However, such written documents are often left underutilized as they mainly serve as an indication of submission as part of the course or are processed briefly by non-quantifiable means. Since such written documents are rich in content, this can potentially be an avenue to access the "thought process" behind the teams' decisions instead of conducting personal interviews separately [4]. In such cases, the NLP models become useful to evaluate these rich text datasets and eventually enable a quantifiable analysis. NLP models such as the LSA [11] or the Word2Vectors (Word2Vec) [31] models are useful tools that are able to compute and map out the relationships of words used by the design team at various stages of the design process.

Research Methodology

To begin the research methods, there are two concurrent sub-components that are happening simultaneously. One is the setup of the base data cloud using a text corpus, while another is the textual data collection from the design class.

In this paragraph, we will be discussing the corpus setup, followed by the textual data collection as shown in Fig. 2.

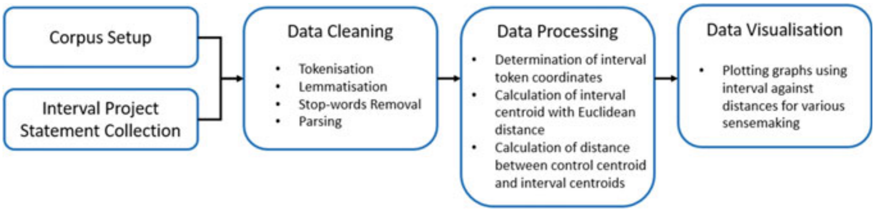

Fig. 2 Methodology step diagram

Corpus Setup

To set up the base data cloud, a combination of NLP models such as the Word2Vec [31] model and the t-Distributed Stochastic Neighbour Embedding (t-SNE) model [32] are adopted. Word2vec computes the similarity degree between one word to another based on the neighbouring words with its skip-gram and CBOW (Continuous bag-of-words) models [31, 33, 34] in dimensions that are hard to visualise. To simply visualise such high dimension data, the t-SNE model is then adopted to map high dimensional data to lower dimensions while preserving the neighbouring relationships between words [35]. The t-SNE model works by having an input corpus. In this case the Body of Knowledge from the Product Development and Management Association [36] was used to construct a base data cloud using the relationship of words within the corpus. Each word within the corpus will be added sequentially to the data cloud with a distance and direction influenced by the existing words. Eventually the completed data cloud becomes a representation of relationships between the words within the corpus, shown in Fig. 3.

Data Collection

Textual data is collected from the student designers at intervals of time during the class (typically once every week). This data (referred to as interval data from this point forward) is then further manipulated and plotted according to the methodology explained below. A single-line design statement is collected from each individual student (even if the student is working in a team) at the end of each session (the interval data) which consists of three subcomponents. These three sub-components are the "what is the design", "who is the user" and "why so" respectively to seek design clarification about the reasoning behind the students' intentions. As previously mentioned, the ability to express cognitive intention is essential in project-based classes, especially for design. Such statement collection was done at every session so as to constantly extract from the students why they are developing the project in the way they are doing it. Since the class content for each session differs within the scope of the 4D framework, each class becomes a stimulus which influences the

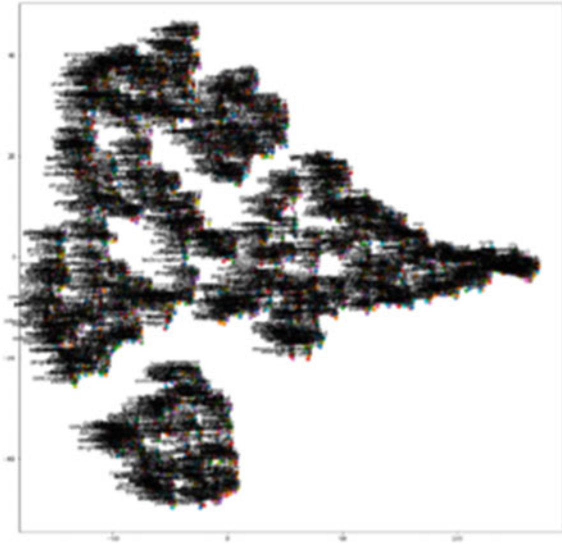

Fig. 3 The t-SNE data cloud and clustering

students' understanding on the existing problem statement. Although the students work in groups, individual design statement collection allows each student to submit the sentence based on their personal interpretation. With this flexibility, students of the same team are allowed to answer the three stated questions based on their own individual understanding and liking. As such, the data collected can then be used to test for any form of convergence within each team throughout the term, or across teams in class.

Data Cleaning Using NLP

Before the textual data is converted in plottable numerical data, the collected design sentences go through 4 processes. These textual data are first Tokenised to extract each individual word into tokens, removing them from the original sentence-based relationship. These individual word tokens then go through the Lemmatise process to convert all words within the token into their root form to simplify the sorting process [4]. Thirdly, the tokens go through a process of removing any texts that are not inside the NLP corpus and "removing stop words" which removes any conjunction tokens. Eventually, the final step is to Parse the tokens to conduct Part-of-Speech (POS) tagging. The adoption of parsing framework allows the model to not only take the word for its superficial meaning, but make use of pre-trained sentence structures to determine the usage of words by tagging their word class. Apart from the POS ability, another important aspect of parsing is the word dependency. The pre-trained model is able to locate common word types like nouns and use them as a basis to determine the word class of the words around it. Dependent parsing is a procedure

Interval	Design What?	For Who?	Reason Why?	Cleaned Word Tokens	Divergence
Week 2	Orange jucier	Adults	It should be adaptable and ease for use for adults	['adaptable', 'ease', 'use', 'adult']	0
Week 3	Orange juicer	Elderly	Such that it will be fun for the elderly to handle the juicier	['fun', 'elderly', 'ease', 'handle']	0.33567
Week 4	Orange juicer	Elderly and children	It meet the need of the selected user to have ease of handling and must be safe to operate	['meet', 'need', 'select', 'user', 'ease', 'handle', 'must', 'safe', 'operate']	0.166101
Week 5	Orange juicer	Elderly and children	Simplicity to enhance user experience	['simplicity', 'enhance', 'user', 'experience']	1.402852
Week 6	Orange juicer	Elderly and children	Achieve simplicity to enhance user experience	['achieve', 'simplicity', 'enhance', 'user', 'experience']	0.957332
Week 7	Orange juicer	Elderly and children	Ease of handle with good user experience	['ease', 'handle', 'good', 'user', 'experience']	0.979599
Week 8	Orange jucier	Elderly	Ease of handling with good user experience	['ease', 'handle', 'good', 'user', 'experience']	0.979599

Fig. 4 Chart showing the development of reframed design sentence and token extraction

that is essential in research which has to do with linguistic categorization due to its ability to perform analysis on grammatical structures [37]. The above summarises the NLP process where the words extracted from the design statements are now tokenised, cleaned and ready to be converted into numerical values as shown in the "Cleaned Word Tokens" column in Fig. 4.

Data Processing

At this stage, the processed data remains in a textual format in the tokenised form shown in Fig. 4. In order to visualise the design process, the obtained tokens from the data collection point will be mapped against the same word on the word cloud from the corpus generated using the Word2Vec model. To set the control point, the initial interval data (the very first sentence collected) will be kept as the control point on the data cloud, whereas the subsequent interval data will be matched against the control point to present a graph of deviation across time in relation to the control point. However, each interval data point will in general contain a different number of tokens, which makes it hard to analyze and compare. To solve this, the solution was to create an artificial boundary that uses the location of all the tokens in that interval as the external boundary and to define the centroid of the shape created by the tokens [38]. The computation of this centroid is done through the averages of the X and Y coordinates of all token points within the corpus. The left of Fig. 5 illustrates how a centroid can be easily computed based on the location of the surrounding words using vector addition of their Euclidean distance. When all interval centroids are located, the distance of these centroids to the initial data point (itself a centroid) is also calculated. The created distance computed by Euclidean distance function [39, 40] represents the deviation of thoughts throughout the intervals from the design statement as show on the right diagram of Fig. 5.

Data Visualisation

With the individual interval (e.g. weekly) difference-in-centroid distances obtained tracing between interval and the control, each of the distances is then used to plot

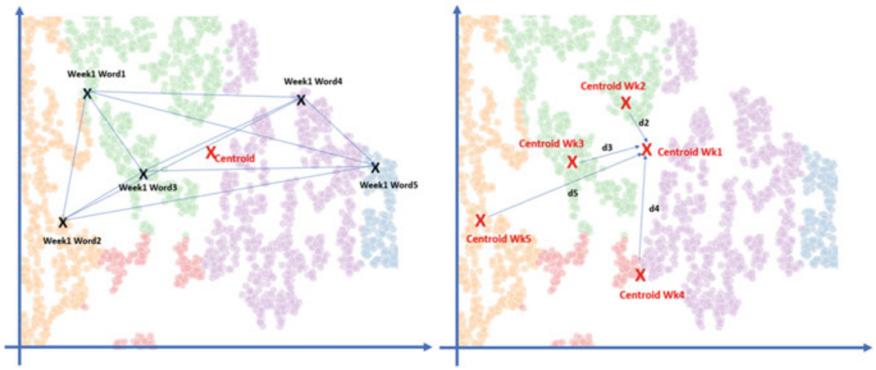

Fig. 5 Pictorial representation of the interval distance identification using the centroid of words

a chart shown in Fig. 6. The graph represents a measure of how much the design intention deviates from the original statement with each interval (e.g. weekly). The graph aims to understand the divergence and convergence of each student during a particular design period organically. The attempt to map out a divergence graph seeks to further understand the organic transition and pattern as suggested in the 4D Double Diamond framework [9, 10, 15, 28]. Such data does not capture the actual design outcome but the change in the thought process that goes into solving the problem statement: a sort of continuous reframing of the problem statement in each of the intervals of time.

Besides looking at the divergence graph on an induvial basis, the graph can be stacked to form group graphs to capture group behavioral trends. The group graphs which make up the Design Progress Dashboard (DPD) contain the opportunity to further study the group behaviors in 2 approaches, (1) the Spike Diagram—where the individuals' patterns within the group are studied and (2) the Synergy Diagram—to capture the group standard deviation using the Maxima, Median and the Minima

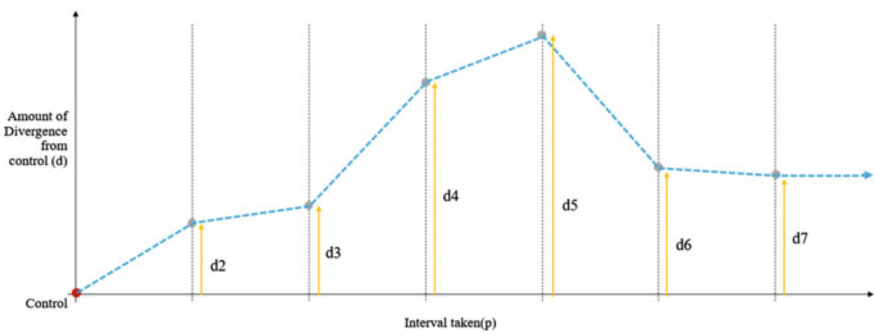

Fig. 6 A pictorial example of visualization of the design progress through the deviation from the students' initial problem statement for 1 person

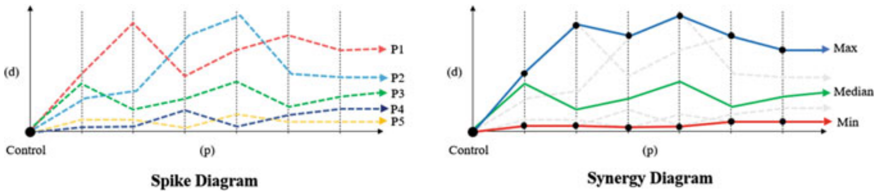

Fig. 7 Group divergence graphs in the Design Progress Dashboard (DPD). P1 to P5 on the left diagram depict the evolution of each of the team members in a team

obtained from the points of the Spike Diagram as shown in Fig. 7. These DPD diagrams present a graphical representation of the collective change of thoughts throughout the design process which may help teams to perform better due to the idea of "collective group memory" [41, 42]

Results and Discussion

Data Visualisation Framework

For this research, a design class involving 26 students with diverse background to design an orange squeezer [8] from the Singapore University of Technology and Design (SUTD) was chosen which adopts the 4D double diamond design framework [9, 10]. Figure 8 presents the Spike Diagram of the Design Progress Dashboard (DPD) which consists of several graphs that represents the design progress of all 26 students in the design class sorted in 7 teams. The data shown on the DPD comes from the design statements collected, and are processed according to the above-mentioned research methodology. The entire class was tasked with the same initial design brief: to design a household orange juicer. The students were assigned into teams to develop their project over the period of 8 weeks. As week 1 of the design class was spent on mostly administrative matters and building up of some simple methods and ice-breaker exercises, the data collection began in week 2 as shown in Fig. 8. Upon receiving the original design brief, the students are free to interpret and develop the project according to their own insights throughout the 8 weeks, subject to the different stimuli from the instructor team in each week during class. On top of the individual curves for each of the teams, a pink curve is presented as the team mean average score and a black curve represents the Overall Average (OA) of all teams.

The DPD can potentially be useful for two main purposes, one is to be used as evidence-driven tool for post analysis during review for the class, while another is to be an interactive tool for the instructors to understand the class progress in real time. This method of data capture and visualisation can potentially act as a way to measure students' design progress in terms of divergence/convergence from their

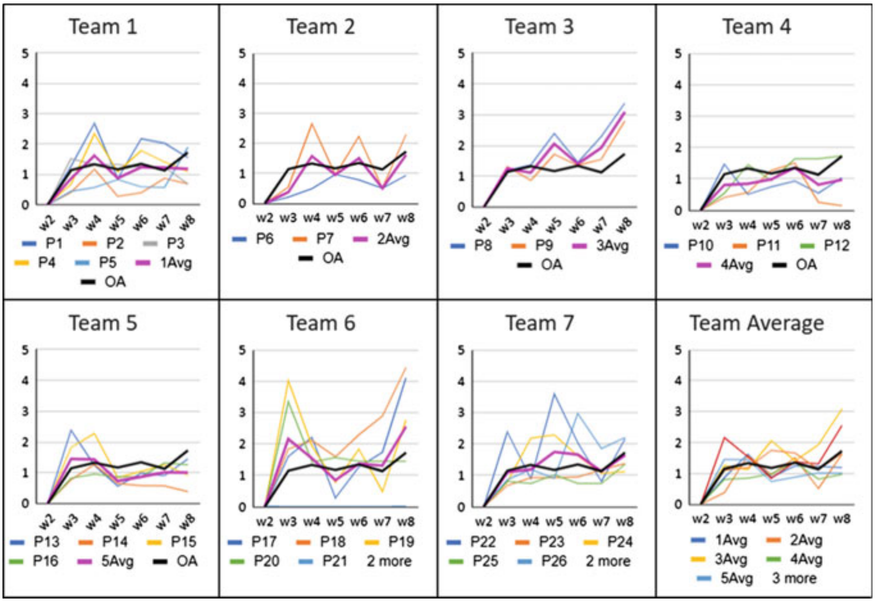

Fig. 8 The spike diagram for a design class of 26 students

initial statement, which would otherwise be difficult to quantify and visualize. The graphs in the DPD are also useful for the instructors to measure the performance of students on 3 different levels, which are the individual, team and even the performance of the entire class.

Individual, Team and Class Representation

On the individual level, the graph represents the total amount of divergence and convergence that the particular student experience throughout the design process. Since the design statement was collected on a weekly interval in this case, the statement evolves as the students are exposed to stimuli from the class while more relevant insights revolving around the problem statement are discovered. Using the initial point (week 2) as the control, the deviation in each interval captures how far the student has explored; and if the student diverges or converges at critical points throughout the term, according to the intent of the course.

At the team level, the information presented on the DPD can be evaluated using the Synergy Diagram in Fig. 9. In Fig. 8, the team information allows the instructor to have an easy glance at the performance of all students within the group. The DPD also includes the team average for the instructor to spot any students which are off-track, and an OA to compare the performance of each team against the others. Whereas in Fig. 9, some further data can be extracted from the Spike Diagram to illustrate and

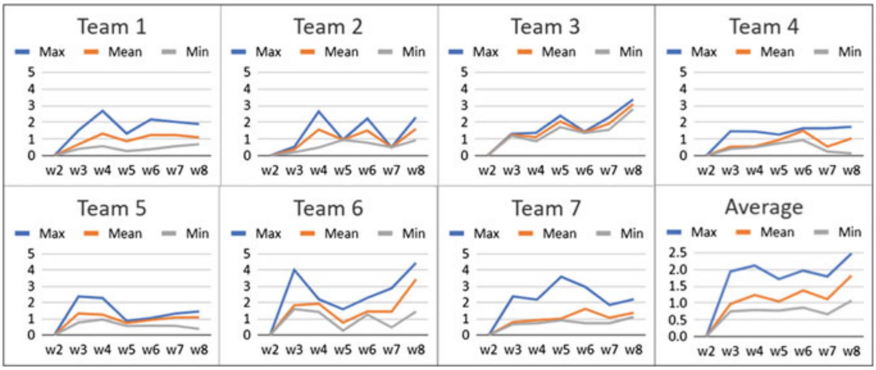

Fig. 9 An example of the synergy diagram for a design class of 26 students

convey team synergy. The Synergy Diagram consists of the peaks, averages, valleys and even standard deviations extracted from the Spike Diagram of the DPD. Such diagram allows the instructor to understand the synergy within the team by assessing the band between the lowest and highest divergence for each time interval within each team: the smaller the band, the more cohesive is the team thinking. The diagram also can act as an indicator for the direction of the team in terms of continuous divergence or convergence respectively. By determining the location of the peak of the average graph along the 8-week timeline, it is observed that the maximum exploration for all teams is between weeks 3 and6 which is in-line with the way the class was setup, following the 4D framework: this coincides with the "develop" phase.

At the scale of the entire class, the DPD can act as an informative tool for the instructor to tell the performance of all teams and individuals at a glance. When there is a student of concern, the instructor can immediately point the pattern of such student and compare the performance against the rest of the class. Such visualisation approach offers a birds-eye view on the performance of the class which is otherwise difficult, and the instructor will also be able to make informative and evidence-based decisions on the go. When it comes to moderations and administrative processes, the DPD also grants the instructors an evidence-driven and non-biased approach to represent the students' progress.

Final Peer Assessment

At the end of the 8-week design course, a simple voting session was conducted after the presentation of the final class on week 8 to vote for the winning team. Every person was given 2 votes such that they do not only vote for themselves in this process. A total of 26 students and the instructor casted 54 votes in total shown in Table 1. It was observed teams with the higher mean score tend to get more votes as shown for teams 3, 6 and 7… With the results from Fig. 9, a possible observation

Table 1 Voting results on the final session

	Mean Divergence	Standard deviation	Votes received
Team 1	1.098	0.534	2
Team 2	1.613	0.966	2
Team 3	3.083	0.408	15
Team 4	1.029	0.795	2
Team 5	1.094	0.466	8
Team 6	3.428	1.367	15
Team 7	1.373	0.503	10

is that teams with higher eventual mean divergent score (the deviance that the team has on week 8) is more likable by the audience which is shown in Table 1.

The reason can be explained as teams with higher mean divergent score having explored wider and uncovered more latent needs than the rest of the class; this may be corelating to more interesting and developed projects. Amongst team 3 and team 6, the standard deviation score at week 8 was higher in the case of team 6 (a possible explanation may be the number of team members, higher for team 6). Referring to Fig. 9, it is observed that the synergy diagram for team 3 is very tight and consistent throughout compared to team 6.

Case Study

A case study which uses mostly Team 6, one of the winning teams, was selected as it best represents the ideal scenario of the capability of DPD's data capture and visualisation framework. The enlarged synergy diagram of team 6 in Fig. 10 was extracted from the overall Synergy Diagram in Fig. 9 with added measuring parameters. Figure 10 shows three curves, the peak divergence of all students in team 6, the mean divergence and the valleys in the span of the 8-week design class. This diagram shows that the maximum divergence X which lies on the first half of the period A. Students were tasked to go through the project using the 4D double diamond design framework from inception to week 7 (period A), while week 8 was spent on the final pitch (period B). Thus when $X < 0.5A$, it represents that the students have explore "enough" to be able to reframe to the problem statement to combat the latent needs, which is in line with the "define" phase of the 4D framework, as shown in the yellow bar in Fig. 10. On the other hand, if $X > 0.5A$, students may not have explored "enough" to enter the "develop" phase yet managed to learn greater insights upon the ideation or prototyping process. The synergy diagram is also a good representation of the consistency of thoughts within a team. In the usual scenario of a design class, the team will be tasked to work on a consolidated design statement that best represents the project. On top on that, this design statement data capture allows individual interpretation to be reflected; this means that the weekly tracking will be

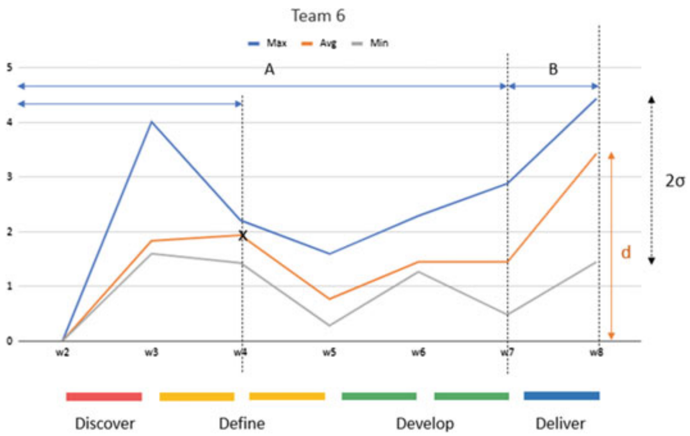

Fig. 10 Synergy diagram for team 6

based on each student's personal interpretation. Occasional spikes in the diagram can represent the correction to realign goal as shown in the peak curve between week 3 to week 5. Following which the Synergy Diagram became consistent as the band between the peak and valley tightens, which may suggest that the team is in harmony and everyone in the team understood and agreed the team approach until week 7, the end of the 4D framework. The final increment of the graph on week 8 seems to represent that the market analysis and pitch preparation may have allowed the students to obtain insights that were not available earlier.

A discussion about the shape of the Synergy Diagram in Fig. 10 can be traced to Fig. 11, where it is observed that the team evolved their "what" statement from an orange squeezer and reframed to a product for stay-home mothers instead of a general consumer product in the "who" column. The shape of the graph reflects the degree of divergence since inception as the design statement evolves, where the change in statement was captured by the NLP process mentioned earlier to produce the numeric output. To make the NLP process more accurate, only the "why" component was used in the NLP process, while the "what" and "who" serves as a guide to monitor any potential point of pivot. Finally, a wider range of standard deviation at week 8 in Table 1 suggests that team members have used different textual expressions to represent their team's project; thus more exploration occurred within the team.

To put to comparison using Team 1, although both graphs present a generally tight band in between the 3 curves, the magnitude in Team 1 is smaller shown in Fig. 12. This suggest that the synergy in the two teams is quite coherent due to the tight band, whereas Team 1 seems to be working on the safe side in terms of design exploration. This is so because of the lower magnitude observed in Team 1, which means that the design statements for the team remain in close proximity throughout the 8-week period. On the other hand, both teams also have a local divergence peak between weeks 3 and 4 which is in line with course material of the "define" stage of the 4D design process where students are encouraged to find a new focus and

Student #17 (P17)			
w2	Orange Juicer	General user	Any user will be able to use the product with ease
w3	Orange Juicer	Stay home mum and Primary school kids	User is able to extract orange juice with ease and safely with minimal fuss
w4	Orange Juicer	Stay at Home Mothers and 8 years old child	Easy to use, child friendly, efficient
w5	Orange Juicer	Stay Home Mum and Primary School Students	Ease of use
w6	Orange Juicer	Stay Home Mum and Primary School Kid	Easy to use, easy to wash
w7	Orange Juicer	Stay home Mum and Primary School Kids	Ease of use, portability
w8	Orange juicer	Stay at home mum, Primary school kid	Convenient, portable, child friendly
Student #18 (P18)			
w2	Orange juicer	General user(anyone)	any user will use the product with ease.
w3	Designing a smart orange juicer	Stay home mums and primary school kids.	It is child-friendly and convenient for users to extract orange juice with ease safely.
w4	An electric orange juicer	Mothers with young kids	It is mess free, easy to use and child-friendly.
w5	Designing a smart, child-friendly orange juicer	Mums and primary school kids	It is safe, easy to use, child-friendly, portable.
w6	Designing a portable, child-friendly orange juicier	Designing for young mothers and primary school kids.	It is easy to use, durable, food safe,portable and child-friendly.
w7	Designing a portable orange juicer	For stay home mums with young primary school kids.	Relatively lightweight, easy to assemble, use, wash and child-friendly.
w8	An orange juicer	Stay-at-home mums and primary school kids	A automatic, child-friendly, portable juicer!
Student #19 (P19)			
w2	Orange juicer	General user (anyone)	Any user will use the product with ease
w3	A smart juicer	Stay home mum and primary children	It is child friendly and convenient for users.
w4	Portable orange juicer	Stay at home mum and kids	It is simple and time saving for user, even for child.
w5	Orange juicer	Stay home mum and primary school kid	Product is portable and easy to use for user.
w6	An orange juicer	Stay at home mums and young children	The product caters to our target audience being easy to use and clean. Aesthetically
w7	Orange juicer	Stay home mum with young kids and primary school children	It is easy to use and easy to clean up.
w8	Orange juicer	Stay at home mothers and primary school kid	Its is child friendly and easy to use/clean.
Student #20 (P20)			
w2	Juicer	universal	it is efficient
w3	Orange Juicer	Stay-home mothers and Primary school children	it is able to extract the orange juice with ease.
w4	orange juicer	stay-home mum	portable
w5	Orange Juicer	Stay-Home Mothers	it is easy to use and portable
w6	Orange Juicer	Stay-home mum	Child-friendly
w7	Orange Juicer	Stay-home mother's	It is child-friendly.
w8	Orange Juicer	Stay-home mum and kid (above 7 yrs old)	Child friendly

Fig. 11 Detail data of Team 6 with individuals from Fig. 8

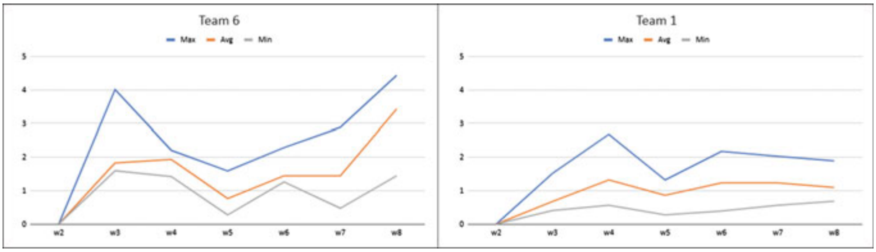

Fig. 12 Synergy diagram comparing Team 6 and Team 1

reframe their initial problem statement. Lastly, in terms of overall comparison, the smooth curvature, tight band and the eventual converging nature suggest that Team 1's project remains in the "safe zone" throughout the duration of the class and might lack the potential for the novelty element which is important in the design process.

Conclusion

In conclusion, this data capture and NLP visualisation framework for the Design Progress Dashboard (DPD) seems to be able to capture some of the essential components of a design process. This framework does not measure the output of the design project, but only the process of divergence and convergence of thought captured during the project. The reason for such an approach is because there are already many studies that focus on the various measurements of design outputs such as creativity [14, 43]. but not that many try to capture the evolution of the design process. This is an opportunity to allow both sense making of the data presented in the DPD to be a standalone outlook into the process of designing and also an opportunity to combine this DPD with output measurements and seek deeper understanding and potential correlation between the two. Furthermore, as the 4D double diamond framework (4D framework) is merely a representation of the design strategy in two distinctive diamond phases, this DPD framework provides the opportunity to quantify and study in some way the organic pattern of the design process by using the same divergence and convergence matrix. This also provides an opportunity to investigate how this double diamond would look like for design projects of different domains such as the architecture, engineering, healthcare or even entrepreneurship areas. Corelating to the study of design signatures [28], the benefit in attempting to classify signature curves between different domains may help designers to better quantify the organic pattern between project typologies, thus contributing to a better understanding of design research. In short, the DPD is like a dashboard view of the design progress in terms of the deviation of thoughts, for class instructors to understand the overall progress of projects they oversee, to have the ability to identify and respond to potential problems at an early stage. The Spike Diagram serves as an evidence-based tool to spot uncoherent graphical patterns while monitoring large samples, whereas the Synergy Diagram showcases the level of cohesiveness of teams by the assessment of bands in the respective graph.

Limitations

As all research frameworks, the DPD has its own set of limitations currently. The limitation of this research lies in 4 main areas, (1) the collection method of user data, (2) the usable data for NLP, (3) the types of NLP models used, and (4) the way the graph is produced. Firstly, the current method used to collect user design sentence data is to incorporate a weekly quiz or reflection at the end of every design class, and collection is done through a QR code which links to an online form. Such a process is manual and time consuming. On the other hand, since the question is consistent throughout all intervals, some participant fatigue was observed where participants began to write the same input to the data collection despite physical changes to their project work. The second limitation observed is on the usage of collected data. Mentioned in the Data Collection section, the collected design sentence comes in three parts which consists of "What is the design", "Who is it for", and "Why is that so". As of the current stage, only the "Why" component was taken in for the NLP model processing as that segment contains the bulk of the information as compared to the other two. The unused segment in the collected sentence currently serves as a general observation, thus the NLP model may become more accurate when taking all segments in the design sentence into account. Thirdly, as the advancement in the NLP domain, better text to number processing tools may be discovered. As such, there are opportunities to test and experiment with the more than one set of NLP tools in an attempt to recreate the DPD. For example, the Word2Vec model used to process high dimension spaces can be replaced with the LSA model; the Euclidean distance used may potentially be interchanged with the cosine similarity to get the distance of divergence in another manner. Lastly, the way of sensemaking currently is tailored to the need of the module. The attempt in this paper is to find and compare the average divergence between the team (Fig. 8) against one another to indicate the mental exploration comparatively. Such sensemaking can be easily altered using the current set of data in another manner which may be of use to a design class of another typology in nature.

Future Work

As the DPD is a new approach to understand the design progress, the finding is rather preliminary; more data and experiments will be needed to test for the consistency of such method. In the authors' opinion, there are four areas that can be potential avenues to improve the DPD framework. The first aspect is to apply this research framework to design classes or projects of a longer period. As the number and length of intervals increases, it will be interesting to observe how the shape of the graph evolves, the magnitude and the overall deviance from the initial point. It is also interesting to partition the diagrams into phases of design and observe whether the divergence and convergence pattern matches the intent of the design class. As the project becomes longer, the curve may behave differently thus it will be interesting to compare such differences. The second opportunity is to measure and compare DPD's of different domains (e.g. in architecture, fashion, consumer goods, or sports goods, or healthcare products), and test if they produce different signature patterns. Although the design process may be similar and follow the same design framework, different reactive/academic behaviour may result in a change in the Spike Diagram since it is up to the individuals who take the content and synthesize it internally to their team. The third opportunity is to bridge such research framework with research which measure the design output. As mentioned earlier, the opportunity to create a modular research system using DPD framework against various design output research presents a new take towards design research as a whole.

The final opportunity is to translate the DPD into industrial environments as a tool to monitor design progress by product managers. The authors believe this would be a valuable tool to complement the more typical stage-gate process [44] that seems to be favored currently.

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TechNet 2.0: Expanding Technology Semantic Network with Qualitative Relations to Enhance Reasoning Capabilities

Serhad Sarica and Jianxi Luo

This paper introduces a new semantic network knowledge base that can support both explicit and implicit inferences across engineering design concepts. Our approach is to merge the previously constructed Engineering Knowledge Graph (EKG) and Technology Semantic Network (TechNet). The terms in EKG are mapped to TechNet and then their qualitative relations are added into TechNet. We call the synthesized new knowledge base TechNet 2.0. TechNet 2.0 contains both qualitative and quantitative relations among elemental engineering design concepts. We exemplify the structure of TechNet 2.0 and its new capabilities to enrich and augment design knowledge representation and reasoning. The new knowledge base may fill the infrastructure gap in the process of creating artificial intelligence agents that can support various design understanding, inference, and generation tasks, especially in the very-early phases of the product development lifecycle.

Introduction

Semantic network representations of knowledge are increasingly employed in the design process to support various design activities [1, 2]. In common semantic networks, nodes represent specific knowledge pieces or concepts, which are known as semantic entities. The nodes are connected to one another via links that are knowledge semantic relations, via which knowledge can be accessed from one another. Employing semantic networks to represent design knowledge has several advantages, such as empowering the reasoning, analysis, and synthesis of the knowledge contained in design documents or data by enhancing design knowledge inferences.

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Table 1 Database statistics of TechNet, EKG, and TechNet 2.0

	# Terms	# Relations	# Relation types
TechNet	4,038,924	8.5×10^{12}	1[a]
EKG	288,807,731	794,956,771	234,955
TechNet 2.0	4,038,924	242,191,653[b]	4,776

[a] TechNet only supports quantitative relations. The only relation between terms is semantic similarity
[b] The number only indicates the qualitative relations. TechNet 2.0 also inherits the quantitative relations represented in TechNet

One example of such semantic networks is Technology Semantic Network (TechNet) [3] while another one is Engineering Knowledge Graph (EKG) [4]. Both are trained on the entire USPTO patent text database while they employ different methodologies to retrieve and relate the engineering terms, which are elemental engineering design concepts. While TechNet employed statistical methods to retrieve terms up to 4 words long, EKG employs a set of rules based on Part-of-Speech (POS) tags to identify multi-word units. TechNet trains a language model on processed patent texts to derive quantitative relations, based on the cosine of the terms' high-dimensional embedding vectors. Such quantities can facilitate numerical computation and reasoning, but their meanings are explicit. EKG employs hard-coded rules based on POS tags and syntactic parse tree of the sentences to retrieve qualitative relations between terms, <entity, relationship, entity> triplets. These qualitative relations are explicit and can be understood easily by humans.

The differences of these two knowledge bases are summarized in Table 1 with statistics. Figure 1 illustrates the terms and their semantic relations of a specific patent, retrieved from TechNet and EKG respectively.

Although TechNet has proven to be useful in certain reasoning settings through the utilization of pairwise quantitative semantic similarity and graph theory based techniques [5–7], it is limited to explain the relations between the engineering concepts qualitatively. Despite the usefulness of quantitative relation representations in supporting knowledge computing, the communication of the knowledge encoded in an embedding space to designers is a tedious task and the explainability of the quantitative relations is limited.

In this study, our aim is to leverage complementary knowledge represented in TechNet and EKG to create a combined knowledge base, which is an expansion to TechNet, to provide a better medium that can support both qualitative and quantitative reasoning tasks together. This enhanced knowledge base, namely TechNet 2.0, can represent the EKG-derived qualitative relations between technical terms together with their quantitative relations provided in TechNet.

In next sections, we will introduce the steps we employed to merge the two prior knowledge bases, depict the new knowledge graph structure, and provide examples of the functions that TechNet 2.0 can have. Finally, we will conclude the paper with our plans for future work and a discussion on the research and application opportunities that this knowledge base may provide.

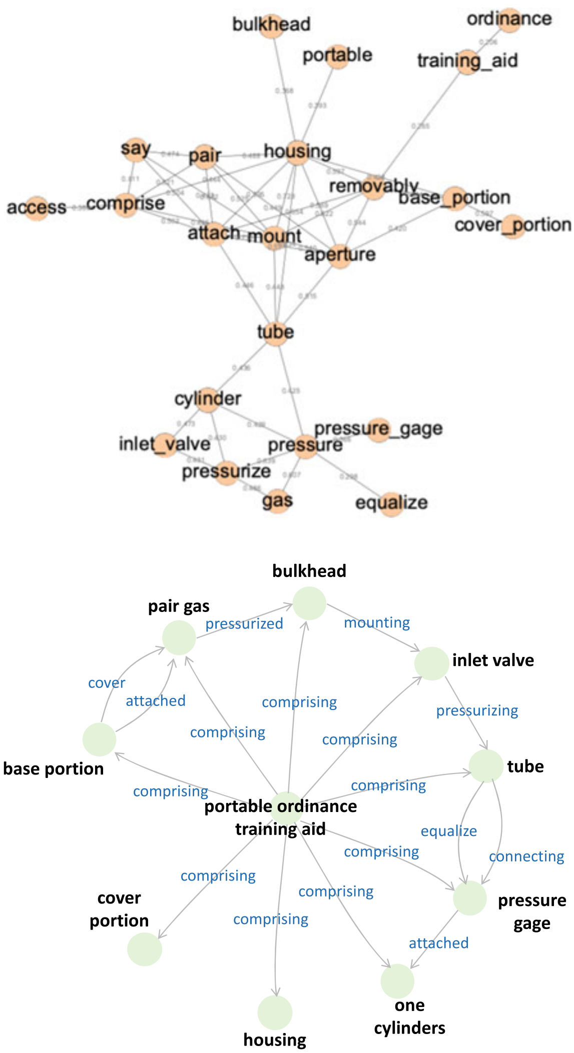

Fig. 1 Visualizations from TechNet and EKG. *Top*: Terms and relations in claims of the patent US4014111 visualized by methods described in Sarica et al. [3] using TechNet. The numbers on edges are cosine similarities between terms *Bottom*: Terms and relations in claims of US401411 visualized by EKG (adopted from Siddharth et al. [4])

Merging TechNet and EKG

Although they were both trained on the USPTO patent database, the two knowledge bases differ in two main aspects. First, while TechNet uses titles and abstracts of patents as the data source, EKG sources patent claims. Second, the methods to construct them differ. TechNet retrieves phrases up to 4-tokens long by relying on statistical significance of tokens appearing together in the patent text corpus. Despite the susceptibility of co-occurrence based statistical methods to noise, encoded filters in TechNet term-retrieval processes considerably reduced the noisy phrase formations. There exists a considerable number of noisy terms in TechNet. On the other hand, EKG builds its vocabulary by relying on Part-of-Speech (POS) tagging, syntactic parsing and hard-coded rules to derive <entity, relationship, entity> triplets. Despite rule-based methods' popularity on determining well-structured text within corpora of a limited size, they lack generalization. This issue can also be observed in EKG, where very long and diverse phrases, which sometimes do not constitute a meaningful multi-word unit, are treated as technically meaningful terms. In addition to multi-word unit, we can observe different kinds of noise in relation types, such as many misspelled words and multiple inflections of same words. Hence, both the vocabulary size and number of relations are extremely large and noisy.

Since TechNet covers a considerably smaller vocabulary than EKG, we determined to create a mapping from EKG and TechNet. We tried to directly map phrases up to 4-tokens long while we assumed that the last four tokens of the phrases longer than 4-token are the main technical term, while the tokens prior to the last 4-tokens considered as the modifiers of the phrase detected in last 4-tokens. Figure 2 presents a graphical example of mapping a specific term's EKG representation to TechNet 2.0 representation. Since EKG has more and longer terms in its dictionary, the mappings are either one-to-one or many-to-one from EKG to TechNet. For example, both "infrared electromagnetic signal", and "jamming electromagnetic signal" terms are mapped to "electromagnetic signal". To retain the knowledge, we relate both "infrared" and "jamming" to "electromagnetic signal" through a "modified_by" relation.

Because the many-to-one mapping can create ambiguity and confusion in subsequent tasks such as design knowledge retrieval and representation, we retain the patent and classification information in TechNet 2.0. As a result, patent classes are on top of the knowledge graph hierarchy whereas patents are children of patent classes and terms are children of patents. Hence, the new knowledge graph database structure supports searching similar semantic relations in different technology domains. In addition, retaining the classification information in the semantic network will support merging information in other innovation and patent informatics studies, such as the network information covered in a series of studies by Luo et al. [8, 9].

We used the verbs contained in EKG and represented in TechNet as the relation types in TechNet 2.0. As a result, 5,462 verbs (or relation types) are detected. We mapped the relations of EKG if the lemmatized version of these relations appears in the set of TechNet 2.0 relation types. For example, EKG relations "expand, expanding, expanded" are all mapped to "expand" relation. As a result, we have 4,776 qualitative relations in TechNet 2.0.

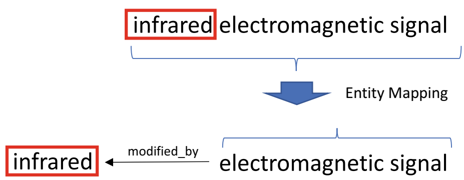

Fig. 2 Example of the entity mapping procedure from EKG to TechNet

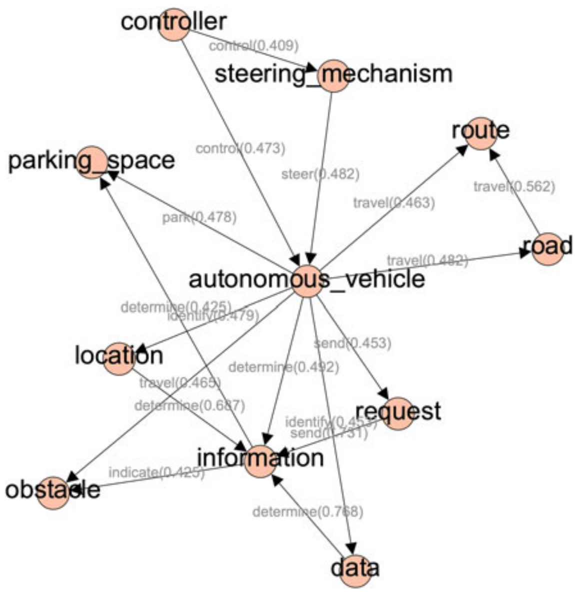

Fig. 3 A subgraph of TechNet 2.0 surrounding the term "autonomous vehicle"

Following the procedures described above, we mapped 54,286,973 EKG terms to 2,189,480 TechNet terms and produced 242,191,653 relations among which 191,972,609 stand for the SOA triplets that can be represented through TechNet terms and 27,876,516 are the "modified_by" relations which account for the noun and adjective modifiers of their parent terms (see Fig. 1 for example). In brief, TechNet 2.0 contains 4,038,924 terms and 242,191,653 qualitative relations among the terms, together with the pairwise quantitative relations among all terms.

Figure 3 represents a sub-graph of TechNet 2.0 surrounding the term "autonomous vehicle". We collected 10 different terms that draw the strongest relations to "autonomous vehicle". The connection strength is based on the qualitative relation in TechNet 2.0. In addition, we collected next strongest relations among these 10 terms so that each node has at least two edges. In fact, there are many more relations between the presented nodes, but we kept the graph sparse for a better visualization. The term network is non-hierarchical as illustrated in Fig. 3. The network can be expanded through the strongest relations as well as through more structured queries supported by the qualitative relation-based reasoning capabilities of TechNet 2.0.

TechNet 2.0: New Reasoning Capabilities

TechNet 2.0 will continue to provide the basic functions of TechNet (http://www.tech-net.org/) based on quantitative inter-term semantic similarity. This key feature is leveraged in TechNet 2.0 to assign relatedness measures to the relations within

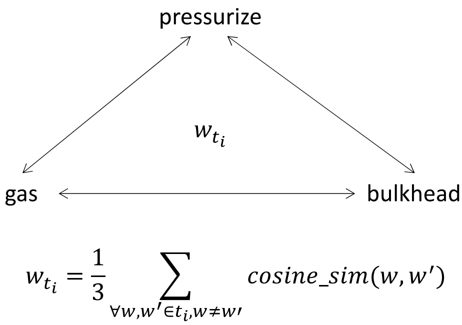

Fig. 4 A relation triplet example, <gas, pressurize, bulkhead> and how its relatedness measure is calculated

and among triplets. The relatedness of a relation triplet <term1, relation, term2>, w_{t_i}, where t_i is a specific triplet, is calculated as the mean of semantic similarities between the terms that constitute the triplet. This measurement is illustrated with an example in Fig. 4. Using this method, we calculated every single triplet's relatedness. The relatedness of a triplet can indicate the overall commonness or novelty of the terms and their relation through the verb or action. Given the relatedness values of triplets, we can search among a single term's qualitative relations (actions) to other terms and sort them in terms of each triplet's novelty or commonness.

Figure 5 illustrates how the new features can be used for graph inference. First, the claims of the patent US401411 are represented by blue and white nodes. We can visually compare this part of the visualizations with the EKG representation given in Fig. 1 to draw an understanding about the term and relation mapping methods employed to build TechNet 2.0. As an example of entity mapping, we can observe how "portable ordinance training aid" is mapped to "training_aid" along with new "modified_by" relation to form the <"training_aid", "modified_by", "portable"> and <"training_aid", "modified_by", ordinance> triplets while retaining the already encoded knowledge in EKG. In addition, multiple forms of qualitative relations such as "comprising" and "connecting" are mapped to their root forms such as "comprise", "connect".

We used the "bulkhead" term as an anchor point to make inference and expanded the graph of the US401411 patent, which is primarily classified in F01D21/003 (Arrangements for testing or measuring) one hop towards another patent US4813898 which is classified in B63H23/34 (Propeller shafts; Paddle-wheel shafts; Attachment of propellers on shafts). In the previous version of TechNet, such structured explorations and queries were impossible since the semantic network was flat and fully connected. On the contrary, TechNet 2.0 is a multi-graph which consists of different types of nodes and relations.

In addition to targeted queries which let the graph grow towards other patents or technology domains, we also introduced a function to search for terms connected to a specific term via a specific relation. An example is given again for the "bulkhead" term in Fig. 5. When we queried the other terms which "pressurize" the "bulkhead" component, the query returned three terms, namely "aircraft", "bottom tank" and "tunnel".

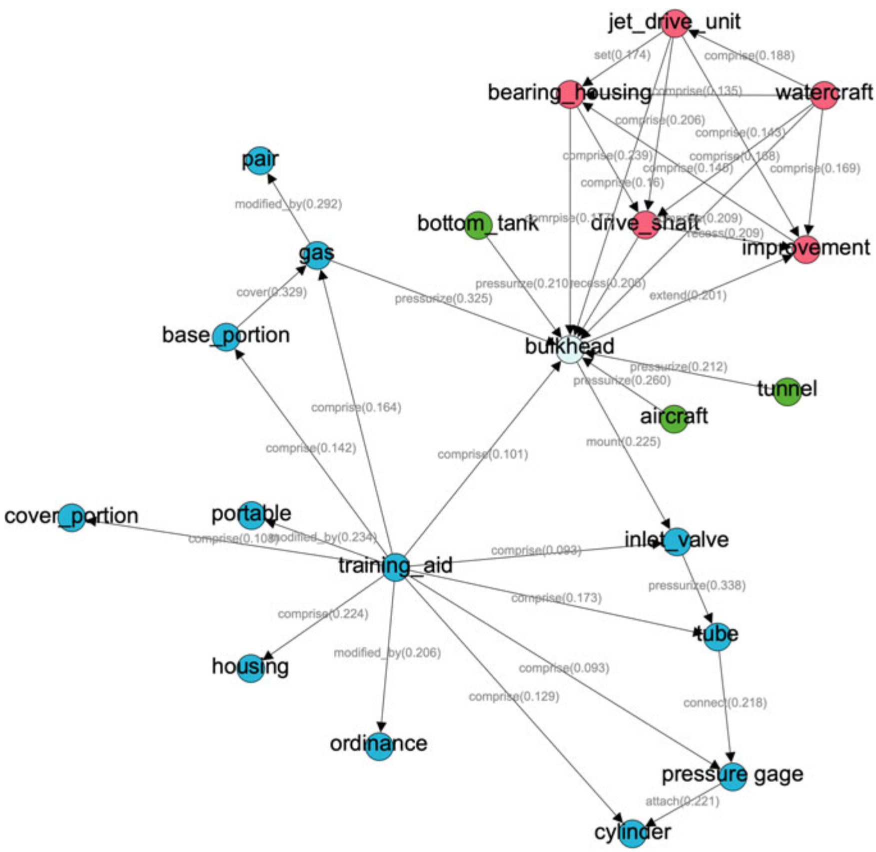

Fig. 5 The terms and relations in the claims of the patent US401411 visualized by TechNet 2.0 (blue and white nodes), terms in US4813898 claims (red and white nodes) which are one hop away from the common ‘bulkhead’ term and other terms in TechNet 2.0 which have the ‘pressurize’ relation to the ‘bulkhead’ term (green nodes). The layout of the graph is constructed by Force Atlas algorithm [10]. The numbers in the brackets denote the triplet relatedness, i.e., w_{t_i}

Discussions and Outlook

The new knowledge base, TechNet 2.0, leverages and synthesizes two previously constructed large design knowledge bases to aid engineering design research and practice. TechNet 2.0 addresses the limitation of TechNet—it provides only quantitative relations between terms despite its fully-connected structure. TechNet 2.0 adds to the original TechNet with the compact and human-readable qualitative relational representation of the knowledge space created by EKG.

Meanwhile, those readily available public knowledge bases such as WordNet [11] and ConceptNet [12] can provide common-sense knowledge to support general knowledge inference applications. Our vision is to work towards developing such a knowledge base to capture comprehensive engineering design knowledge reliably and serve the design research community and industry. There have been increased inclination towards creating semantic representations of engineering design knowledge by the availability of state-of-the-art data science and database infrastructure [13–16]. The findings, successes or failures, datasets, and the know-how of such studies may be consolidated to introduce robust data retrieval and validation procedures to achieve our future goals.

In the context of computational methods in engineering design, a comprehensive and accurate knowledge infrastructure is essential for creating intelligent engineering design agents which can contextualize a problem conceptually and functionally and search for potential solutions. A very knowledgeable AI partner in design teams, actively involved in brainstorming activities, can increase the innovation speed and lead humanity to new horizons. Yet, our community could only bring forward either limited knowledge bases or comprehensive ones with limited capabilities. Our new knowledge base and upcoming iterations and updates can potentially fill this gap and provide the necessary infrastructure to AI applications in engineering design to support various design tasks, especially the ones in the early product development phases, such as knowledge exploration and representation, creative reasoning, gap finding, brainstorming, concept generation, and more. Such progresses and new capabilities further empower creative artificial intelligence for design and data-driven innovation [17].

Last but not the least, the comprehensiveness of the knowledge bases is directly related to the data source. One limitation of the current engineering design-based studies is that they mostly rely on textual data sources, especially on the patent database. Research on using other kinds of data sources, such as images or videos, to enable multi-modal representation and learning may provide additional opportunities to support more accurate, nuanced, and meaningful reasoning and decision-making tasks.

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Design Cognition—1

A Classification of Methods and Constructs in Design Cognition Research

Emma Lawrie, Laura Hay, and Andrew Wodehouse

This paper provides a classification of the methods and constructs in design cognition research. It does so through reviewing the migration of knowledge from cognitive psychology used to drive design cognition research. To tackle the lack of scientific rigour and ontological fragmentation in design cognition research, there has been an appeal to align with current knowledge founded in cognitive psychology. However, incomplete understandings of foundational paradigms, and differing terminology hindering access to cognitive psychology literature, pose challenges for this initiative. The reviewed research indicated that the use of current cognitive psychology methods and theory is underway in design cognition research but remains preliminary. The work reported in this paper aimed to determine the fundamental constructs and methods in conceptual design cognition research and align these with cognitive psychology. The classification provides mutual intelligibility between the disciplines and eases access to cognitive psychology knowledge.

Introduction

The scientific investigation of mental processes is known as cognitive psychology [1]. When the mental processes being studied belong to designers while designing, this is the discipline of design cognition research. The study of design cognition became a focus of design researchers following work conducted in the 1960s that began viewing the design process through a scientific lens [2]. Much of this research has focused on the conceptual design phase—an early stage of the design process that aims to identify the basic outline and foundational principles behind a design

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concept [3]. While much has been learnt about conceptual design cognition, issues remain regarding scientific rigour and fragmented ontology in the discipline [4].

Lack of scientific rigour has been observed amongst design research at large and the discipline's complexity requires a diverse range of research methods to fully contend with the topic [5]. The study of design cognition is no exception to this. However, the discipline's reliance on protocol analysis—studying design cognition through the designer's verbalisation of their thoughts [6]—has driven a tendency towards qualitative, subjective, and small-scale research [3, 4]. Additionally, recent rapid research growth requires comprehensive overview to support the field's progression. Recent reviews have noted the persisting issues of poor research method diversity, lack of cognitive models and theories, lack of common ontological basis, and fragmented terminology [3, 4]. Suggestions for tackling these challenges have appealed to introducing and aligning with the research methods, ontology, and theory from the more established field of cognitive psychology [2]. However, diversifying research methods by using those established in other fields is often done with an incomplete understanding of the foundational paradigms involved [5]. This can lead to using unsuitable and unfamiliar methods in an improper way, and the production of flawed data [5].

The work reported in this paper aimed to tackle these challenges by developing a classification of constructs and methods in conceptual product design cognition research that aligns with the theory and terminology found in cognitive psychology literature. Providing such a classification will ease access for design cognition researchers aiming to utilise methods founded in cognitive psychology. Additionally, by formalising the theoretical roots of conceptual design cognition constructs, design cognition researchers will more fully understand the foundational paradigms and theory underpinning the field. This could ultimately foster improved scientific rigour, greater mutual intelligibility between design cognition and cognitive psychology research, and diversification of methods in future design cognition research.

Methods

The classification reported in this paper is based on a mapping review of conceptual product design whereby the literature was mapped and categorised to identify research gaps and suggest directions for future design cognition research [7]. This paper focuses on product design research—that is, the discipline involving the design of products concerning their functionality, usability, aesthetics, and ergonomics [8]. Due to similarities in the design process, research performed in other disciplinary contexts (e.g. architecture, industrial design, and mechanical engineering) is often used as a foundation for product design cognition research—such papers were included. The review was conducted using 6 databases (Compendex, DAAI, Embase, PsychInfo, ScienceDirect, and Web of Science). The search terms combined the domain (e.g. product design, industrial design), participants (e.g. engineers, designers), and cognitive aspects (e.g. cognition, mental). Initial searches conducted in October 2020 covered studies from 2010 to 2020. Follow-up searches conducted in October 2021 focused on the research methods used and included studies conducted pre-2010 and those published since the initial search. Journal articles, conference papers, and books were included in the sample. Due to space constraints, the entire sample of papers gathered is not included. Rather, an overview of the key findings is given.

Defining Terms

To develop the classification, two key formalisms discussed in conceptual design cognition literature were defined: (1) constructs; and (2) accounts. Constructs are conceptualisations of cognitive processes, defined in psychology and neuroscience as “entities that transform or operate on mental representations” [9]. From this, ‘mental representations’ are “mental entities that stand in relation to some physical entity… or abstract concept” [9].

Accounts are defined here as models, theories, and frameworks that formalise and explain relationships between design cognition constructs. A framework denotes a group of defined constructs and potential relationships between the constructs and concerned phenomena; however, it lacks the organisation required for a theory [10]. Theories can be derived from frameworks when the relationships between the constructs can be described, and testable hypotheses can be deduced [10]. A theory remains broader still than a model, which is created when a theory is applied to a certain phenomenon [11]. Models are often accompanied by schematic representation [10].

These definitions were used to develop the classification of the constructs and research methods reported in the relevant literature. Constructs were identified from accounts of design cognition and grouped based on similarities between authors’ definitions even where terminology differed. To trace the theoretical roots of these constructs, we explored and mapped related foundational accounts in psychology (often documented in disciplinary textbooks introducing key topics and their evolution). The constructs were then categorised based on current and established psychological definitions. The methods used by design cognition researchers to study each construct were then mapped and grouped into self-report, behavioural, and physiological categories informed by cognitive psychology and work by other design cognition authors. The following sections present the results of this process, beginning with an overview of methods used in design cognition research, followed by a discussion on the identified constructs. The developed framework is then presented and discussed, highlighting observations about the evolution, current state, and future directions for design cognition research.

Research Methods for Investigating Design Cognition

Behavioural research, in the broadest sense, involves the study of psychological, sociological, and educational phenomena [12]. However, in psychology, researchers often draw the more useful distinction between self-report, behavioural, and physiological experimental methods [13]. Within this distinction, self-report measures involve the participant reporting on aspects such as their feelings and judgements through methods including verbalisation, surveys, and rating scales [12]. Behavioural measures are distinguished as direct observations of behaviour [13]. Lastly, physiological measures assess bodily outputs such as heart-rate monitoring [13]. This includes neurophysiological measures relating to brain outputs from brain scanning and imaging. Self-report, behavioural, and physiological measures have seen varying application and extent of use in conceptual design cognition research; a summary of this is given in the following subsections.

Self-report

Self-report measures, where the participant reports on their behaviour, dominate in design cognition research. Such methods include surveys, rating scales, and the most notable regarding design cognition—protocol analysis [4]. Protocol analysis examines the designer's mental processes through the verbalisation of their thoughts [6]. Many design cognition research methods originated in cognitive psychology—protocol analysis being an example this, with Ericsson and Simon [14] developing the method's most influential framework. In design research, protocol data is gathered from video and audio recordings of designers that are then transcribed, encoded using a coding scheme, and analysed for insight into the designer's cognition [6]. Alongside verbal reports, given during (concurrent) or after (retrospective) the task, behavioural data from sketches and motor actions can be analysed [4].

Self-report measures, including protocol analysis, have provided valuable measures of attitudes, emotions, intended behaviour, cognitive products, and other perceptual constructs [15]. However, they have flaws that are hindering the progression of design cognition research. This includes their inadequacy in capturing nonconscious thought, and the intensive process of extracting conclusions from qualitative data often resulting in small-scale studies and difficulty in generalising results [3, 16]. The various coding schemes used for protocol analysis also obstruct result comparisons, and are contingent on the subjective nature of the reporting and analysis [17]. The dependency of design cognition research on protocol analysis has often been highlighted; however, other methods are becoming increasingly common.

Behavioural

Direct observations of behaviour have also recently seen increasing use. In design, output-based behavioural experiments are common. This involves analysing the outcome of a design task and making inferences about the cognitive processes involved [17]. Such studies use a control and experimental condition, with the outcomes being analysed comparatively [17]. Output-based studies applying standardised psychometric tests (often used in cognitive psychology research) have also been reported in recent years (e.g. [18]). It has been proposed that using standardised measures, along with greater standardisation of conventional design cognition research methods (e.g. protocol analysis coding schemes), could improve generalisability, facilitate meta-analysis, and increase scientific rigour in the field [2, 19].

In addition to output-based behavioural experiments, social science methods have been used to study design cognition. While research on collaborative design cognition has used ethnography methods, the study of individual designers using such methods has mostly employed case studies [20]. However, reviewing the gathered literature indicated that the use of such methods is less common than other behavioural and self-report methods.

Physiological

Physiological measures relate to bodily outputs such as heart-rate monitoring (ECG), eye-tracking, electro-dermal activity (EDA), and emotion tracking [13, 17]. Neurophysiological measures, which concern brain outputs, are a subset of physiological measures including functional magnetic resonance imaging (fMRI), functional near-infrared spectroscopy (fNIRS), and electroencephalography (EEG). While physiological outputs can be measured directly, they do not inherently reflect cognitive processes and must be interpreted as an indirect correlate of these processes [17].

In the past five years, the use of physiological measures in design cognition research has grown rapidly. Eye-tracking has provided insight into fixation [21], divergent/convergent thinking [22], and reasoning [23]. Heart rate monitoring (ECG) has also been applied (e.g. to study designer's mental effort and stress [24]), although far less extensively. Neurophysiological measures—used to study how brain areas support cognitive processes [25], are also gaining popularity in design cognition research. However, despite discoveries in the early 1990s leading to the invention of fMRI and fNIRS [26], and the first recorded human EEGs in the 1920s [27], its use within the discipline has only recently received greater focus. Such studies have offered initial support from a neurological view that design differs from general problem solving and involves distinct brain areas [25]. EEG studies have examined visual reasoning [28], divergent/convergent thinking [22], logical reasoning [29], and decision making [30]. fMRI studies have given insight into the neural basis of design

[25], and analogical reasoning [31]. fNIRS has also supported divergent/convergent dual-process theories [32].

Design cognition researchers have also explored which physiological measures can be used simultaneously, such as eye-tracking and EEG [22], and ECG with EEG [24]. Recent work has also applied a mixed methods approach using protocol analysis and eye-tracking data [23]. However, the recent introduction of physiological measures to the field continues to pose challenges in interpreting results and inferring implications for design cognition theory [2]. Hay et al. [33] discussed challenges facing fMRI studies in design cognition; they identified the development of experimental protocols, establishing a common ontological foundation, the identification of areas of neural activation during design, and managing methodological constraints as key challenges for future research. Many of these challenges have parallels affecting other physiological and neurophysiological measures.

Design Cognition Constructs

Having outlined the methods used in design cognition research, in this section we provide an overview of the constructs studied and trace their theoretical roots in cognitive psychology. As discussed previously, constructs in this context refers to the cognitive processes and mental representations that are theorised to be involved in design activities. Constructs and their potential relationships are formalised in accounts, i.e. frameworks, theories, and models. The majority of design cognition accounts have been developed within one of two key overarching viewpoints on design [4]. These viewpoints are discussed at length by [4], and may be summarised as follows:

- Design viewed as a rational and linear problem solving process of search conducted within the problem space (i.e. an abstract space representing the designer's task situation) [34]. This view stemmed from information processing theory founded in cognitive psychology and remains a major view in cognitive psychology research.
- Design viewed as a an exploratory and situated process conducted through transformations between two abstract spaces: the problem and solution space [35]. This view developed from situated cognition theories in cognitive psychology which considered information processing theories to lack insight into the social, cultural, and physical aspect of cognition [36]. This view has led to prominent frameworks such as FBS [37], and remains popular in design cognition research.

Several papers gathered in this review focused not on cognitive processes but on cognitive strategies, which may be interpreted as a set of cognitive processes engaged to move towards a goal. This includes, problem decomposition (dividing a problem into subproblems) [38]; and problem structuring (defining the problem space through knowledge retrieval) [39]. Another focus of design cognition research that could be viewed as a cognitive strategy is the duality of divergent and convergent thinking—terms coined by Guilford [40]. Divergent thinking in design is an intuitive, associative process that can generate a wide variety of ideas [41]. In contrast, convergent thinking is an analytic process that consolidates knowledge to move towards a solution [41]. The role of divergent and convergent thought has been researched in design and cognitive psychology across cognitive processes such as attention, reasoning, and memory. While cognitive strategies often feature in design cognition research, the higher-level focus of such studies was incompatible with the categorisation presented in this paper, which focuses on constructs at the level of cognitive processes.

It is not always clear how design cognition constructs relate to the well-established constructs and accounts of cognition in cognitive psychology. In the following subsections, we discuss the fundamental design cognition constructs identified through our literature review and illustrate how they align with cognitive psychology in both terminology and theoretical origin.

Reasoning

The cognitive processes of reasoning, decision-making, and judgement, each have their theoretical roots in a different normative theory [42]. Reasoning, or the process of making inferences, stems from the normative theory of logic; decision making, or the process of choosing amongst options, from utility theory; and judgement, or determining the probability of uncertain outcomes, from probability theory [42]. However, much cognitive psychology research since has focused on the factors behind why these rational norms are often violated [42]. This theme has presented in design cognition research through investigating biases and heuristics. While reasoning and decision-making are explicitly studied in design cognition research, judgement is often indistinctly grouped with these two processes and will, therefore, be discussed within the reasoning and decision making sections.

Reasoning processes are central to conceptual design [43]. Design reasoning has been elaborated as the lines of thought, transformations of information, questioning, and inferences that lead to conclusions being drawn beyond the designer's given information [44]. In design, reasoning research has focused on logical reasoning, analogical reasoning, visual reasoning, dual-process reasoning, heuristics, and biases. While such research has mostly used protocol analysis, use of physiological measures is growing.

Logical Reasoning

Logical reasoning processes—deductive reasoning (inference from the logical result of multiple true propositions), abductive reasoning (inference of a cause from an effect), and inductive reasoning (probabilistically true inference based on evidence) have been discussed in design cognition research since the 70s [45, 46]. In particular, inductive reasoning research in design has emphasised how knowledge from a previous problem-solving experience can assist solving a new problem. This is termed analogical reasoning with research into this phenomenon, as with much recent design cognition research, focusing on the differences between implicit, intuitive aspects, and explicit, effortful aspects of cognition (here termed 'schema-driven' and 'case-driven/based' analogical reasoning respectively) [43].

Visual Reasoning

Following the definition of reasoning as drawing conclusions beyond the given information, the information involved in visual reasoning is visual information e.g. a sketch [44]. While differing terminology is used to discuss visual reasoning processes in design [44, 47], they largely refer to the same three processes: visually perceiving what is before them (e.g. a sketch), forming a judgement on this perception through the discovery of intended and unintended consequences, and acting on this judgement to imagine a new solution. This shows the close involvement of visual perception and mental imagery processes in visual reasoning. Research on visual reasoning emphasises the 'situated' aspect of cognition—in that the designer takes part in a 'reflective conversation' [20] with the information. However, such research shows that information processing views are not entirely conflicted with situated cognition (a design cognition framework linking the views has been proposed [48]). Rather, that situated views emphasise aspects that information processing views tend to neglect and decontextualise [49].

Dual-Process Theories of Reasoning

Another theory founded in cognitive psychology that has recently entered design cognition research is dual-process theory (DPT). DPT, sometimes referred to as dual-system theory, is a widely recognized and studied theory of human reasoning and judgement within cognitive psychology [50]. At a simplistic level, the theory divides cognition into: autonomous, intuitive, and fast processing (Type 1), or reflective, rule-based, and slow processing (Type 2) [50]. While DPT is widely accepted within cognitive psychology, it is yet to make a wider impact on design research. However, dual-process models of creative thinking are gaining traction [51, 52], and a 'dual-process ideation model' of design cognition has been recently proposed [53]. In design, both Type 1 and 2 thinking have been linked to the drivers of novelty alongside errors and biases in judgement [54]. Furthermore, initial work has aligned DPT with design ontology [51]. Current DPT design research is preliminary and has consulted only a few of the many models from cognitive psychology. For future design cognition research to build on this, challenges will be faced regarding intradisciplinary fragmentation between reasoning research and creativity research in cognitive psychology. Calls have been voiced within cognitive psychology to align creativity and reasoning researchers focusing on DPT [55]. To effectively build on existing DPT knowledge, future design cognition research would benefit from an interdisciplinary approach aligning creativity, reasoning, and design perspectives.

Decision Making

Conceptual design cognition greatly relies on decision making processes. Decision making can be defined as the processes that consider alternatives and select one alternative under the presence of uncertainty and through consideration of context, preferences, and boundaries [1]. In design, this can refer to the selection, or dismissal, of concepts over other concepts [16]. The reliance on subjectivity in decision making has been linked to conceptual design considerations such as functional requirements and customer needs which rely primarily on human preference [56]. The subjectivity in conceptual design also relates to intuition. However, early theories of decision making developed in cognitive psychology consisted of normative descriptive models that assumed the decision maker not to rely on intuition, but to be an entirely rational information processing system [57]. Such models described the decision maker as taking a probabilistic approach [58]. That is, that the decision maker would assess the options and information, and choose the alternative that provides the most utility [58]. These theories ultimately failed and are now largely disregarded as ways to describe decision making [57]. Simon [59], in his theory of 'bounded rationality' discussed how rather than making optimising decisions, designers make satisficing decisions. This results from designers not being given alternative concepts (as solely rational decision-making models assume), but rather that they generate and develop their own options [59].

Knowledge and Memory

Knowledge and memory are another two key constructs in design cognition. Knowledge can be defined as information and beliefs stored in memory [60], and memory as the cognitive processes that store and retrieve this information after its presentation [46]. The close relation of these constructs means they are most easily discussed together. The idea that designers possess more knowledge than they can express is often discussed [61]. Knowledge held by designers that can be expressed directly through words is referred to as explicit knowledge [61]. Contrastingly, implicit knowledge, or tacit knowledge, cannot be articulated and refers to the designer's intuition and understanding gained through experience [61]. These types of knowledge are often termed declarative (explicit) and procedural (implicit); again, stemming from formalisations made in cognitive psychology [62].

Early conceptualisations of memory in cognitive psychology distinguished between long- and short-term memory [63]. Long-term memory holds information over extended periods of time (minutes to years) and holds both declarative and procedural knowledge [46]. Long-term memory is also theorised to hold schemas—abstract knowledge structures that constrain and influence the problem-solving process [64]. Schemas function as the automatic recognition of a category of previously experienced problems from which the previous solution procedure is abstracted and applied to a current similar problem [64]. Schemas hold both declarative and procedural knowledge of how to classify and best solve problems in each group [43].

Declarative knowledge can be stored in episodic or semantic memory ("memory for experiences" and "memory for facts" respectively) [46]. Neither of these have been widely discussed regarding design cognition and have been identified as a direction for future research [16]. Semantic processing, a process connected to semantic memory, is the method by which stored information on the attributes of concepts is retrieved from this memory, acted upon, and expressed through language [65]. In design, semantic processing has been studied through the designer's interpretation of meanings from stimuli e.g. words describing artefacts, and sketches [66].

Initial research in cognitive psychology on short-term memory (memory of the previous 15–30 s) focused on its storage capacity and timeframe [46]. This led to the development of Baddeley and Hitch's [67] model of working memory (later developed in [68])—a concept that replaces short-term memory and instead proposes a multi-component model that aims to better explain complex cognition. Few attempts have been made to reconcile this model within design (e.g. [39]). However, gaps in design cognition research regarding executive control mechanisms reveal an apparent need for future consideration of such control mechanisms as discussed in Baddeley's model. This links to the discussed potential in DPT accounts for the field regarding how Type 1 and Type 2 processing is controlled.

Metacognition

Another area of cognition research that has only recently received increased interest regarding design is metacognition, despite it being identified as an essential component of creativity for some decades in cognitive psychology literature [69]. Metacognition, originally coined in the mid 70s by Flavell [70], refers to the cognitive processes that facilitate the ongoing supervision and regulation of thought to achieve efficient cognitive processing [70, 71]. In other words, metacognition is thinking about thinking [70]. In design, metacognitive processes are essential in managing the complexity of problem solving, concept generation, evaluation, and development [69].

A focus of metacognitive research in cognitive psychology has been metacognitive reasoning [71]. Such research has influenced similar design cognition work. In particular, the role of uncertainty perception and heightening uncertainty as metacognitive triggers for regulating the design process have been used to model the progression of design activity [69, 72]. Further such work has been identified for future research by several authors [69].

Executive Functions

Similarly to metacognition, executive functions are a set of cognitive processes that have recently entered design cognition research [2, 16, 28], despite being discussed in cognitive psychology for some decades [73]. The term refers to the cognitive processes involved in controlling behaviour according to changes in environment which is required when intuitive and automatic processes are insufficient or impractical [73, 74]. Within cognitive psychology there is a general consensus on three 'core' executive functions: working memory, cognitive flexibility (ability to shift mental task and content), and inhibition (ability to ignore distractions and focus attention) [74]. Similarly to metacognition, executive functions play a role in monitoring, interpreting, and regulating cognition [74]. However, executive function research in design cognition literature is even more limited than that of metacognition in the same context [2]. While certain executive functions have been discussed in design research (e.g. working memory [39]), studying the holistic role of executive functions is inviting for future research.

Attention

Attention can be considered as the capacity to focus on certain stimuli when simultaneously processing additional things is impossible [1]. In cognitive psychology, the defocusing and focusing of attention has been linked to divergent and convergent thought respectively [41]. This stems from associative thinking being facilitated by defocusing attention, while the focusing of attention facilitates analytic thought [41]. While there are parallels with DPT, the concepts do not map directly onto one another. However, studying the relationship between divergent and convergent thinking regarding attention through a DPT lens invites future design cognition research. The ability to shift attentional focus has also been related to an individual's creativity [41]. This aligns with current DPT views that link creativity to the ability to switch between Type 1 and 2 processing [41].

Another area of attention research in design cognition investigates how designers overcome mental blocks and impasses during design. Such blocks can be considered a cognitive bias—consistently occurring errors in cognition that form an inaccurate view of reality [23]. These blocks are often referred to as fixation. Within design, fixation is an illogical adherence to a perceived set of limitations or ideas during while designing [75]. These restrictions can block finding a successful solution and often lead to limiting creativity. Fixations on the function of an artefact; a problem-solving approach or solution; inspiration sources; and being limited by emotional, cultural, and environmental factors have all been researched in design [75]. Although fixation can hinder the design process, it can also foster inspiration [21]. In line with recent research into nonconscious aspects of design, initial work regarding this in fixation has used physiological methods [21].

Visual Perception and Mental Imagery

Visual perception and mental imagery are cornerstones of conceptual design cognition. The two are closely related cognitive processes and play a key role in absorbing external information and imagining new ideas. Visual perception can be defined as the cognitive process of extracting and recognising visual information entering through the eye [1]. Contrastingly, mental imagery is processing involving the recreation of perceptual information without any external source of this information present [1, 46]. In conceptual design cognition research, the two are often investigated together. Such studies have examined aspects such as the effects of visual stimuli on mental imagery and the effects of tools for external representation on mental imagery [76, 77]. Although protocol analysis has remained dominant in visual perception and mental imagery research in design, newer methods to the field—such as eye-tracking, have recently provided further insight [78].

Classifying Methods and Constructs

The main contribution of this work is presented through a visual classification and timeline of the research methods, constructs, and theoretical roots discussed in conceptual design cognition literature. The previous sections discussing these were developed into Fig. 1, which shows the accounts of the theoretical roots (left); the influence of these accounts on the study of cognitive processes of conceptual design (centre); and a timeline of the empirical studies investigating these processes and the type(s) of research method used (right). Each dot shows the use of a method to study a cognitive process in the literature using a self-report (green), behavioural (orange), or physiological (red) measure. Studies using a mixed methods approach are denoted by a halved dot coloured in each half according to the methods used.

This classification conveys several observations about the state of design cognition research and its future. In the sample reported in this classification, 39% used self-report measures, 27% physiological, 23% behavioural, and 11% used mixed methods. Until recently, the domination of self-report measures was even greater. Prior to 2016 the percentage of studies using self-report measures was 55%, 13%

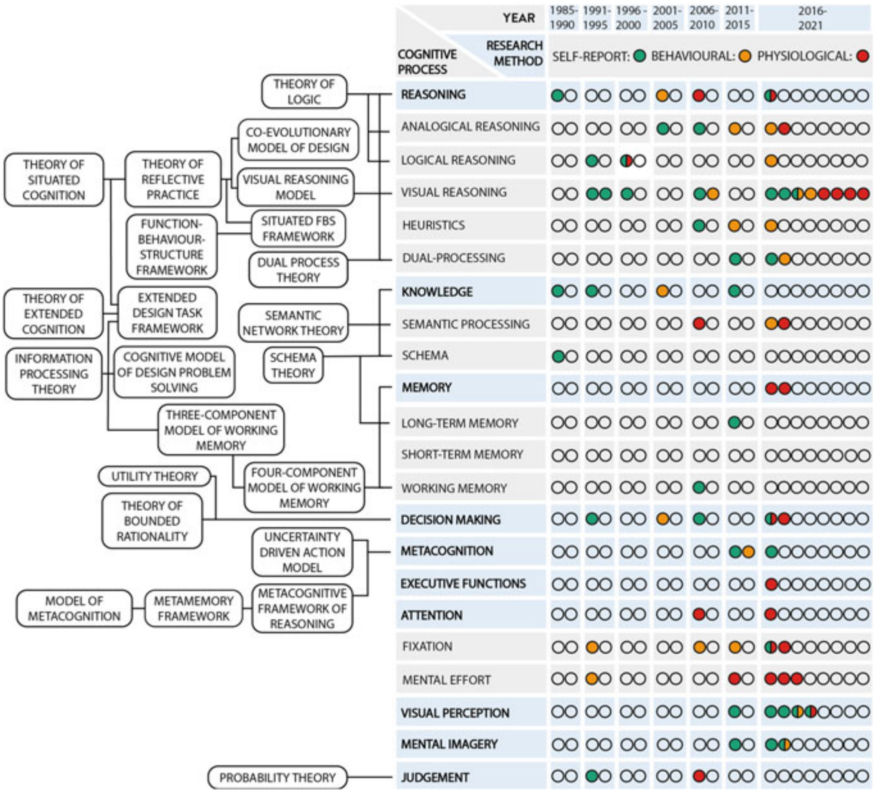

Fig. 1 A timeline (1985–2021) of the cognitive processes, theoretical roots, and research methods in conceptual design cognition research on individual designers

used physiological, 29% used behavioural, and 3% used mixed methods. This shows signs of a considerable shift in design cognition research. A greater emphasis on scientific rigour has seen increasing use of physiological measures in addition to traditional design cognition methods like protocol analysis. Mixed method approaches—combining self-report, behavioural, and physiological measures are also increasingly used. However, relatively few studies reported in this review followed this approach. This reflects the continued tendency of design cognition research to rely on single methods despite calls from authors to use more mixed methods (e.g. [2]). Continued efforts towards mixed methods approaches would allow the field to harness the advantages of triangulating findings across methods and data sources and address subjectivity in protocol analysis. The combination of behavioural methods with physiological and neurophysiological methods would also aid in advancing the field by building connections between cognition and brain activity.

The complex array of accounts depicted in Fig. 1 shows what could be considered both healthy pluralism and debate. However, it also shows that design cognition constructs can largely be aligned with current knowledge in cognitive psychology.

In accordance with design cognition researchers promoting the alignment of these two fields, using more consistent terminology like that used in this classification would aid in mutual intelligibility between the fields, and ease access to knowledge in cognitive psychology. Furthermore, such efforts would provide a basis for the wider reach of design cognition research such that knowledge would not only transfer from cognitive psychology to design cognition but vice versa. Recent advancements in DPT design cognition work also show promise for building a wider framework within which cohesion in design cognition research can be built.

This classification provides an overview, rather than great depth, regarding each of the identified constructs. Therefore, design cognition researchers can use this classification as a guide and starting point to learning about the research methods, theoretical origins, and terminology to use regarding conceptual design cognition phenomena and planning their own research. It can also be used to identify constructs that are yet to be researched using non-self-report measures; trends regarding the type of measures being used to study each construct; definitions of constructs that are consistent between design cognition and cognitive psychology literature; potentially related constructs; and the prominent related accounts regarding each construct.

Conclusions

This paper provides a classification of the methods and constructs in conceptual design cognition research. This is achieved through a review of conceptual design cognition constructs and methods focusing on the disciplinary roots of these constructs in cognitive psychology. The review shows the growing use of physiological, behavioural, and mixed methods use which shows initial progress regarding the drive to align design cognition research with cognitive psychology [51]. However, physiological and behavioural measures present their own challenges for interpreting results [17]. Much room remains for harnessing the full potential of recently applied methods, methods yet to be applied (e.g. EDA), and methods yet to be combined in a mixed-method approach. Despite this, the trend towards diversifying methods shows promise for closing this knowledge gap between cognitive psychology and design cognition. More recent cognitive constructs and theory to enter design cognition research from cognitive psychology (e.g. metacognition, executive functions, and dual-process theories) have been identified as key to developing the field. The classification presented in this paper can assist such future design cognition research through supporting the continued diversification of methods, easing access to foundational paradigms, highlighting gaps in current research, and improving mutual intelligibility between design cognition and cognitive psychology.

This paper covered a broad range of design cognition research. However, several limitations were faced. The wide scope of the review has limited the detail of analysis and the focus on individual designers has neglected the study of design teams. The review concentrated on product design cognition research and although knowledge from other fields (subsequently used in a product design context) was discussed, relevant papers in adjacent fields may have been missed. While this paper provides a comprehensive classification of constructs and methods in conceptual design cognition research that aligns with cognitive psychology, cognitive psychology is far from an ontologically consistent field. Although cognitive psychology has a more established knowledge base that this paper draws upon, defining a common ontological basis in design cognition requires continued efforts. Despite this, this paper has covered the most prevalent areas of research within its scope, aided in the alignment of design cognition and cognitive psychology research, and provided a classification that can aid in method diversification, consistency, and scientific rigour in future design cognition research.

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Is the PSVT:R Suitable for Evaluating Spatial Skill in Design? A Critique

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Design educators and spatial researchers frequently use the Purdue Spatial Visualization Test: Rotations (PSVT:R) to assess students' spatial abilities. Some researchers have claimed that the PSVT:R is the strongest measure of mental rotation ability, that relative to other tests, the PSVT:R most incorporates the "gestalt thinking process," and that the gestalt thinking process is widely accepted as the key component of spatial ability. In this study, we present evidence that the claims surrounding the PSVT:R's validity may not be accurate and represent a co-construction of gender and spatial ability. We suggest that the PSVT:R is not an ideal tool for assessment of spatial skill in design disciplines, and instruments that allow for open-ended responses are needed.

Background/Motivation

The Purdue Spatial Visualization Test: Rotations (PSVT:R [1]) is one of the most common tests of spatial ability used in engineering design graphics research [2] and has been frequently used to assess spatial abilities in engineering, STEM, and product design education [3–5]. The PSVT:R contains 30 questions presented in multiple choice format. An example question is shown in Fig. 1. The questions are framed as analogies, showing a model shape in two positions that differ by a rotation around one or more axes. The test-taker must select from an answer bank the correct view of the shape in question that represents the same rotation that was demonstrated in the model shape.

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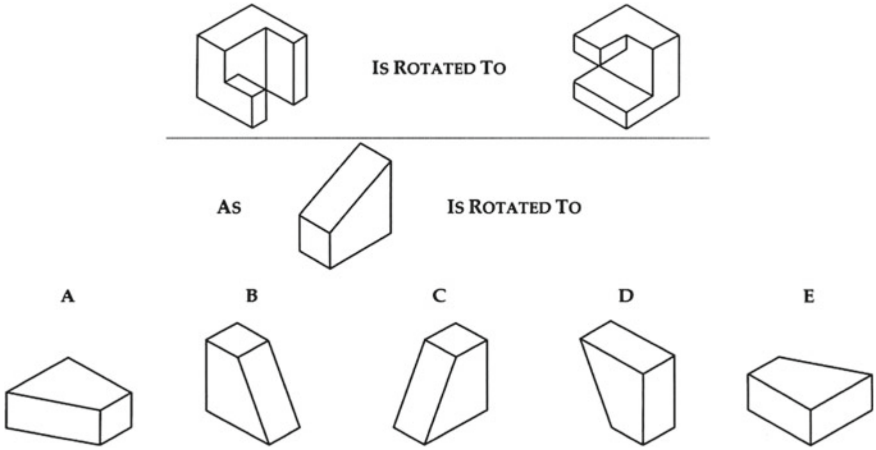

Fig. 1 Example problem from the revised PSVT:R [6] (correct answer is "B")

Some researchers have pointed out various problems with the PSVT:R, including mistakes in the isometric projection drawings in the original version [7], which were later corrected in a revised version [6]. However, even correctly drawn isometric projections have limitations that make them less than ideal for use in evaluating 3D spatial skills [8]. In fact, some test takers reportedly interpret the shapes as 2D patterns rather than 3D shapes [9]. Though the PSVT:R is supposed to be a test of mental rotation, understanding the shapes in the questions may be an additional cognitive task that is required to solve the items besides just mental rotation [10]. According to a factor analysis, the PSVT:R cannot be considered a single-construct measure of mental rotation ability [11]. Degree of rotation is not the only variable that contributes to item difficulty on the PSVT:R; complexity of the shapes is likely a contributing factor as well [12].

Aims

While various issues regarding the construct validity of the PSVT:R for assessing mental rotation ability have been investigated by researchers, little attention has been given to the validity claims about the instrument that were made by the test's creator and by subsequent researchers who have used the assessment. According to Maeda and Yoon, "the PSVT:R has been frequently cited as the strongest measure of [the] spatial visualization ability mental rotation that most incorporates the holistic or gestalt spatial thinking process and least incorporates the analytic or analogical spatial thinking process" [13]. Bodner and Guay further claim that the gestalt processing style "has been widely accepted as the key cognitive component of spatial ability" [14].

The present work aims to examine the term "gestalt processing" and investigate the claim that gestalt processing has been widely accepted as the key cognitive component of spatial ability." We provide a critical appraisal of the evidence supporting the claim that the PSVT:R is the strongest measure of such processing.

Significance

Spatial ability is seen as an important component for designers who must think in three dimensions, and has been repeatedly investigated in various design disciplines including engineering [5, 15, 16], interior design [17], apparel design [18, 19], and architecture [20] over the course of many decades. The PSVT:R is highly popular in engineering design education and research [2–5, 13], however, validity claims about the instrument are rarely scrutinized. In our review of the literature, we did not find any examples of critical inquiry into the claims surrounding the PSVT:R. Instrument validity is important, particularly when instruments are used to make claims such as gender differences in cognition, as has been done with the PSVT:R. The PSVT:R was used in a meta-analysis to support the idea that men have better mental rotation skills than women [13]. Furthermore, if the PSVT:R is not truly an accurate or valid measure of spatial ability or of mental rotation, this would point to a need for improved instruments to measure spatial ability in design disciplines. The widespread use of the test, as well as the fact that it is used to support claims about gender differences in cognition which may have implications for design education, indicate the need for careful scrutiny of the validity of the instrument for evaluating spatial ability.

Method

We utilized the techniques of document analysis and discourse analysis to examine the previous writings about the PSVT:R in order to investigate the validity claims surrounding the instrument. A snowball sampling method was used to select the documents to be included in the analysis, starting from a recent meta-analysis on gender differences in the PSVT:R [13]. We traced back the references that were cited in support of claims about gestalt processing, and sought to understand the justification behind claims about the PSVT:R, especially the claims regarding instrument validity for the assessment of spatial ability. Key literature is shown in Fig. 2.

This study seeks to answer the following research questions:

(1) What do spatial ability researchers mean by the term "gestalt processing" in the assessment of spatial ability?
(2) Why do researchers believe "gestalt processing" better captures the construct of spatial ability than does "analytical processing"?

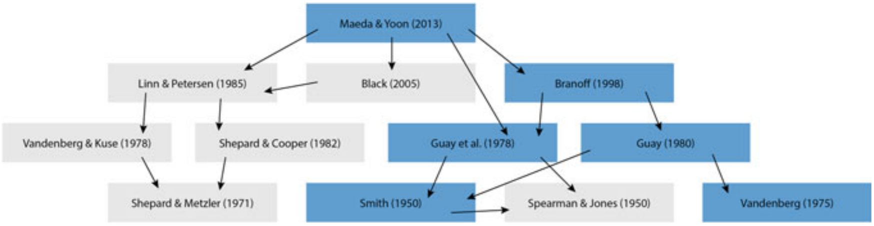

Fig. 2 Literature map. Gray boxes indicate papers that did not discuss two distinct problem-solving strategies (gestalt/holistic vs. analytic)

(3) How was it determined that the PSVT:R is the test of spatial ability that best measures "gestalt processing"?
(4) What are the implications for using the PSVT:R instrument to assess spatial ability?

Results

What Is the Origin of the Term "Gestalt Processing" in Spatial Ability Assessment?

Maeda and Yoon [13] state that "the PSVT:R has frequently been cited as the strongest measure of spatial visualization ability of mental rotation that most incorporates the holistic or gestalt spatial thinking process and least incorporates the analytic or analogical spatial thinking process" [13]. Two opposing thinking processes are presented here: the holistic/gestalt spatial thinking process and the analytic/analogical thinking process. While Maeda and Yoon [13] cite Black [21] in support of their statement about gestalt thinking and the PSVT:R, Black [21] and the antecedent citations within the work do not discuss the PSVT:R, and only make mention of gestalt thinking as a *general process* that is always utilized in mental rotation, not as competitor to analytic thinking. Shepard and Cooper [22] is the root source of Black's [21] citation, but make no mention of gestalt processing versus analytic processing. Shepard and Cooper [22] briefly mention Gestalt psychologists and their ideas about apparent motion being revealing of the way the brain is organized, but not in reference to any spatial test-solving strategy.

The proposition that the PSVT:R leverages a gestalt thinking process as opposed to an analytic thinking process appears to be original to Guay et al. [23]. Before discussing whether or not the PSVT:R uses a gestalt thinking process, we need to understand what that term is supposed to mean. Guay et al. [23] state that "gestalt processing is widely accepted as the key cognitive component of spatial ability," however, only one of the references cited in support of this statement actually says anything about gestalt processing at all.

However, some of the references cited by Guay et al. [23, 24] in support of the gestalt processing idea contain no discussion of gestalt processing whatsoever: Bock and Kolakowski [25], and Michael et al. [26]. Where Guay et al. [23] states that "gestalt processing is widely accepted as the key cognitive component of spatial ability" only one of their cited references supports the idea. The idea that gestalt processing is key component of spatial ability appears to have originated with Smith [27]. Though Smith [27] and Guay et al. [23] quote Spearman and Jones [28] in support of their arguments, in reading Spearman and Jones [23] we do not see support for the idea that gestalt thinking and analytic thinking are opposing strategies that would be required by different spatial tests. Instead, Spearman and Jones [28] state that analytic processing is present in *every* test. They state "The role played by the analytic procedure may be comparatively small, but it appears—with the human mind, at any rate—to be never completely absent from anything likely to be employed as a test" (pp. 70–71). Spearman and Jones [28] defined analytic as "attention wanders from one element of the figures to another" and "synthetic" [gestalt], as when figures are "mentally grasped in much larger units" or "wholes" (p. 70). In summary, the origins of the dichotomy between "gestalt/holistic" and "analytic" processing appears to be the writer Smith [27].

How Are Gestalt and Analytic Processing Defined?

What, then, is meant by the term "gestalt processing," and why is it thought to be important in the assessment of spatial ability? Smith [27] defined spatial tests as "involving critically the perception of gestalten of shape, but not those involving gestalten of magnitude (e.g. discrimination of sizes of circles, squares, etc.)" (p. 203). Smith also argued that a test with a spatial factor would be characterized by a need to retain an impression of a shape or pattern as a whole rather than a need to note significant details [27].

There appears to have been general agreement among the set of authors in this investigation that there were two types of mental processing that could be invoked by supposedly spatial tests, and one type was called gestalt processing [23], or a holistic approach [29]. The opposing type was analytical processing [23], which was also called verbal analytical [29], or verbal reasoning [30, 31], and tasks that leveraged this processing style were not seen as true measures of spatial ability. Gestalt processing was non-verbal [23], and was concerned with perception, retention, recognition of configuration, pattern, or shape as an *organized whole* [27, 30], while analytical processing was concerned with perception of details [30]. There was some inconsistency with the use of the word "perception," as some authors said that only mental manipulation [24] or transformation [23] enabled a task to measure spatial ability, rather than perception. The gestalt/holistic problem solving was seen as most often employed by males, while females were seen as likely to use verbal/analytical strategies [23, 29]. This dichotomy is summarized in Table 1.

Table 1 Dichotomous division of mental processing strategies

Spatial	Not-spatial
Gestalt processing [23], holistic approach [29]	Analytical [23]
Perception, retention, recognition of configuration, pattern, or shape as *organized whole* [27, 30]	Perception of *details* [30]
Mental manipulation [24] or transformation [23]	Form perception [24, 31] or retention [24]
Non-verbal [23]	Verbal [29–31]
Most often used by males [23, 29]	Most often used by females [23, 29]

While there appears to have been a general consensus among this small group of authors regarding this particular dichotomy, not everyone subscribed to this thinking. The idea that females are better with verbal skills and males with spatial has been called the "earliest and most persistent of cognitive dichotomies" [32]. Sherman [33] pointed out that there is a strong tendency to arbitrarily divide characteristics into two groups, giving males one characteristic and females the opposite characteristic. The arbitrary nature of the dichotomy discussed in this paper is apparent, as other researchers placed men and women on opposite sides. Sherman [33] states that it was commonly believed that *women* took a "global" (holistic) approach while *men* took an "analytical" approach. Even within the authors in our literature map, there was disagreement about perception versus manipulation. Smith [27, 30] placed perception or retention of a whole in the "gestalt" side, while others placed form perception or retention on the "analytical" side [24, 31].

Though Smith [27] was highly cited by subsequent researchers, critics have pointed out that many of the claims about gender differences in spatial ability in the book were made without supporting references, and called the material "stuff indeed to make a myth" [32] (p. 249). By defining the spatial factor as paying attention to *form* rather than *detail*, this allowed Smith the opportunity to discount spatial tests in which females outperformed males as "not true spatial tests." In another highly-cited book, in describing the spatial test "Identical Pictures," a test in which girls were consistently scoring higher than boys, Smith states: "The writer maintains, however, that this is not a true spatial test, since gestalt perception is not critical for success in the items. The test can be done by attending to details in the figures, for they usually differ only in respect of *detail* and not of *form*" [30] (p. 448). In describing another spatial test (Memory for Designs), Smith describes an experiment in which scoring the test for accuracy of detail led to a gender difference in favor of females, while scoring for correctness of proportion led to gender difference in favor of males [30].

At least in the case of Smith [27, 30], ideas about gender differences in spatial ability and the definition of spatial ability itself appear to be co-constructed. In the studies they referenced, males performed better when it came to paying attention to the whole form (gestalt) versus the details, males were believed to have better spatial ability than females, therefore paying attention to the whole form (gestalt processing) rather than details (analytic processing) became the key component of

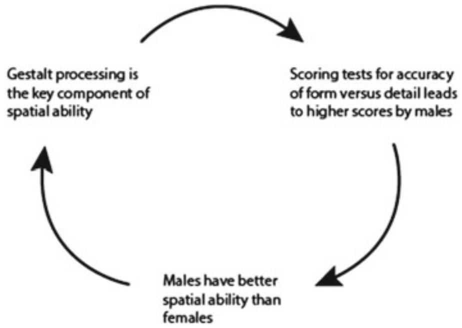

Fig. 3 Circular flow illustrating the co-construction of gender and spatial ability

spatial ability. Rather than flowing logically, these ideas flow in a circular pattern, and are co-constructed. The circular pattern is illustrated in Fig. 3.

A similar circular flow is seen in the writings of Guay [23, 24], the creator of the PSVT:R. The fact that males scored significantly higher than females in some administrations of the PSVT:R is presented as "evidence for construct validity" because it is "expected for measures of spatial ability" [24]. When male and female performance on another spatial test (Minnesota Paper Form Board; MPFB) was equal, Guay [24] states that these data "suggest that the MPFB may be measuring something other than spatial ability for the majority of the people taking the test" [24].

How Was It Determined That the PSVT:R Is the Test of Spatial Ability that Best Measures "Gestalt Processing"?

Now that we have established what is meant by "gestalt processing" and why it was seen as the best measure of spatial ability, we will discuss how it was determined that the PSVT:R is among the instruments that most employs gestalt processing. This determination was made in one study performed by Guay et al. [23]. Their study sought to investigate a three-part hypothesis: (1) spatial tests vary in the degree to which they provoke certain mental processing strategies (analytic vs. gestalt), (2) tests maximizing the use of gestalt processing while minimizing the use of analytic processing are the best measures of spatial ability, (3) males and females differ in their use of analytic and gestalt processing in solving spatial tasks. Though they put forth a three part hypothesis, part two was not actually tested in the experiment and, in any case, is more of a belief than a testable hypothesis.

The subjects in the experiment included 16 undergraduate university students (eight female). The researchers selected nine tests of spatial abilities for use in the study. They attempted to select fives tests that were "least confounded by analytic processing" and four which were "most confounded by analytic processing." No description is provided as to how they determined whether a test was confounded by analytic processing, or what criteria was used in that assessment. Following the selection of nine tests, the researchers took a few representative questions from each test and assembled them into a combined test booklet which was administered to the students. After the students completed the representative items from a test, the students gave a tape-recorded description of what went on inside their minds as they were solving the questions. Transcriptions of these recordings were reviewed by four "judges" who rated each response on a scale from "very analytic" to "very gestalt," and assigned points associated with each rating. Based on the averages scores from the judges, a final ranking order of the tests from "least confounded" to "most confounded" was compiled. The final ranking placed the PSVT:R at the top, and along with an MRT-type rotation task, these tests were said to be "least confounded" by analytical processing. The Minnesota Paper Form Board Test was said to be "most confounded" by analytic processing. (This is the same test that Guay [24] said could not be measuring spatial abilities since men and women performed equally well.) The study also concluded that males and females do not differ in their use of analytic versus gestalt processing in solving spatial tasks, based on the way the subjects described their problem-solving strategies. This did not confirm part three of the original hypothesis—the dichotomy put forth in the previous section of this paper that men are more "gestalt" and women are more "analytical."

This experimental study has multiple weak points. First, the methods used in the study may have been suitable to learn how the subjects *described* their experiences solving the spatial problems, however, we have no way of knowing how closely the descriptions of how they solved the problems align with the actual underlying mental processes that they used to solve the problems, which is what the study claims to have been evaluating. Typically, in a study that analyzed qualitative data as this one did, we would expect to see some examples of the responses provided by the subjects, and examples of how they were coded and categorized by the judges. Unfortunately, no such examples are provided. We receive no definitions that the judges used to categorize tests as "most confounded" or "least confounded" by analytical processing, nor are there any rating criteria provided as to how the judges rated subject responses as "analytical" or "gestalt." Without this information, the experiment is not replicable.

A more recent study by Kafumann et al. made a similar inquiry into holistic/spatial versus analytic thinking in solving problems on spatial ability instruments [34]. This study had students solve problems from the PSVT:R by "thinking aloud," and found that PSVT:R problems were frequently solved by using analytic strategies. Unlike Guay et al. [23], Kafumann et al. [34] concluded that the PSVT:R was processed by more analytic strategies while the MRT was more processed by more holistic strategies.

What Are the Implications for Using the PSVT:R to Assess Spatial Ability?

Based on the findings of this study, it does not seem likely that the PSVT:R is the strongest measure of "gestalt processing." We also did not find support for the idea that "gestalt processing" is the strongest measure of spatial ability. Most likely, *all* spatial tests have a component of analytic processing [28], and there is not a strong reason to believe that the PSVT:R allows analytic processing less than other tests of spatial ability. Furthermore, many researchers have repeatedly pointed out that there are many different abilities which fall under the umbrella term "spatial ability," [35–37] so having a single instrument that is the "best" measure of spatial ability is not actually possible.

While the PSVT:R has been shown to yield gender differences [13], studies using the PSVT:R have not corrected for other factors such as past training in graphics (e.g., drafting courses). Students with past graphics training perform better on the PSVT:R [2]. The fact that the PSVT:R yields gender differences has been used as evidence of instrument validity [14] is problematic from a construct validity standpoint, as it represents a co-construction of gender and spatial ability. Indeed, there are other spatial instruments which do not tend to show gender differences [38], and this fact does not mean that those instruments have weaker construct validity in assessing spatial ability.

In general, spatial tests do not align well with the spatial problems faced by professionals who use spatial problem solving in their fields [39]. In design disciplines, where creative problem solving is crucial, "open-ended" spatial assessments are likely to be more meaningful than multiple choice assessments like the PSVT:R. The question of gestalt versus analytic processing would not even be applicable if open-ended assessments were used. Moreover, design professionals generally solve open-ended spatial problems where they must use their creativity to devise a solution. Multiple choice tests are popular in research because they are accessible and can be scored quickly, however, the fact that an instrument is popular does not necessarily mean it is accurate.

Conclusions

In this study, we investigated the claims that the PSVT:R is the strongest measure of mental rotation ability, that the PSVT:R most incorporates the "gestalt thinking process" relative to other spatial tests, and that the gestalt thinking process is widely accepted as the key component of spatial ability. We failed to find strong support for any of these claims. Within the chain of literature that we reviewed, the definitions of "analytic processing" and "gestalt processing" were not consistent. We did not find support for the idea the gestalt processing was "widely accepted as the key component of spatial ability.” Instead, the ideas about gestalt processing being the best measure of spatial ability were traced to one single author [27].

The dichotomy of “gestalt processing” and “analytic processing” in spatial assessments appears to be highly linked with gender, to such an extent that suggests a co-construction of gender and spatial ability. Researchers considered that a test was a better instrument if males performed better, and they ensured this outcome by scoring for form versus details. Therefore, it was decided that perception of form was the best measure of spatial ability. The logic is circular, designed to favor a particular result by defining the criteria for spatial tests in ways that would favor males. Similar logic was used in the PSVT:R’s validity claims, which used gender differences as evidence of instrument validity [14].

Present-day educational researchers know that when groups perform differently on tests, it can be for a variety of reasons, including inbuilt bias in the instrument. We doubt that today’s researchers would consider disparity in group performance appropriate evidence of instrument validity.

The study which claimed to find that the PSVT:R is the best measure of spatial processing [23] had serious methodological problems, did not provide enough details to be replicable, did not provide definitions or criteria that were used to score responses, and did not provide examples of how subjects used gestalt and analytic processing. Unsurprisingly, the study’s conclusions also ranked a spatial instrument in which men and women performed equally well as the worst measure of spatial ability. A similar study failed to confirm the findings, and instead found that the PSVT:R was subject to analytic processing [34].

The dichotomy between “analytic processing” and “gestalt processing” is not one that would be relevant to the design discipline. Designers must frequently solve spatial problems in their work, but not by selecting from choices in an answer bank. Most designers solve spatial problems in their work creatively. For example, sketching, building CAD models, or building physical mockups and prototypes are often used to solve spatial problems in design. Creativity and insight are critical to spatial problem solving in design, but these are difficult to assess with multiple choice tests. Open-ended assessments, in which respondents have to come up with their own answers, would be preferable to multiple choice tests for assessing spatial ability in design disciplines. As future work, we plan to create a new spatial assessment instrument that is more suitable for use in design disciplines. In conclusion, researchers who want to assess spatial abilities of designers would be better served by updated instruments besides the PSVT:R. The validity claims of the PSVT:R are not well-supported, and the type of spatial problem solving in the instrument does not appear to be relevant to design.

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Effects of Open-Endedness on Problem Solving Behaviour

Hanan Alattas and P. Robert Duimering

Design is a form of ill-structured, open-ended problem solving. However, most experimental research on problem solving investigates well-structured problems with pre-defined solutions. We use an ill-structured categorization task to investigate effects of varying degrees of open-endedness on three indicators of problem-solving behaviour: solution variability, path dependency of solutions, and perceived problem-solving difficulty. Four-person groups solved three categorization problems, grouping 16 randomly selected pictures into four groups of four items each. Task goals and participants' open-endedness beliefs were varied to create three levels of problem open-endedness. In two tasks, participants grouped pictures based on similarity, seeking either a single best "expert" solution (least open-ended) or a "good" solution (more open-ended). In a third task, participants grouped pictures by creating four simple stories involving the items (most open-ended). Story versus similarity goals significantly influenced solution variability, path dependency and perceived problem-solving difficulty. Expert versus good open-endedness beliefs significantly influenced perceived difficulty.

Introduction

Design is a form of ill-structured, open-ended problem-solving, where designers develop integrated solutions from diverse problem elements, and a variety of different solutions may satisfy the requirements of the problem [1–3]. Research on design behaviour and cognition has built on psychological studies of problem-solving by individuals or groups, providing insights into such phenomena as design fixation [4]

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and design creativity [5, 6]. However, most problem-solving research has investigated well-structured problems with pre-defined solutions, rather than ill-structured, open-ended problems with many possible solutions. The effects of problem open-endedness on cognitive and behavioural aspects of problem solving are not well understood. A difficulty has been the lack of experimental methods that enable the controlled manipulation of structural properties of problems, such as open-endedness, or the measurement of effects of problem structure on relevant cognitive and behavioural outcome variables.

This paper presents results of a group problem-solving experiment investigating effects of problem open-endedness on problem-solving behaviour. We adapted a method developed by Adejumo et al. [7] that enables the manipulation of various dimensions of problem structure, and the measurement of certain cognitive and behavioural aspects of problem-solving. Specifically, we investigated the following three-part research question: What are the effects of the degree of problem open-endedness on: (1) the variability of solutions developed by different problem-solving groups; (2) the path-dependency of solutions (i.e., the degree to which solutions depend on initial conditions); and (3) problem-solvers' perceptions of problem-solving difficulty?

The study contributes to the design cognition literature by providing experimental evidence for specific effects of problem open-endedness on problem-solving behaviour, and by introducing a flexible method for future experiments investigating effects of structural properties of problems on problem-solving behaviour and cognition. The next sections will discuss relevant background and the hypotheses for the study. Then we present our experimental method and results. Finally, we discuss implications of the study, limitations, and potential directions for future research.

Problem Solving

The problem-solving research literature has been dominated by two main perspectives: Gestalt theory and information processing theory [8–10]. Gestalt psychologists investigated various effects of perception on problem-solving behaviour, based on a structural understanding of human perception, whereby stimuli are perceived as organized patterns and holistic figures against a background [11]. For example, in the well-known nine-dot problem [12], initial perceptions of problem structure introduce self-imposed constraints [13] that prevent the person from finding the solution, and the problem can only be solved after perceptual restructuring—a figure-ground shift characterized by the "aha" experience of insight. Duncker [8] used a candle task to investigate effects of functional fixedness, where individuals perceive problem elements as organized based on functional relations between parts and wholes. Participants were given a candle, tacks, and a box of matches, and told to mount the candle on the wall. Those given the matches inside the box had more difficulty solving the problem, because they could not perceptually separate the box from its function as a container for matches and recognize it as a potential candle stand. Luchins [14] used a water jug filling problem to investigate the Einstellung effect, a form of fixation where a previously learned solution procedure is rigidly applied, although there exists a simpler way of solving the problem.

Information processing theory considers the human as an information processing system and describes problem solving in terms of information search operations needed to move from the initial problem state to the solution state [10]. The theory explains human problem solving in terms of three main components. First is the information processing system, which views a human as a symbol manipulation system, with memory storage, a processor, sensory receptors, and motor effecters. Second is the task environment, which is objectively defined by the experimenter and includes the goal, the problem, and other relevant external factors. The third component is the problem space, which is a computational space subjectively defined by the problem solver, expressed in terms of a state space, operators, evaluation functions, and search strategies. The structure of the problem space is shaped by the interaction between subjective constraints inherent in the problem solver, and objective constraints imposed by the task environment. The problem space can be viewed as containing many nodes, or knowledge states, reflecting the knowledge that the problem solver attains at a specific moment in time. The problem solver searches the problem space until a knowledge state that includes the solution is found.

Ill-Structured, Open-Ended Problems

Reitman [1] (see also [15]) classified problems from well-structured to ill-structured, based on the availability of information about three components of the problem: the start state, the goal state, and the transformation function. An example of a well-structured problem is the Towers of Hanoi problem [9, 10], where the start and goal states are clearly defined and the transformation function completely specified in terms of rules for transferring a stack of disks from one peg to another. An example of an ill-structured problem is preparing dinner for guests [16], where information about the start state (e.g., how hungry the guests are), the goal state (e.g., how satisfied the guests will be with the meal), or the transformation function (e.g., whether food will be ordered or cooked at home) may be unavailable. Well-structured problems are typically close-ended, with one or a few possible solutions. Ill-structured problems are more open-ended with multiple solutions, where some may be better than others.

Design problems are prominent examples of ill-structured open-ended problems [2, 3]. Goel [2] described design as a four-stage process of gradually moving from an ill-structured to a well-structured state: problem structuring; identifying preliminary solutions; refinement; and detailing. Gunther [17] similarly described design problem solving in four stages: clarifying the task; searching for concepts (i.e., principal solutions for the subfunction of the design problem); evaluating and selecting solutions to achieve an overall concept for the design problem; and finally fixing the concept by optimizing it with consideration of the technical and economic criteria of the design problem. Whereas rational decision approaches such as optimization are suitable for certain well-structured design decisions, naturalistic decision approaches seeking satisfactory alternatives are more typical of ill-structured design problems [18].

Goel [2] distinguished design from non-design problems based on the variable nature of design constraints, ranging from rules and requirements that are often negotiable, to natural laws that are not negotiable. Ullman and Dietterich [19] noted that in mechanical design some constraints are given with the problem, while others are introduced by the domain knowledge of the designer, or derived by the designer while exploring solutions. The situated nature of constraints implies that solutions are often domain-specific and not easily transferred to other settings [15]. As new constraints are encountered during the solution process designers may need to reframe and restructure the problem to resolve trade-offs between conflicting goals and requirements [20], leading to the co-evolution of problem and solution over time [3, 21–23].

Design creativity often depends on a designer's ability to manipulate and reconcile conflicting constraints, and creative designs often involve modifying internal constraints (those imposed by designers themselves) relative to less negotiable external constraints (those imposed by external forces, e.g. clients) [24, 25]. Akin [26] reported that architects exercise the freedom to change design goals and other constraints as they gradually develop a comprehension of the problem and definition of a solution. Research investigating differences between experts and novices solving ill-structured problems [27] suggests that domain-specific knowledge may facilitate better solutions [28] but functional knowledge can also inhibit creativity by introducing constraints that prevent thinking beyond the bounds of prior knowledge [29].

Relatively little is known about the effects of varying degrees of problem open-endedness on problem-solving behavior and cognition. A recent review [30] indicated that much of the available evidence on design problem-solving is based on case studies, observations, and focus groups [2, 3, 17, 31, 32], often using protocol analysis methods to analyze think aloud, video or sketching data [23, 33–35]. Such methods provide valuable insights into design and other open-ended problem-solving domains, but sample sizes are often too small to test hypotheses about the effects of variables like open-endedness on cognition and behaviour. Educational research has used computer simulations of complex problem scenarios for the assessment of problem-solving skills [36], but the complexity of simulation scenarios makes it difficult to isolate effects of specific problem characteristics on cognitive or behavioural outcomes.

Psychological experiments on problem-solving have generally emphasized well-structured problems with predefined solution states, rather than ill-structured, open-ended problems with multiple potential solutions. Few experimental methods have been developed to investigate effects of structural properties of problems, such as open-endedness, on cognitive and behavioural processes in problem solving. Researchers have also had limited success integrating Gestalt and information processing aspects of problem-solving. Information processing studies often assume the problem structure is known a priori. Studies of perceptual phenomena often rely on single-step insight problems, where conceptual restructuring and reaching the solution occur more or less simultaneously, making it difficult to observe information search processes involved.

A group problem solving experiment by Adejumo et al. [7] (see also [37, 38]) addressed some of the above methodological limitations. Research on group problem solving investigates problem situations where group members identify solutions collaboratively by sharing and processing distributed information. Most studies have focused on group decision tasks where solution alternatives are known in advance and investigate effects of incomplete information sharing on group decision quality [39, 40], or the social decision schemes by which individual preferences combine to yield group decisions [41, 42]. By contrast, Adejumo et al. [7] used a distributed information task with unknown solution alternatives to investigate effects of structural properties of problems on cognitive and behavioural processes in group problem solving. They devised a flexible card categorization task, in which four participants exchanged 16 pictorial cards until each possessed a set of four of a kind. By varying the pictures on cards, they created a variety of different problem structures, ranging from simple information sort tasks to complex structures where participants had to perceptually restructure the problem to reach solutions and navigate detour paths to avoid or escape blind alleys. Participants sat around a table with a barrier that permitted them to see and speak to each other but prevented them from seeing one another's cards. This forced them to verbalize their thoughts and make explicit card exchanges to explore the problem space and solve the problem. The card movements and discussions were recorded by installed cameras, providing a degree of access to cognitive and information processing aspects of problem-solving that might otherwise be inaccessible to observation.

The Present Study

The Adejumo et al. [7] categorization task is flexible and provides a means of manipulating structural properties of problems and quantifying effects of problem structure on outcome variables relevant to understanding cognitive and behavioural aspects of problem solving. They used well-structured problems with pre-defined solutions to study effects of specific problem structures on group problem solving behaviour. In the present study, we modified the task to create ill-structured open-ended problems with no pre-defined solutions. We also manipulated the task instructions given to participants to vary the degree of problem open-endedness.

Our main experimental task involved groups of four participants solving a sequence of three open-ended categorization problems, in which they grouped 16 pictures into four sets of four pictures each, based on specific relations between the pictures. Problem open-endedness was introduced in three ways. First, the 16 pictures were randomly selected from collections of images, such that there was no right or wrong way to categorize the items. Second, two different categorization goals were used as the basis for grouping pictures: similarity-based categories (less open-ended) and story-based categories (more open-ended). Third, for similarity-based categorization problems, participants' beliefs about the open-endedness of the problem were further manipulated by varying the task instructions to suggest either that the best solution had been identified by experts and groups should seek this "expert" solution (less open-ended), or that there were multiple acceptable solutions to the problem and groups should seek a "good" solution (more open-ended). Thus, we used three different categorization tasks. In two of them participants grouped items based on similarity of the pictures, seeking either "expert" (least open-ended) or "good" (more open-ended) solutions; in a third task, participants grouped items by coming up with four simple stories that each involved four of the pictures ("story"; most open-ended). Further details of the experimental method are discussed below.

We investigated the effects of problem open-endedness on three outcome variables: (1) the variability of solutions developed by different problem-solving groups, (2) path dependency (i.e., the effects of the initial problem state on the solution state), and (3) perceived problem-solving difficulty. Hypothesized effects of open-endedness on these variables are based on two general assumptions. First, we assume problem solvers have bounded rationality and are likely to exhibit satisficing behaviour in their search for solutions [43]. That is, once they discover a satisfactory solution to the problem, they are unlikely to continue searching for an optimal, or best possible, solution if this is not a requirement of the task. For well-structured problems with one pre-defined solution, there may be little or no difference between satisficing and optimizing behaviour. However, for ill-structured, open-ended problems, there may be substantial difference, particularly when the problem space is large and complex.

Second, we assume that all problems have inherent constraints that influence search behaviour and potential solutions. Constraints are introduced by properties of the task situation and by the problem solvers. With respect to the task situation, well-structured close-ended problems generally introduce more constraints on problem-solving behaviour than ill-structured open-ended problems. As noted above, different instructions varied the degree of problem open-endedness, using either similarity-based or story-based categorization goals, and by encouraging participants to identify either "good" or "expert" solutions. Problem solvers introduce further constraints due their perception of the task situation and their background knowledge, which influence the perceived structure of the problem space and the information processing operations available to search that space. In our experiment, participants form categories of picture items based on certain perceived relations between them. In the two similarity tasks, participants group items based on either direct visual perception of similar picture features (e.g., two round items perceived as similar based on shape) or their conceptual knowledge of similarity relations associated with the pictures (e.g., a plant and an animal grouped together based on participants' knowledge of the items as living things). In the story task participants group items into simple stories, drawing on their conceptual knowledge of a much wider variety of potential relations than just similarity. For example, stories might group items together based on various functional or logical relations between them, on different ways the pictured objects might interact with one another, and so on.

Solution Variability

Intuitively, increasing open-endedness should lead to more solution variability. Given that many more varied conceptual relations are available for participants to group items into stories than similarity-based categories, solution options for story problems are less constrained than for similarity problems. Thus, more variability in the solution categories was expected in the story than in the similarity-based tasks.

It was expected that problem solvers' beliefs about problem open-endedness would alter solution variability by influencing the extent to which they adopted optimizing versus satisficing solution strategies. Specifically, for the similarity tasks, if participants believe a unique "expert" solution is required, they should analyze the situation more carefully and draw on more background knowledge to identify optimal similarity relations that maximize similarity between items within each category and minimize similarity between items of different categories [44]. In contrast, due to bounded rationality and cognitive limits to information processing [43, 45], if participants believe multiple solutions are acceptable they are likely to accept solutions perceived to be satisfactory, rather than search exhaustively for the best possible solutions. The set of solutions that are acceptable is larger than the set of solutions based on the best possible similarity relations. Therefore, more solution variability was expected for the "good" similarity task than the "expert" task.

H1: Problem open-endedness has a positive effect on solution variability.

H1a: Groups that form story-based categories exhibit more solution variability than groups that form similarity-based categories.

H1b: Groups that believe there are multiple solutions exhibit more solution variability than groups that believe there is only one correct solution.

Path Dependency

Path dependency refers to the general idea that past states can affect current and future states. In the present context, problem solvers are likely to start searching the problem space in the vicinity of the initial problem state, and gradually search more widely until a solution is found. For close-ended problems with a single solution, the initial state cannot alter the solution but may influence other factors such as problem-solving difficulty or search path complexity. For open-ended problems, multiple potential solutions may be acceptable, so cognitive limits to information processing imply that problem solvers should engage in satisficing behaviour, accepting a satisfactory solution found near the initial state, rather than rigorously searching the entire problem space for the optimal solution. Thus, problem open-endedness should influence the degree to which solution states depend on initial states.

H2: Problem open-endedness has a positive effect on the path dependency of solutions.

H2a: Path dependency is greater for groups that form story-based categories than groups that form similarity-based categories.

H2b: Path dependency is greater for groups that believe there are multiple solutions than groups that believe there is only one correct solution.

Perceived Difficulty

Problem solvers are likely to perceive problems as difficult when they encounter barriers that limit their progress or require them to navigate detour paths to reach solutions. The experimental tasks were open-ended, without right or wrong solutions. However, participants should face some difficulties solving the problem in both the story and similarity-based conditions due to the different knowledge, constraints, and information processing demands associated with the different categorization goals. Similarity-based categories are constrained to include only similarity relations from which to identify solutions. Story-based categories are less constrained and allow for a wider variety of conceptual relations from which participants could select to make up stories. Therefore, it was expected that participants would experience greater difficulty in the similarity than the story condition. The difficulty of a problem should also be influenced by problem solvers' beliefs about task open-endedness. That is, believing in the availability of different acceptable solutions reduces the need for exhaustive exploration of the problem space, compared to believing that a single best solution must be found. Therefore, within the similarity condition, problem solvers are likely to indicate less difficulty if they believe the problem is open-ended than if they believe it is not.

H3: Problem open-endedness has a negative effect on perceived problem-solving difficulty.

H3a: Groups that form similarity-based categories experience more difficulty than groups that form story-based categories.

H3b: Groups that believe there is only one correct solution experience more difficulty than groups that believe there are multiple solutions.

Method

Participants and Experimental Design

To examine the effects of problem open-endedness on problem solving behavior and solution outcome, we used a 3×2 within-by-between design. Each group was given a sequence of the three (within group) open-endedness task conditions (Expert, Good, Story), and was randomly assigned to one of two (between group) initial conditions, representing different initial distributions of the pictures to group members. 192 participants (90 female) completed the experiment, in $N = 48$ four-person problem-solving groups.[1] Of the 48 groups, 30 began with one initial condition, 18 with the

[1] We recruited an extra fifth participant per group to reduce the risk of cancelation due to no-shows. When all five arrived, the fifth person was given an observer role, instructed to mute microphone

other. Participants were undergraduates who received extra course credit for their voluntary participation.

Experimental Conditions and Stimuli Design

Problem open-endedness was manipulated by varying the goal of the categorization problem (similarity-based versus story-based) and the problem solvers' beliefs about the solution (i.e., that there was a unique correct solution to the problem versus multiple correct solutions). Thus, we included three experimental conditions of problem open-endedness:

1. Similarity-based categories; belief in one correct solution (Expert*)*. Participants were instructed to categorize pictures based on similarity "by exchanging pictures with other members until each of you has four pictures that belong to the same category". They were also told that "this task was given to groups of students in a previous experiment and a panel of experts determined the best solutions. Your job is to try to find the best solution, as judged by a panel of experts".
2. Similarity-based categories; belief in multiple correct solutions (Good). This task was similar to Expert; however, participants were told that "there is no single correct solution to this problem, but your job is to try to come up with a solution that you think is a good one".
3. Story-based categories; belief in multiple correct solutions (Story). Participants were instructed to categorize pictures "by exchanging pictures with other members until each of you has four pictures that make up one story…your group will have a total of four different stories".

Each group solved three problems (one per condition). Three different sets of pictures were used to create three different versions of the stimulus: a Microsoft Word Clipart version [46], a Microsoft Icons version [47], and a version of Walmart products [48]. Items in all three versions rely on general knowledge; thus, we assume that undergraduate participants likely perceive them in similar ways. The selection of the three stimulus versions was intended to control for potential effects due to differences in participant knowledge. To control for any potential bias due to the types of pictures, we balanced the assignment of the three versions to the three experimental conditions across the groups. Each group initially started with Clipart, Icons and then Walmart; however, the order of the three experimental conditions (Expert, Good, Story) was balanced across the groups (i.e., all sequence permutations were balanced across the groups).

The following procedure was used to create the three picture sets. Since pictures in any of the three sources can be updated, any future replication of the experiment

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and take notes on the difficulties the group faced. When only four participants showed up, to be consistent, a confederate played the role of the fifth participant and was assigned the observer role. Observers are not included in the sample size since their data were not used in the analysis of results.

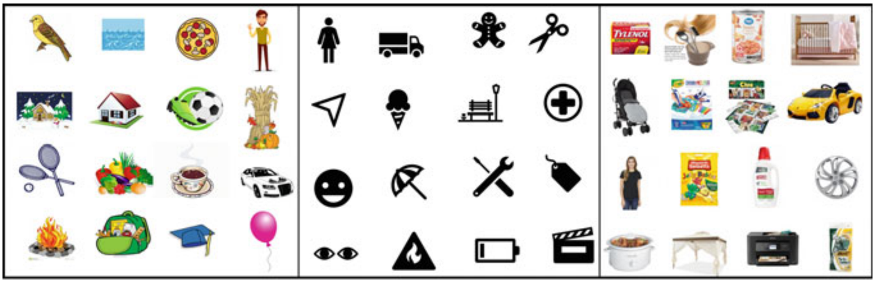

Fig. 1 The three versions of the stimuli

necessitated creating a pool of categories and their picture content to have a fixed set of pictures from which to choose. Each of the three sources provide many categories of images. To create the pools, 16 of the main categories were randomly selected from each source, and one picture was randomly selected from each category. Since product pictures on the Walmart website are organized in a hierarchical classification of categories and sub-categories, random selection proceeded down from main categories to the lowest subcategory level until reaching the product pictures used in the stimuli. After creating the picture sets, we did a trial run to make sure that the pictures were clear for the participants; three of the pictures were ambiguous for participants so we replaced them with other randomly drawn pictures. The three versions of the stimuli are presented in Fig. 1.

Procedure

The experiment was conducted virtually using WebEx video conferencing software [49], which allows screen recording and transcription of the groups' conversations. Participants were informed in advance that the video call would be recorded. Each group comprised four participants randomly assigned to each session. Each group member received an invitation to the video call. Upon starting the call, participants were introduced to each other, then presented with a screen sharing showing the tasks and their instructions.

Participants began with two training tasks, which were simplified versions of the experimental tasks with different pictures, followed by the three experimental tasks. Every categorization problem contained 16 pictures that were distributed equally among the four participants. Participants were presented with a screen that was divided into four quadrants with four pictures per quadrant; each participant was assigned to one of the quadrants. Group members were instructed to exchange pictures with one another until each member possessed a set of four pictures belonging to a category based on either a similarity or story goal. The experimenter served as facilitator, moved the pictures as requested by group members and wrote the names of the solution categories that participants identified after exchanging the

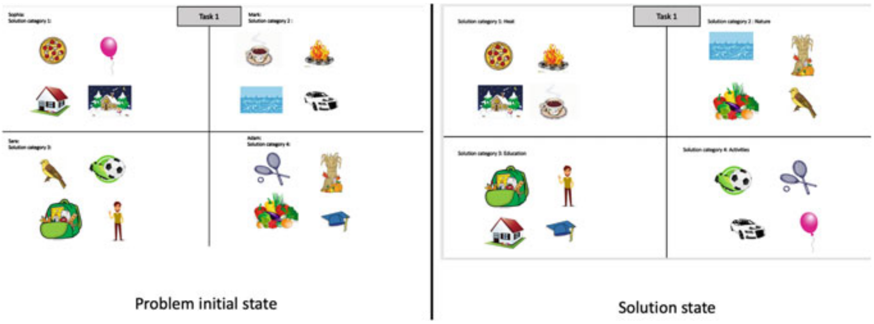

Fig. 2 Example of the interface that was shown to the participants before and after solving the problem

pictures. After completing the three tasks, participants were emailed a screenshot of their solutions with a link to an online questionnaire related to the three tasks they solved. Figure 2 displays an example of the interface presented to participants, showing the initial problem state and a solution state.

Measures

To measure solution variability across the three conditions, we used the Rand index (RI) similarity measure [50], which computes the similarity between two different partitions of a set of items into disjoint subsets. For our categorization task RI ranges from 0.6 when two solutions are maximally dissimilar, to 1 when two solutions are identical. We randomly selected one group's solution as a baseline for each stimulus version and experimental condition, and then measured the RI of the other groups' solutions relative to these baselines.

To investigate path dependency, for each of the three experimental tasks we used the two different initial distributions of the 16 pictures to the four group members. These two distributions were maximally different from one another, such that the RI between them equaled 0.6 and any items assigned to the same category in one initial distribution were assigned to different categories in the other initial distribution. To examine the effect of initial conditions on solutions, we used the RI to measure the similarity of each solution to the initial picture distribution used for that task, and we also measured the RI similarity of the solution to the opposite initial picture distribution. The difference between the two RIs for each solution was used as indicator of path dependency.

Perceived task difficulty was directly measured through the survey given to participants at the end of the experiment. Participants rated the difficulty of each task on a scale from 1 (very easy) to 7 (very difficult).

Results

Solution Variability

One-way repeated measures ANOVA was conducted to test the effect of problem open-endedness on the variability of the solutions between the Expert, Good, and Story conditions. The results indicate significant statistical differences in the mean RI similarity scores across the three conditions, $F(2, 76) = 35.698$, $p < 0.0001$, generalized eta squared = 0.349. Mauchly's test for sphericity was non-significant ($p > 0.05$). Shapiro's test for normality indicated $p < 0.05$ for the Good condition only ($p > 0.05$ for Expert and Story), but q-q plots indicated relatively small deviations from normality so we chose to use standard ANOVA methods. As shown in Fig. 3, post-hoc analyses using pairwise t-tests with a Bonferroni adjustment revealed that both the Expert and Good conditions had significantly higher similarity scores than the Story condition ($p < 0.0001$), but differences between the Expert and Good conditions were not significant ($p > 0.05$).

These results provide mixed support for H1. Solution variability was significantly higher in the most open-ended Story condition than both the Good and Expert similarity-based conditions (H1a). However, in the similarity-based conditions the belief in one unique solution instead of multiple solutions did not significantly affect solution variability (H1b).

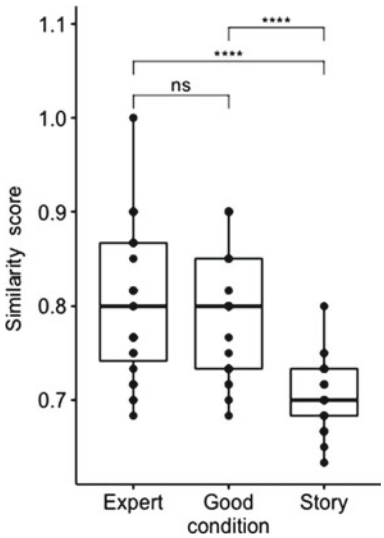

Fig. 3 The effect of problem open-endedness on solution variability. $^{****}p < 0.0001$; ns, $p > 0.05$

Path Dependency

To test the effect of the initial picture distribution on the final solution under the three conditions, we conducted repeated measures ANOVA on the difference between the RI comparing each solution to the initial distribution and the RI comparing each solution to the opposite initial distribution. We found that the RI difference scores were significantly different across the three conditions, $F(2, 94) = 8.629$, $p < 0.001$, generalized eta squared = 0.112. Mauchly's sphericity test was non-significant ($p > 0.05$). Shapiro's test indicated $p < 0.05$ for the Story condition only ($p > 0.05$ for Expert and Good), but q-q plots indicated relatively small deviations from normality so we chose to use standard ANOVA methods. Post-hoc analyses using pairwise t-tests with a Bonferroni adjustment revealed that RI difference scores were significantly lower in the Expert than Story condition ($p < 0.01$), and in Good compared to the Story condition ($p < 0.05$), but there was no significant difference between the Expert and Good conditions ($p > 0.05$) (see Fig. 4).

These results provide mixed support for H2. Solutions to the most open-ended Story problem exhibited significantly more path dependency than solutions to the less open-ended Good and Expert similarity problems (H2a). However, Good versus Expert open-endedness beliefs did not significantly affect path-dependency (H2b).

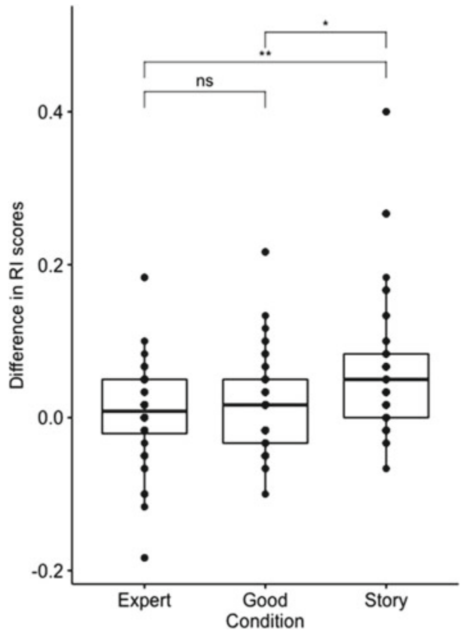

Fig. 4 Path dependency effect of the initial condition on solution across the three conditions. **$p < 0.01$; *$p < 0.05$; ns, $p > 0.05$

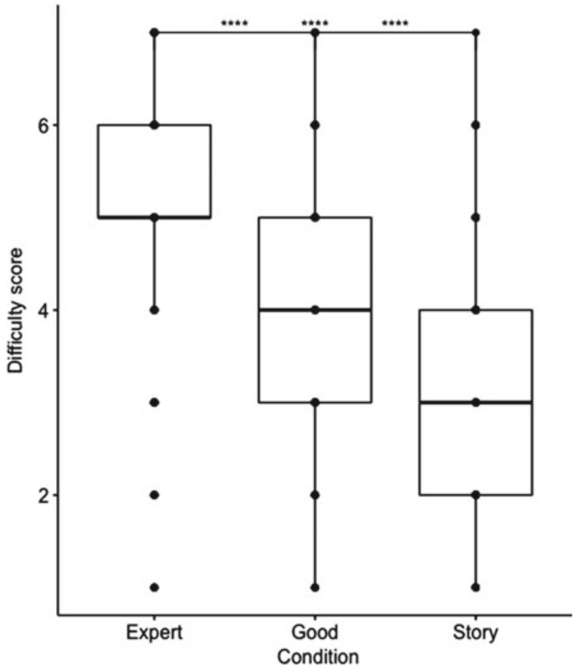

Fig. 5 The effect of problem open-endedness on task's perceived difficulty. ****$p < 0.0001$

Task Difficulty

Distributions of perceived difficulty scores deviated significantly from normality for all three task conditions (Shapiro's test $p < 0.05$). Therefore, a non-parametric Friedman test was used to test the perceived difficulty hypotheses. Results showed significant differences between the three conditions, $\chi^2(2) = 121.09$, $p < 0.0001$. Post-hoc analysis using pair-wise Wilcoxon signed-rank testing was conducted with a Bonferroni correction, revealing that difficulty scores for the Expert condition were significantly higher than both the Good and Story conditions ($p < 0.0001$), and difficulty scores for the Good condition were significantly higher than the Story condition ($p < 0.0001$) (see Fig. 5). These results provide strong support for H3. Increased open-endedness reduced perceived difficulty for both the Story versus Similarity (H3a) and Good versus Expert (H3b) manipulations.

Discussion

This study contributes to the design cognition and problem-solving literature by providing experimental evidence for the effects of problem open-endedness on solution variability, path dependency and perceived problem-solving difficulty. We used a flexible categorization task based on the work of Adejumo et al. [7] and created ill-structured open-ended problems with no predetermined solutions through the random selection of pictures. By varying the task instructions, we created three levels of problem open-endedness (from least to most open-ended): similarity/belief in a best solution (Expert); similarity/belief in multiple solutions (Good), and story/belief in multiple solutions (Story). We found large significant differences in solution variability between Story- and similarity-based categorization problems, but not between the Good versus Expert similarity tasks. We found the same pattern of results for path dependency, where solutions to Story problems exhibited significantly greater path dependency than both Good and Expert similarity problems, but path dependency was not statistically different between Good and Expert. Effects of open-endedness on problem-solving difficulty were highly significant. Similarity problems were perceived as significantly more difficult than Story problems, and the Expert similarity task as significantly more difficult than the Good task.

The Story versus Similarity results strongly support our hypotheses for the three outcome variables. Various factors may account for the non-significant Good versus Expert differences for solution variability and path dependency. Given that the distribution means were in the predicted direction, they may be due to sample size and a more powerful study with larger sample might reveal significant differences. They may also be due to task order effects in our repeated-measures design. Despite randomizing the order of Good versus Expert tasks, patterns of search behaviour established under prior tasks may have influenced behaviour under subsequent tasks, reducing the differences between them. Another factor might have been the use of three different stimulus versions (icons, clipart, and Walmart images), which was done to control for potential effects due to specific types of images, but potentially added variability to the repeated-measures data. Problem space complexity for the 16-item categorization problem might also play a role, in that the task may not be complex enough to induce detectable differences between satisficing and optimizing behaviour under Good versus Expert tasks respectively. Future work with larger samples, single task designs or more complex problems could explore such possibilities. The significant differences for perceived difficulty imply that the Good versus Expert manipulation did in fact alter participants' open-endedness beliefs, but perhaps not enough to significantly change problem-solving behaviour with respect to the solution variability and path dependency measures.

The study also contributes by introducing experimental methods for investigating effects of ill-structured open-ended problems on cognition and behaviour in problem-solving. Although the experimental task is not explicitly a design problem, the method provides a means of experimentally manipulating open-endedness and other structural properties of complex problems in a controlled manner and measuring cognitive and behavioural processes relevant to understanding aspects of design problem solving. The present work focused on effects on the properties of solution states (solution variability, path dependency) and participants' overall perceptions of difficulty. However, the fact that our task is performed by groups provides a potential means of investigating other effects. The group situation forces participants to verbalize their thinking and to make overt picture exchanges that reflect internal cognitive processes involved in problem-solving that are difficult to observe with other methods, such as information processing and search. Future work could analyze discussion and exchange data as groups formulate categories, to investigate cognitive processes involved in moving from the initial problem state to a solution state, how participants process information to search the problem space, how they dynamically structure and restructure the problem space over time, or factors affecting the adoption of optimizing versus satisficing solution strategies.

More generally, design problem solving involves aspects of both information processing [10] and gestalt perceptual structuring [11, 12], and the categorization task used here provides a potential means of investigating the interaction between these two interdependent aspects of design cognition. Information search operations required to solve the problem (e.g., exchanging pictures) have explicit structural effects, incrementally altering the structure of the problem as participants gradually move from the initial problem state to the solution state. Intermediate states correspond to a series of different structural partitions of the 16 picture items into subsets of four items each. As Goel [2] has suggested, design involves the transformation of an ill-structured problem into a more well-structured state. The method provides opportunities to observe such structural transformation processes in a controlled manner, potentially leading to new insights into design problem-solving and cognition. For example, the method may provide a means of experimentally investigating processes involved in the framing of design problems [51] and the coevolution of problem and solution in design [3].

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A Focussed Literature Review of Dual-Process Thinking to Inform the Study of Hackathons

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Dual-process theory has emerged as a method for theory-driven design research. While its application in design is in its early-stages, the insights unlocked from a dual-process theory perspective is appealing in many design contexts. Particularly interesting is the consideration of cognition during intense instances of design, such as hackathons. Hackathons are short-term events during which teams collaborate to design an artefact, in turn, engaging with each phase of the design process. In this paper, we present a focussed literature review on dual-process theory in design research. The design process is considered, exploring Type 1 (fast) and Type 2 (slow) thinking at each design phase. Equipped with this knowledge, we theorize about how the hackathon environment might impact cognition. This paper serves as a foundational understanding of dual-process theory-driven design research to encourage further research on dual-process theory in unique design settings.

Introduction

Design research historically relies on field and experimental study design, often communicating descriptions of design activity or prescriptions of how design should occur. A major challenge facing design research is the demand for increased rigour, which Cash [1] suggests can be met with a paradigm shift towards more theory-driven design research. This call for theory-driven design has been met by the emergence of dual-process theory as a means to understanding design [2–6]; however, despite these initial studies, the full potential of dual-process theory for understanding design has yet to be realized. While some research has emerged studying design according to dual-process theory, all study typical design projects, failing to consider the ways

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in which a unique environment, such as hackathons, may alter cognitive design processes.

Hackathons are short-term, typically 24–48 hours, events during which teams progress through the entire design process to build an artefact, typically software in nature [7]. Hackathons are rapidly growing in popularity and have emerged as an opportunity for design research [8], likely due to their short duration, which increases the feasibility of conducting research in the setting, coupled with the authentic design behaviour of participants [9]. Research at hackathons is situated as an alternative to traditional design research, where the design activity is easier to control than in field studies and more authentic than experimental data [8]. The application of dual-process theory at hackathons is intriguing as the characteristics of hackathons—mainly the time constraint, high levels of fatigue and stress, and loud environment—present unique circumstances under which design occurs, challenging what is currently known about design cognition. In this paper, we rely on current knowledge of dual-process theory in design to theorize about the cognitive activity at hackathons.

Background and Motivation

Dual-Process Theory

Psychologists have long theorized about cognition, suggesting two processes of mind: Type 1 and Type 2 thinking. This dual-process theory is broadly accepted and states that Type 1 thinking is automatic, quick, and intuitive, requiring little effort or control; in contrast, Type 2 thinking is effortful, slow, and involves associations and computations [10]. Both processes remain active while awake, but Type 2 thinking is needed when the abilities of Type 1 are too limited to properly perform a cognitive task. On average, however, most cognition can be categorized as Type 1 (automatic process), with Type 2 (the analytic process) taking over in difficult situations [10]. Type 1 and 2 thinking are considered to co-occur across a task; however, the individual processes may be more dominant during specific periods of a design task [11].

A Dual-Process Theory of Design

Design thinking is a non-linear problem-solving approach emphasizing the user [12, 13]. Understanding how designers know, act, and think while engaging in design thinking often serves as a foundation in design research. The increased demand for theory-driven design research suggests a need for increased rigour when studying design cognition. An emergent viable path for this theory-driven design research is the application of dual-process theory, which has a wide acceptance as a basis for understanding human behaviour and cognition in other fields [5].

In response to Cash's call for theory-driven design research [1], Cash et al. proposed dual-process theory as a method for connecting established theory to design research [3]. Cash et al. used dual-process theory to explain designer cognition, extending Type 1 and Type 2 thinking to design contexts [3]. They identified three uses of dual-process theory in the literature: to elaborate on existing design research, to address gaps in design research theory, and to support the impact of design research in other fields. Cash et al. [3] argued that dual-process theory offers a reconceptualization of research methods such that the cognitive processes of designers link methodology and theory. The authors also framed dual-process theory as a common lens for understanding design concepts, such as fixation, and a common language to transcend design findings into other fields. As such, dual-process theory would be the core platform for understanding design research.

Perhaps the most extensive use of dual-process theory in the field of design was the work done by Kannengiesser and Gero to link dual-process theory with design thinking [6]. They mapped Type 1 and Type 2 thinking onto what they term "fast design thinking" and "slow design thinking", explaining fast design thinking as effortless, intuitive, reflexive design decision making and slow design thinking as analytical, associative, reflective design decision making typical in non-routine design situations. By applying the Function-Behaviour-Structure ontology, a new process, 2', was proposed. This new process provides a shortcut from Function to Structure, which is equated to fast design thinking. The authors then outline four instances of designing to demonstrate Type 1 and 2 thinking in the common design activities of fixation, case-based design, pattern-language-based design, and brainstorming. They found Type 1 thinking to play a distinct role in all four activities, either reproducing existing design structures or generating new, while Type 2 thinking primarily involves the monitoring and assessing of design decisions in hopes of catching biases. This work ultimately shows the potential of dual-process theory to represent design thinking.

Description of Hackathons

The popular speed-design events called "hackathons" have slowly emerged as a phenomenon of interest within design research [8]. While the exact description of hackathons may vary due to the flexibility of the features of the event, in general, hackathons are short design events, usually spanning 24–48 hours, during which groups of participants collaborate on a design project of their choosing [7]. Hackathons usually begin with an opening presentation, during which the theme of the event, rules, and awards are described. Then, there is a period of team formation. Teams may have formed before the event, in person, or on the virtual communication channel set up by the hackathon, such as *slack* or *Microsoft Teams*. The teams will then undergo rounds of ideation, building, and testing. Finally, teams present their design ideas and compete for prizes in the final pitch competition. Most hackathons are sponsored by industry partners who attend the event to network, provide mentorship, and reward a prize. Most hackathons have an overall theme, for example finding solutions to problems in "smart villages" [14], or the events have "tracks", which are thematic categories such as finance, healthcare, education, and business [15].

In a literature review on hackathons, Flus and Hurst [8] found that the design activity at hackathons broadly follows the *Double Diamond Design Process* [16], such that teams participate in periods of divergence when exploring the problem space, then converge on an idea, diverge again during prototype building, before converging on a design and pitching the result. Specific design activities can be identified in the overall design process, including *problem identification* [17], *brainstorming and production* [18], *concept ideation* [19], *embodiment* [20] and *presenting* [17].

Study Objectives

Despite the budding application of dual-process theory in design, the existing studies are limited to typical design settings. Flus and Hurst [8] present hackathons as rich opportunities for design research; their review concludes that despite their short duration, we indeed see evidence of a typical design process at hackathons. This suggests hackathons are a suitable setting for design research.

Therefore, this study aims to explore the intersection of dual-process theory for design and hackathons. The unique characteristics of hackathons, such as the increased stress, fatigue, and time pressure, offer an extension of studies on cognition. Dual-process theory, in particular, is suited for modelling design cognition to grasp the nuance between fast and slow design decisions in the hackathon environment. In this paper, we ask the following research questions (R.Q.):

R.Q.1. What is known about design cognition according to dual-process theory?

R.Q.2. Given this knowledge, what can we hypothesize about cognition at hackathons?

This study will succinctly describe research on design cognition at hackathons from a theory-driven approach. The findings will further the understanding of design cognition at hackathons, a particularly impactful contribution considering the rising popularity of hackathon events.

Methodology

A scan of existing literature revealed no results for studies on dual-process theory at hackathons. Therefore, to answer R.Q.1, we conducted a focused literature review with the aim of providing an informative review of relevant literature within design research. The methodology will guide future evidence-based decision making and research [21]. We began the literature review by identifying current, high-quality work on the topic. The paper, *Design thinking, fast and slow: A framework for Kahneman's dual-system theory in design* [6] was identified as an appropriate starting point for our search since it presents an actionable research ontology for studying design cognition using dual-process theory. Further, Kannengiesser and Gero's work offers a promising avenue for future theory-driven design in response to Cash's call [1].

We then employed backwards and forwards citation searching, meaning we created a citation network of the works referenced in the publication (backwards) and works that cited the publication (forwards). All abstracts in this citation network were screened for relevance before reading full-texts. Eligible texts were written in English and discussed dual-process theory within design research. We completed multiple rounds of searching, assessing citations of the citations. Engaging in such a methodology permitted a focussed approach to finding literature on a relatively broad topic and resulted in the identification of 19 relevant publications to be included in this review. Similarity networks generated by *connectedpapers.com* were referenced to confirm our search covered appropriate publications. The network for the initial paper by Kannengiesser and Gero [6] is provided in Fig. 1. To answer R.Q.2, we triangulated our findings with the design process outlined in Dym et al. [22] and what we know about design at hackathons from previously completed research. The resulting discussion theorizes about design cognition within the hackathon context.

Findings

Dual-Process Theory in the Hackathon Design Process

The design activities at hackathons can be mapped onto design processes, such as *problem definition—conceptual design—preliminary design or embodiment—detailed design—communication* outlined by Dym et al. [22]. The activities at hackathons are reflective of design processes, so can serve as a framework of design; thus, connections can be made between what is known about cognition at different phases of the design process according to dual-process theory and cognition at hackathons. Psychologists assert that, while dual-process theory outlines two distinct cognitive processes, these processes do not occur in isolation of one another, but rather interact, either trusting intuition (Type 1) or requiring further analytical thought (Type 2). For example, brainwriting involves intuitive idea generation followed by reflective clustering and evaluation; therefore, it would follow that both types of processing are engaged to different extents along the timeline of the task [11]. In what follows, more details will be given to outline cognition during the design phases outlined in Dym et al. [22], emphasizing the interaction of the two cognitive processes across the entire design process. We then extend these findings within the hackathon context, answering the second research question in the Discussion.

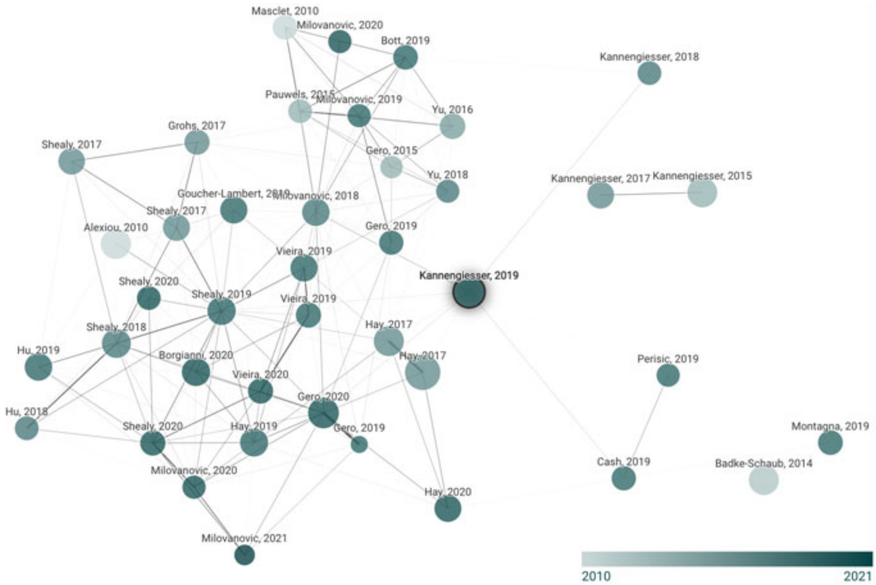

Fig. 1 Network of papers modelling their similarity using co-citation and bibliographic coupling from *connectedpapers.com*. Colour represents publishing year, size represents number of citations, and distance indicates strength of similarity metric between the paper and origin paper, *Design thinking, fast and slow: a framework for Kahneman's dual-system theory in design* [6]. Generated on March 31, 2022

Dual-Process Theory During Problem Definition

During the *problem definition* phase, designers frame the problem by clarifying objectives, identifying constraints, establishing functions, and gathering information from their client [22]. At a hackathon, *problem definition* is just that: identifying a problem to tackle as a team. The problem may come from the industry partners, a team member during "idea pitches" hosted at the start of the hackathon, or team brainstorming [15]. Teams will also complete some research in order to fully understand the problem, but are often limited in their engagement with clients and users due to an absence of these stakeholders at hackathon events, inhibiting asynchronous connection.

With respect to dual-process theory, both Type 1 and 2 thinking occur during problem definition. In order to explore the problem and solution spaces, the designers engage in rapid and associative thinking typical of Type 1, but rely on Type 2 thinking to reframe, recontextualize, or redirect thoughts [2, 23]. This thinking is more deliberate and reflective in order to focus their exploration. Finally, to narrow down the problem, slow design is likely engaged. Teams are forced to critically evaluate their ideas, consider the constraints, and deliberately choose a project that is realistic within the context. This portion of cognition would be primarily Type 2. It is clear that the identification of a problem uses both fast and slow design to fully understand the problem space.

Dual-Process Theory During Conceptual Design

The traditional *conceptual design* phase involves translating customer requirements into engineering specifications to generate alternatives, involving brainstorming and concept ideation [22]. The activity at this phase of hackathons is typical of traditional design projects, with teams brainstorming solutions to the problem previously defined [8]. The distinction between the first two phases at a hackathon can be unclear because it is not known if teams tend to initially ideate problems or solutions [15]. In the latter, the team may engage more with conceptual design than problem definition, as they jump to ideating the solution rather than understanding the problem.

Gonçalves and Cash [5] distinguished between Type 1 and Type 2 thinking in eight archetypes of ideas generated. They used *Linkography* to determine how ideas were related to prior and subsequent ideas. This paper suggested that both Type 1 and Type 2 thinking occurs throughout ideation, linking creation with judgement however, certain idea archetypes are indicative of a dominance in one type of thinking over the other, or a balance of both. The first idea archetype was the *shaping idea*, understood as an idea that generated many links to subsequent ideas, suggesting the idea was foundational in future ideas. The authors predominantly identified these shaping ideas earlier in the ideation timeline, indicating fast processing typical of Type 1 thinking. There was also a lack of rule-based reasoning during the generation of these ideas, suggesting Type 2 thinking was limited and therefore a general dominance of Type 1 thinking. The next three idea archetypes were *bridging ideas* (balanced, foresight, hindsight), representing ideas that link previous ideas with future ones. These ideas tended to have repeated variations of elements and were defined both implicitly and explicitly, indicating a presence of both Type 1 and Type 2 thinking. The *incremental idea* archetype was found to occur when participants would rationalize a divergence of ideas. This was a slow and deliberate process involving a strategic exploration of the solution space, corresponding well with Type 2 processing. *Tangent ideas* were deliberate breaks from shaping and bridging ideas. The reframing was slow and deliberate, directly corresponding to Type 2 thinking once again. The final two archetypes, *combinatorial ideas* and *final combinatorial ideas* involved an analysis of generated ideas and a rapid production of a new or final idea, respectively. The process involved little explicit verbalization which the authors suggested was indicative of Type 1 processing; however, the deliberate rationalization, elaboration, and detailing suggest instances of Type 2 thinking as well.

Ideation is characterized by rapid, implicit idea generation [23, 24] suggesting a dominance of Type 1 thinking. This thinking is not based on reason, as wild ideas are often encouraged, ignoring the feasibility of development. However, the initial ideation is often followed by periods of reflection, reshaping, and linking of ideas.

These instances of deliberate and associative thinking is indicative of Type 2 thinking [23, 24]. Therefore, ideation requires both fast and slow design thinking, with Type 1 processing generating rapid ideas and Type 2 generating associative ideas.

Dual-Process Theory During Preliminary Design

In the *preliminary design* phase, designers embody preliminary design schemes to analyze, test, and evaluate the chosen design. This phase is typical at hackathons. Teams evaluate and test their prototypes, although it has been found that this evaluation is often limited due to time and resources—teams cannot complete extensive usability testing and often must test parts of their project rather than the whole [15]. Evaluation and testing become even more challenging in cases when teams do not have a completed prototype, but rather present an idea. In these cases, teams likely depend on heuristic evaluations [25] rather than prototype testing, therefore use a set of principles to evaluate the idea.

The nature of embodiment and evaluation suggests a dominance of Type 2 thinking in this phase of the design process since the work is deliberate and thorough. Type 2 thinking is especially evident here when the results of an evaluation are unexpected [5, 26, 27]. If the prototype does not perform as expected, more deliberate evaluation is needed to check for errors and biases, resulting in slow design. Type 1 thinking, however, is dominant when evaluation depends on intuition, especially among experienced designers. These designers can rely on previous experience, accessing expertise and applying it to new design problems [28]. As such, the evaluation is more intuitive than deliberate, meaning fast design processes are engaged during these preliminary design activities [5, 26, 27]. Type 1 or 2 thinking likely dominates evaluation depending on the thoroughness of the evaluation plan; as such, the constraints posed by the hackathon environment may suggest more instances of fast and intuitive evaluation.

Dual-Process Theory During Detailed Design

The *detailed design* phase involves refining and optimizing the final design. During this phase, the design team makes final decisions on the artefact based on findings from the evaluations completed in the previous stage. At hackathons, this phase is closely linked with the previous preliminary design phase [8] with teams completing quick iterations, requiring both evaluation and selection. The time constraint at hackathons, however, prevents many rounds of iteration. In fact, the final artefact at hackathons can be thought of as an early prototype rather than the final product [15]; therefore, at hackathons, teams develop a detailed design for an early iteration.

Research on dual-process theory during the detailed design phase has primarily focused on selection. Evans and Stanovich [27] have found that selection uses both

Type 1 and 2 thinking. At times, design decisions are selected based on intuition and experience, indicating fast design. However, unique situations may necessitate deliberate thought due to increased ambiguity and lack of experience. In such cases, designers would engage more in slow design. As such, engagement of Type 1 and 2 thinking is situation dependent.

Dual-Process Theory During Communication

According to Dym et al. [22], the final phase of the design process is *communication.* The communication phase is characterized by the documentation of the final design, including justifications for design decisions. Communication occurs at hackathons during the pitch presentations. Most hackathons are competitions based on the information teams pitch about their project in a final presentation; therefore, teams tend to dedicate significant time and resources to developing their pitch [8], focussing on the best way to communicate their identified problem, proposed solution, and prototype.

Dual-process theory was explicitly studied during representation, providing an account of the impact of gesture and sketching as forms of representation [11]. The authors tested the basic dual-process theory elements in the context of design when teams receive the problem and requirements (input), and when they communicate their results (output). The study found that when the mode of representation (gesture or sketching) at input is mismatched with the mode of response, mental simulation is needed to reformulate the input into a different response. This work is typical of Type 2 processing. In contrast, when the modes are aligned, the associations can be made on default, indicating Type 1 processing. Further, the work required to prepare the communication would be fast design when decisions can rely on intuition and default, but slow design when intentional and effortful thought is needed to make associations and decide how to communicate the results. Therefore, the communication design phase will include both fast and slow design to varying degrees.

Impact of Environment on Cognition

The discussion of design cognition at hackathons would be incomplete without a consideration of the environment that contributes to the nature of the event. Hackathons tend to occur in large spaces with many participants—North America's largest hackathon, *Hack the North* hosts upward of 1500 participants [29]—so there is considerable noise and distraction. Further, most events run overnight, implying that participants do not sleep, resulting in high levels of fatigue. Finally, the events are competitive, with top performing teams earning prizes. While the intention for the events is to be fun, the competitive nature coupled with the limited time frame can lead to feelings of stress. Cognition is greatly impacted by both the internal state of the person and characteristics of the external environment [30]. Therefore, characteristics of hackathons should be considered when discussing design at the event. In what follows, the impact of internal and external states on cognition according to dual-process theory will be explored.

The influence of mood on cognition is well-researched in psychology. Mood influences everything from decision making to perception, learning, and creativity [31]. Further, there is a general decrease in memory performance and productivity when in a depressed mood because the depressive state occupies a portion of the cognitive capacity [31]. When tasks are divided between reproductive tasks, which are typically more sedentary and require implicit processing, and productive tasks, which require active and explicit processing, mood is most influential on the productive tasks [31]. We can then draw parallels between the dichotomy of tasks and dual-process theory, where reproductive tasks, like recognition and automatic reactions, would be dominated by Type 1 thinking, whereas productive tasks, such as judgement and controlled reactions, would be dominated by Type 2 thinking. As mood is more influential on productive tasks, we can then hypothesize that mood would more greatly impact Type 2 thinking. This aligns with research on the correlation between mood and task difficulty. It has been found that a depressed mood results in a reduced ability to process a difficult task [32]; therefore, assuming Type 2 thinking occurs when solving a difficult problem, a depressed mood would make it more challenging to engage in the slow design thinking.

Two other internal states are worth noting with respect to their influence on cognition. First, it has been found that high motivation increases working memory performance while low motivation decreases working memory performance [33, 34]. In other words, when one is highly motivated, one is able to perceive, retain, and process information, possibly suggesting greater performance in Type 2 processing. Second, stress impacts response time and working memory tasks. When one is stressed, their response is slower, and the capacity of their working memory is less [35]. As such, stress may challenge the ability to think quickly, suggesting increased instances of slow design. However, higher level processes rely more on working memory capacities, which are limited when stressed, affecting Type 2 more than Type 1 thinking, and suggesting a greater reliance on intuition.

There are two notable external characteristics well-supported as influential to cognition. First, the time of day impacts cognition such that attention can be sustained for longer periods of time in the morning [36], and there is a positive correlation between tiredness and errors [37]. This would suggest a greater cognitive performance earlier in the day when attention is greater and errors are less likely. The second external characteristic is noise level. Lange [38] found that noise disrupts verbal working memory performance, and Ljungberg and Neely [39] have found noise to cause higher subjective scores of task difficulty, suggesting that processing is perceived to be more challenging in loud environments.

The characteristics of hackathons, mainly the competitive nature and overnight working demands, necessitates a consideration of mood, motivation, stress, fatigue, time of day, and noise level and their impact on cognition. According to dual-process theory, the characteristics have varying results on the engagement in fast and slow thinking, introducing complexity to dual-process theory at hackathons.

Discussion

In the previous section, we outlined the hackathon design process and what is known about dual-process theory during each design activity. Despite extensive existing research on dual-process theory, and the recent emergence of dual-process theory-driven design research, the extension of dual-process theory to design at hackathons has yet to be explored. Therefore, we hypothesize about dual-process theory at hackathons based on existing research.

Generally, it has been found that both Type 1 and 2 thinking occur in every phase of the design process, as summarized in Table 1. Type 1 thinking guides decision making based on intuition in instances of fast design, whereas Type 2 thinking is for more analytical thought in instances of slow design. Hackathons present an interesting application of design because the outcomes are highly ambiguous, but the characteristics of the events introduce many constraints. In what follows, we will apply what we know about dual-process theory during design phases to a hackathon context.

Many hackathons have themes and prompts that teams may use to guide idea generation. Yet these prompts tend to be highly ambiguous and therefore, during the problem generation phase, teams may rely on Type 2 processing to thoroughly explore the problem space. Teams have often been found to rely on past experience [15], suggesting either fast design thinking, such that they are relying on intuition and experience, or slow design thinking, such that they are making intentional associations. However, the short timeframe of hackathons necessitates rapid thinking, suggesting that fast design thinking would be more dominant.

In the conceptual design phase, our findings suggested reliance on Type 1 thinking to generate rapid ideas when brainstorming, followed by Type 2 processing to analyze the ideas. Ideation is a dominant design activity at hackathons, although research has yet to be completed to characterize the types of ideas generated as per Gonçalves and Cash's archetypes [5]. We can hypothesize that both processes would be involved in this phase of the hackathon design process because teams may rely on rapid idea generation initially, but must engage in critical thinking to ensure the ideas generated are feasible within the constraints of the event. It has also been found that it is uncommon for hackathon participants to conduct research, often only occurring when there is a designer on the team [15], likely due to both the limited time and the lack of knowledge on the design process (particularly research in design) in non-design education. As a result, a designer may engage in the reflective thinking and research characteristic of slow design, but their non-designer peers may not. Therefore, ideas may be under-researched and formed based on intuition and experience, suggesting a dominance of fast design.

Table 1 Summary of findings on dual-process theory during the design process

Design phase	Type 1	Type 2	Relevant citations
Problem definition	Ideation is a dominant design activity during problem definition. Often, ideation is characterized by rapid, implicit idea generation, focussed not on reasoning, but on intuition	Initial ideation is often followed by periods of reflection, reorientation, and reshaping of the ideas. There are instances of explicit, deliberate, and associative thinking	[5, 23, 24]
Conceptual design	Exploration of the problem and solution spaces, necessary during conceptual design, may involve rapid and associative thinking	The reframing, recontextualization, or redirection of thought may engage deliberate and reflective thinking	[2, 23]
Preliminary design	Some evaluation of early design may depend on intuition and experience	When the results of the design are unexpected, more deliberate evaluation is needed to check for errors and biases	[5, 26, 27]
Detailed design	Designs may be selected and further developed based on intuition and experience	The selection of design decisions may depend on deliberate thinking, especially in unique situations	[27]
Communication	Simple and default associations are possible when the communication style of instructions (input) is represented in the same mode as the output (e.g. sketched input and response)	Mental simulation and reflection are required to process information that has mismatched mode at input as output (e.g. gestured input and sketched response)	[11]

The preliminary and detailed design phases are closely linked at hackathons, with teams producing quick iterations of their artefacts. We hypothesize that instances of fast and slow design at hackathons would follow similar patterns identified in other design research: teams would perform fast, intuitive selections and evaluations, then rely on analytical thought processes when results are unexpected. Research has found that evaluation at hackathons tends to be minimal because usability testing is greatly restricted due to limited access to users [15]. As a result, teams tend to evaluate components of the project and ensure the prototype works, rather than confirm that the proposed solution is an optimal design for users. This testing may be fast, suggesting a dominance of Type 1 thinking during evaluation.

The final step of the design process at a hackathon event is the pitch competition. The only existing dual-process theory research on activities during the communication phase is on the alignment of communication methods between input and output. It is challenging to extend this research to a hackathon context because teams are responsible for their own problem finding and exploration, before all teams present their final artefact using a slide deck and their current prototype iteration. We hypothesize that, if teams have prior experience presenting ideas, they could rely on fast design when creating the presentation, but slow design would be required to determine what should be included in the presentation and assess the best way to communicate their findings. Since prizes are awarded based on the pitches, the teams invest significant thought and effort to the development of their communication, indicating potential for Type 2 thinking.

A consideration of design at hackathons assesses both the design process and the ways in which the nature of hackathons impacts design. The findings of this study highlighted five characteristics—mood, motivation, stress, time of day, and noise level—that are important to consider when studying cognition during design tasks, especially in environments such as hackathons where the characteristics may differ from more typical design tasks. It has been found that a particularly motivated participant may engage more in slow design, taking time to thoroughly consider all design decisions. However, this may be challenged at hackathons because of the competitive nature of the events. Feelings of stress result in a dependency on fast design; therefore, even a highly motivated participant may rely on intuitive design based on their mood. A further conflict in cognitive processes emerges in the consideration of the time of day and noise level of events. Increased noise levels and late working hours cause tasks to be perceived as more difficult. As a result, hackathon participants may engage in more analytical thinking (Type 2); however, increased fatigue suggests a dependency on Type 1 processing. Hackathons therefore emerge as environments in which the environmental characteristics cause conflicting impacts on cognition, as visualized in Fig. 2.

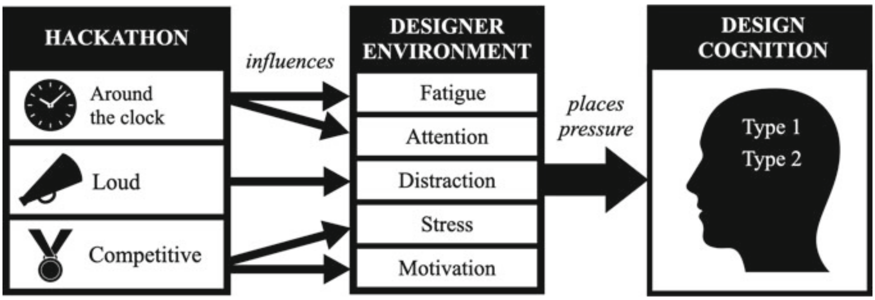

Fig. 2 Summative figure on the theorized impact of hackathons on dual-process cognition

Future Research Directions

While this research was able to produce some hypotheses about the balance between fast and slow design during hackathons based on existing research, future studies are needed to evaluate specific hypotheses. The atypical setting of a hackathon (the dramatically increased time pressure, and ill-defined problem statement, for example) adds new sources of uncertainty. This uncertainty would normally require an increased need for slow design; yet, the requirement to progress through the design process quickly and continuously due to the time pressure at hackathons may suggest an increased inclination for fast design. Thus, further research is needed in order to understand how hackathon participants navigate the demand for slow design in a fast-paced setting.

Limitations

The main limitations of this study are due to the chosen methodology. The focussed literature review allowed us to explore impactful research on relevant topics; however, it does not lead to a systematic exploration of the research space. As a result, the work presented in this paper may not be comprehensive. The findings then serve as an initial foundation for understanding how dual-process theory in design can be understood within the context of design at hackathons.

Further limitations emerge from the selection of dual-process theory as a foundation to study design cognition. Dual-process theory is a well-accepted theory in psychology; as such, it has received many critiques since its origin. A key critique is the ambiguity and variety of definitions across disciplines [27]. Perhaps the most relevant criticism to the work presented in this paper is based on the incorrect assumption that the dual-processes capture modes of discrete thinking. Rather, variation in cognitive ability and project task can affect the type of response (intuitive or analytical) [27]. While there is variation in the type of response during a design activity, the two processes remain discrete. This is an especially important point to consider when attempting to capture nuance in cognition and the impact of the environment, as we have done in this paper.

Conclusion

Dual-process theory has emerged as a foundation for theory-driven design research. In its infancy, however, research on fast and slow thinking is limited to typical design settings. A focussed literature review on dual-process theory in design allowed us to generate hypotheses about instances of fast and slow design in a unique design context: hackathons. We asked two research questions: what is known about dual-process theory in design research, and what can be theorized about dual-process theory at hackathons. We concluded that fast and slow design thinking would likely occur at hackathons in ways similar to what has been outlined in existing research; both Type 1 and 2 thinking actively occur in each phase of the design process. However, the conflict between the demand for slow design thinking in an ambiguous environment and the demand for fast design thinking in a timed event raises questions about the resolution of the two cognitive processes at hackathons. Given the rising popularity of hackathons, there is an increased demand for research on design at hackathons. Such research would aim to understand how the nature of hackathons impact design cognition, and design at speed-events more broadly. Further studies that explore how well-established cognitive processes adapt to unique design environments have potential for high impact in the design community.

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A Systems Thinking Inspired Approach to Understanding Design Activity

Gregory Litster, Ada Hurst, and Carlos Cardoso

Systems thinking is a popular approach for addressing complex problems. System mapping, a tool commonly used to facilitate systemic thinking, can be used to visualize the systems under consideration, and thus its complexity, which is useful in many design contexts. This paper aims to determine the extent to which systems thinking can be used to understand design activity. We review the literature on systems thinking and its relationship to design thinking. Building on this foundation, we introduce a new method for analyzing verbal protocols using system mapping and test it on eight protocols of participants engaged in design activity. Preliminary analyses of the generated maps point at the usefulness of the approach, especially for capturing problem framing. Areas of future research are proposed, including connections to design ideation and fixation, team collaboration in design, and using the approach for assessing systems thinking maturity.

Introduction

As societal problems become more interrelated and interdependent, they manifest themselves at different levels of increasing complexity. As a result, designers are called to go beyond typical problem-solving approaches when designing and thus think more holistically about systems-level change [1, 2]. *Systems thinking*, sometimes referred to as *systems view* or *systems approach*—the ability to understand systems and their behaviour often with the aim of devising modifications that move them in a desired direction [3]—emerges as a critical approach.

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Systemic design, an interdisciplinary approach that combines systems thinking and design principles, when trying to tackle problems in complex sociotechnical systems, is one example of the integration between these two disciplines [4]. We believe that systems thinking and design share similarities and complement each other. As such, similarly to the field of creativity research where systems approaches have been used to build a systems model of creativity [5, 6] and model the developmental patterns of creative individuals [7, 8], we set out to use elements of systems thinking as an approach for understanding design activity. In particular, we introduce a novel approach to analyzing design protocols by using *systems mapping*, which presents many useful properties for investigating design activity. The research question that guides this work is:

> What can a systems mapping approach to analyzing design protocols tell us about design activity?

The rest of the paper is organized as follows. We first provide an overview of systems thinking and its relationship to design. We then go on to briefly talk about systems mapping as a commonly used systems thinking tool and introduce our proposed approach for using it to analyze design protocols. Next, we present a proof of concept of the approach by generating maps of the systems for eight design protocols and explain how various features of the maps can be used to characterize design activity. We conclude with a discussion of the implications of our findings and propose a number of future analyses that can be employed building on this foundation.

Background

Systems and Systems Thinking

A *system* is a representation that describes how a set of component parts work together in an organized manner to accomplish a common purpose. These component parts, when arranged in a particular way, make up systems of various scales and purposes (i.e., the system does something) [9]. In other words, the system is more than just the sum of its components.

Systems thinking, the way in which we engage with and understand systems, emerged as a response to the century-long reductionist view of science, which relied on the analytical approach of taking things apart to understand living systems [10]. Biologists, realized at the beginning of the twentieth century that such systems could not be studied through analysis. Thus, systems thinking surfaced as a new way of looking at the world, where the properties of the parts can only be studied within the context of the larger whole [10]. The approach has been adopted and adapted to fit a variety of contexts and articulated by various theorists such as Ludwig von Bertalanffy under the umbrella of General Systems Theory [11], and subsequently by Russel Ackoff [12], Barry Richmond [13] and Jay Forrester [14], among others.

Systems Thinking and Design

Systems thinking has been a matter of discussion among designers who, albeit often not consciously, recognize that their products live in contexts outside of their own design practice [15]. Espejo [16] explains that systems are mental representations or ways of looking at the world, a view that gives designers the ability to determine a set of interrelated component parts that fit together. Though the language used in the bodies of literature describing systems and early-stage design thinking is different, these two approaches share striking similarities.

Many definitions of systems thinking have been proposed since the term's initial inception [13, 17–19]. Perhaps the most comprehensive and recent definition is articulated in Arnold and Wade [3], who synthesized the various definitions and determined that "systems thinking is a set of synergistic analytic skills used to improve the capability of identifying and understanding systems, predicting their behaviours, and devising modifications to them in order to produce desired effects" (p. 675). This definition of systems thinking also captures more recent thinking about what design is. While design has traditionally been viewed from a problem-solving lens, Dorst [2, p. 123] and Irwin [1], for instance, explain that as problems become truly complex, our understanding of design needs to shift such that it becomes not just the creation of solutions to problems, but rather "high-quality interventions" that move the system towards a more desired state.

Richmond [13] outlines how system thinking requires problem solvers to exercise different thinking skills simultaneously (e.g., dynamic thinking or operational thinking). This is echoed in other writings of systems thinking approaches; for example, Orgill et al. [9] outline that systems thinking involves visualizing relationships between parts of systems, examining how those behaviours change over time and drawing out phenomena from the interaction of system parts. Designers who do this well can anticipate unintended consequences that might emerge from the interactions among multiple parts of a system [20].

Systems Mapping

Across different disciplines, people use a wide variety of visual diagrammatic representations to understand and/or communicate ideas. From a structural perspective, these representations come down to a small range of *map typologies*. These can be radial, hierarchical, tree structures, flow diagrams, Venn diagrams and feedback loops, sometimes combining several of these characteristics into one configuration. These *maps* are often used as tools for different purposes and at various stages of a design/engineering process.

In this research we use *system mapping*, more specifically a type of tool called *Causal Loop Diagrams* (CLDs). CLDs belong to a larger typology of tools called *Dynamic Thinking Tools* [21]. CLDs aim to make explicit the structure of the system(s) being studied as well as the *system dynamics* in place—relationship between parts of a system. Causal loop diagrams are made up of *core nodes*, which are things that can influence/be influenced by something else. Nodes, often named with nouns, are variables that can augment or diminish in terms of quality or quantity. The characteristics of these nodes change due to the transmission and return of information between nodes, also known as *feedback*. Feedback can be *positive* (more of A leads to more of B) or *negative* (more of A leads to less of B) and can sometimes be *delayed* (A changes B, but after some time), adding a timescale to the relationship. Causal Loop Diagrams present an effective way to represent complex systems in a succinct form, by making explicit the inherent dynamic interrelationships between its parts. For the remainder of the paper, we refer to *Causal Loop Diagrams* of the systems we are trying to visualize as *map(s).*

System Mapping for Analyzing Design Protocols: A Novel Approach

Over the last few decades, design researchers have sought to understand the mental processes and representations involved in designing, a research area called 'design cognition' [22]. Though a number of qualitative and quantitative research methods have been used in this endeavor, verbal protocol analysis [23] stands out as one of the dominant approaches [22, 24]. Designers' verbal utterances are recorded, transcribed, and later coded, typically using a predetermined coding scheme, which results in a quantitative data set. These data points enable researchers to investigate many aspects of the design activity from which the protocols were collected.

In this paper, we propose a new way to analyze verbal protocols by creating maps from verbal utterances. Typically, system mapping is used to help the problem solver identify and visualize system components and their interactions as they work to understand the problem and identify interventions. In our study, we use such mapping as a research tool to *retrospectively* visualize designers' evolving mental representations [16] through their verbal narratives while working on a design task.

The process of using system mapping for analyzing design activity differs from other protocol studies, in part because we do not use a pre-defined coding scheme. Instead, we follow a set of rules, or heuristics, derived from the literature, using nodes and arrows to depict relationships that describe the systems dynamics taking place (see section on systems mapping). As design conversations are changing and evolving (as the participants explore the problem and solution spaces), nodes and dynamics can be identified at any point in the session.

To our knowledge, this type of system mapping approach has not been previously applied to protocols in this way. To illustrate the use of the proposed method, and to provide a preliminary assessment on whether the approach can be useful for understanding design activity, we conducted an exploratory study using an existing data set collected by one of the authors.

Method

Data Collection

The data studied in this research consisted of eight verbal protocol transcripts, originating from video recordings. In the study, eight groups of industrial design master students (three per group) were tasked with generating solutions to an open-ended problem. Students were randomly allocated across groups, though most had on average two students from an industrial design background and one from either mechanical or civil engineering backgrounds. The age of the participants ranged from 22 to 26 years old. Each group was provided the following instructions:

> Different people have different waking up experiences in the morning. However, a great number of people consider this process as unpleasant. How might you improve the morning waking up experience? As a team of three, generate new and useful ways (a product/system/service) that provide people with a positive waking up experience. If you generate several ideas, make sure you choose one final concept, and make a clear sketch of it. You should spend approximately 30 minutes on this activity.

The video recordings of the design activity were captured by the students themselves as part of an assignment in a graduate course about design methodology. Students were tasked with watching the video footage and searching for, as well as reflecting on, key moments in their idea generation session with an impact in their thinking and decision-making process. Transcripts from the videos were later generated by a research assistant, and not the students themselves. The eight transcripts each had, on average, 3637 words and ranged from 2090 to 5044 words.

While the length and contextual setting of this 30-min activity is not a realistic simulation of real-world practice, the structure of these sessions shares a reasonable number of similarities with how students would approach this type of design brief in a studio setting. Therefore, and despite the brevity of these sessions, we consider this to be a plausible starting point to explore the use of systems mapping to analyze some aspects of design activity.

Generation of Maps

The following protocol was developed for generating maps of the systems in question from the transcripts. As the coders review the transcript line by line, they seek to identify nodes and system dynamics. A *node* is identified whenever a participant (i.e., student) describes an entity that can influence or be influenced by other entities, and thus has a measurable quality or quantity. The coder then assigns the node a short label that captures its meaning. *System dynamics* describe how one node influences another and is here interpreted in three ways: positive (+), negative (−), or no evident increasing or decreasing effect but somehow related (±). As such, system dynamics labels indicate the nature of influence that one node has on another.

As the design activity unfolds, nodes and dynamics are recorded once only, when they first occur. It is helpful to conduct both the coding and visualization of these elements (i.e., drawing the map) simultaneously. This process helps the coders connect nodes that were recorded earlier in the session to those that are identified much later. However, if a node or system dynamic is articulated in a different way or the group's understanding of that relationship between issues changes, this alteration may be reflected in the maps with the addition of new elements, but not the redefinition of existing elements.

Although all groups were posed with the same problem statement, each session produced a unique set of nodes and system dynamics. As the coders attempted to use the language of the participants as much as possible, to avoid subjective interpretation, no predetermined coding scheme (e.g., by coding for common nodes) could be feasibly created beforehand. In most protocol studies, reliability of the applied codes is determined by an inter-rater reliability score calculated from an independent coding process between at least two coders. However, in this case, a lack of a predetermined codes prevents a reliability score from being calculated in this way. In our approach, the codes emerge from the verbal protocol and how certain verbal utterances are potentially interpreted by the researchers.

Despite efforts to follow the language of the participants, the interpretation of verbal utterances and the use of guidance to build the maps of the different systems [21] often resulted in different node names. Whereas we have no specific metrics to report, we have tested our overall process internally. Two of the authors independently generated maps for a subset of the groups. We observed that while the labeling of the nodes differed, different coders produced maps that were similar along the general patterns that drove most analyses (e.g., number of nodes and interconnections between those nodes). However, it should be noted that when two independent coders create maps individually, though they may reliably identify entities in the same place of the transcripts, the resulting map may be different. It is possible to arbitrate between two sets of coders which would result in a single map used for the analysis, but given the exploratory nature of this work, this was beyond the scope of the project.

In Table 1, we present an excerpt from one of the groups' transcript to demonstrate how nodes and system dynamics were defined during the coding process. Consider the utterance by P3: "*I think we can start with defining what our problems with waking up [are]? And then we can work from there?*" A node is identified and labeled as "Quality of waking up experience". Now consider the next utterance by P1, who says "*Maybe also the sound…it is not a nice way of waking up. Like with stress*". Here, a new node is identified—"Amount of sound", as well as a new relationship (system dynamic): The new node has a negative (decreasing) influence over the previously identified "Quality of waking up experience". Finally, within that second utterance, another new node is also defined and given the name "Amount of stress". Another system dynamic is also inferred: the "Amount of sound" node has a positive (increasing) influence over the node "Amount of stress". The map generated from these nodes and system dynamics is visualized in Fig. 1.

Once we coded all transcripts, the data was formatted in order to be read by an open-source network visualization and analysis platform called Gephi [25]. Gephi

Table 1 Coded transcript excerpt from design protocol of Group 2

Verbal utterance by participants (P)	Generated nodes (N) and system dynamics (D)
P3: I think we can start with defining what our problems with waking up [are]? And then we can work from there?	N1 = Quality of waking up experience
…	
P1: Maybe also the sound…it is not a nice way of waking up. Like with stress	N2 = "Amount of sound" D1 = N2 decreases N1 N3 = "Amount of stress" D2 = N2 increases N3

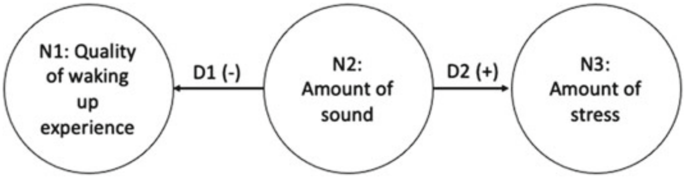

Fig. 1 Nodes generated from excerpt in Table 1

offers a variety of rendering and data analysis tools that are useful for understanding the structure of the maps of the systems being portrayed.

Results

Using the protocol described above, we generated maps from all eight transcripts, as presented in Fig. 2. The generated maps vary both in size (i.e., the number of nodes and system dynamics) and structure (i.e., patterns of interconnections between nodes as determined by the system dynamics). In this section, we describe some preliminary analyses conducted on the maps, along three main aspects: size of the maps, evolution of the maps overtime, and discernable patterns in those maps related to their structure. Their potential significance, extensions as well as other approaches for analyzing the maps are presented in the Discussion.

Size of the Map

The number of nodes and system dynamics provide two simple attributes by which to characterize a map. Figure 3 presents the total number of nodes and system dynamics (labelled "elements") in each of the maps generated from the eight protocols. There is a notable variation between groups, even though all groups worked on the design

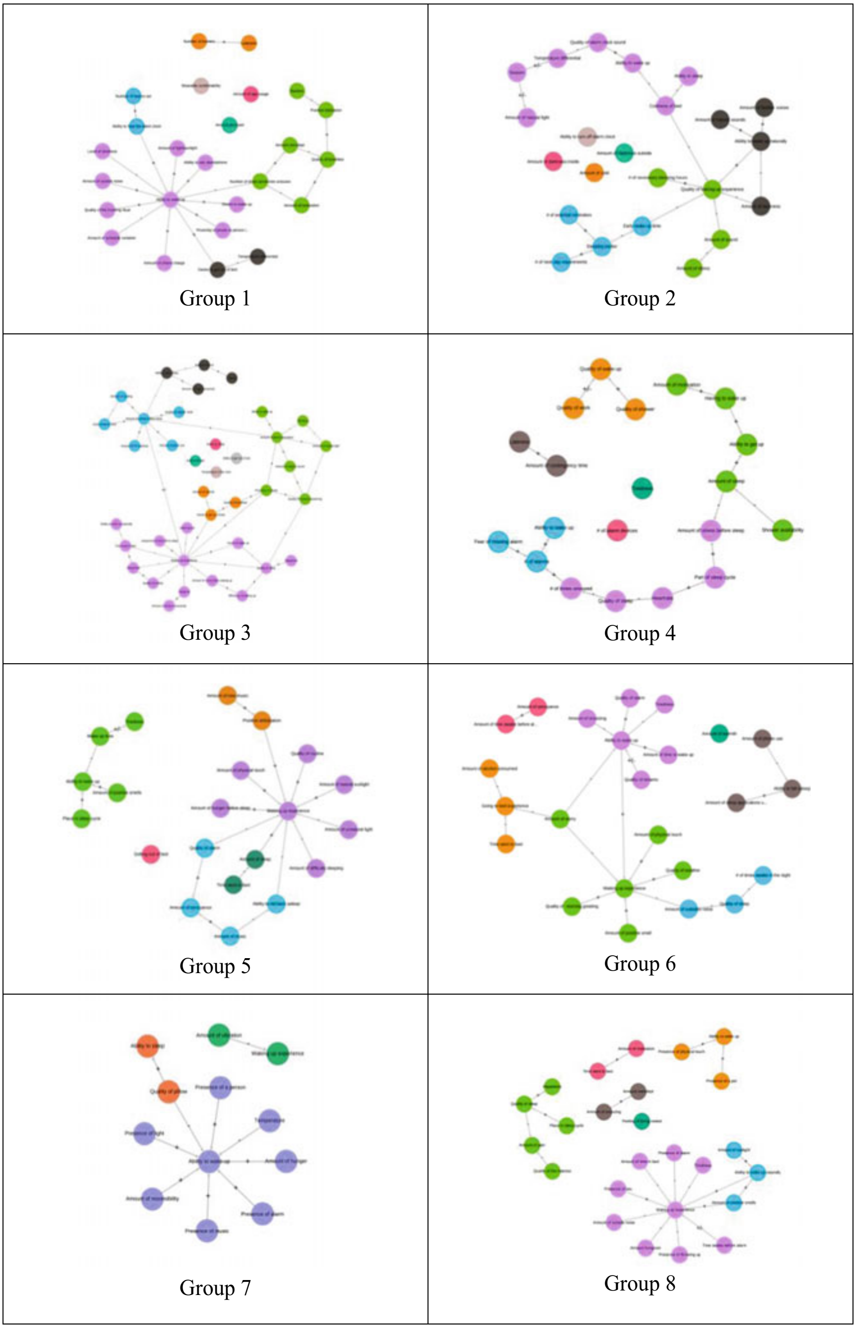

Fig. 2 Generated maps for all eight groups with modularity analysis

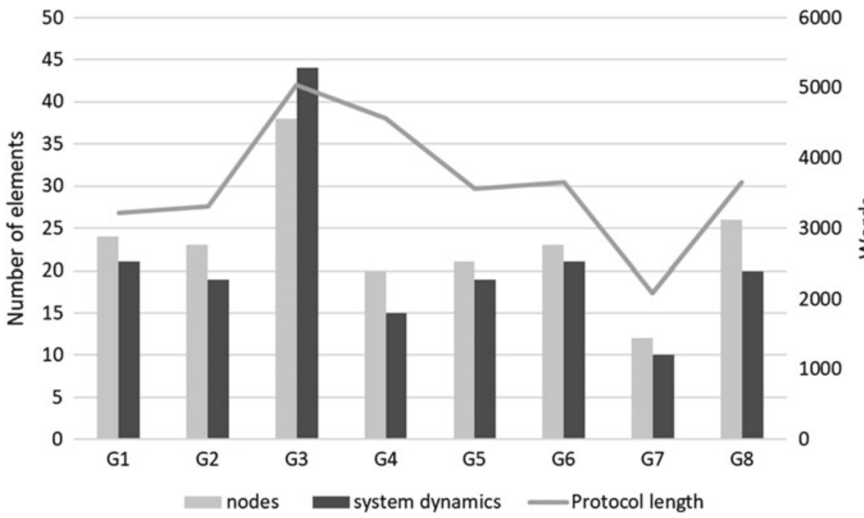

Fig. 3 Frequencies of identified nodes and system dynamics (left axis), and protocol length (in words—right axis), by group

task for approximately the same amount of time (average 34 min across groups). At the extremes, the largest contrast is observed between the number of map elements generated from the design activity of Group 3 and that of Group 7. The map of Group 3 is also notable because it is the only one in which the number of system dynamics is larger than the number of nodes. We also note that except for Group 4, there is a positive relationship between the protocol length (in words) and the size of the map.

Maps over Time

The approach also facilitates analyses in the temporal dimension. To observe how the maps evolved over time, we divided each protocol into 20 equal segments and counted the nodes and system dynamics that emerged in each ventile. Figure 4 presents a cumulative graph of these occurrences, for each group.

A clear general pattern can be observed: in the early parts of the sessions there is a rapid emergence of new nodes and dynamics, as participants begin to analyze the problem. For most groups, new additions to the map taper off about halfway through their design session. At this point, the designers' conversation shifts focus from framing the problem to generating solutions or continuing conversations about topics which were already previously captured by certain nodes and dynamics.

Different groups vary in terms of the rate at which they produce new nodes and system dynamics throughout their session. For example, while Group 7 produces no new additions to the map after the 10th ventile, other groups continue to add new

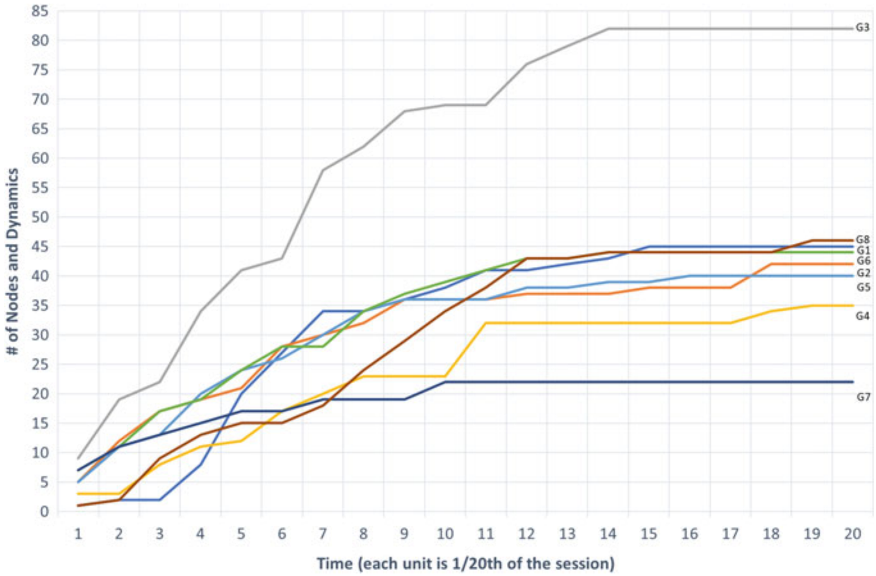

Fig. 4 Cumulative graph of nodes and dynamics emerging over time, by group

elements in the second half of the session (albeit at a slower rate), and as late as the 19th ventile.

Patterns in Maps

The overall structure of the maps may also tell us something about the designers' approach. Visually, we observe that nodes can be organized in various clusters, especially those organized in a "hub and spoke" configuration. To detect these clusters in the maps, we use the modularity function in Gephi, which uses a community detection algorithm [26]. The detected node clusters for each group are color-coded in the maps presented in Fig. 2. When considering clusters of at least two nodes, the eight maps each have three to six clusters.

We take the example of Group 3, which produced the largest and most complex map (Fig. 5), to explore the significance of the detected clusters. In our analysis, we take advantage of both the nodes' labels and the solution ideas that the groups generate that are related to those nodes. The latter are noted in the transcript by the coders, and included in the map in Fig. 5 labelled in red, but are not part of the standard protocol introduced in this paper.

Group 3's map has five clusters of three or more nodes each. The largest cluster (in purple) centers on the "waking up experience" node; but in this case it is hard to detect a clear focus. The nodes in this cluster represent several under-developed

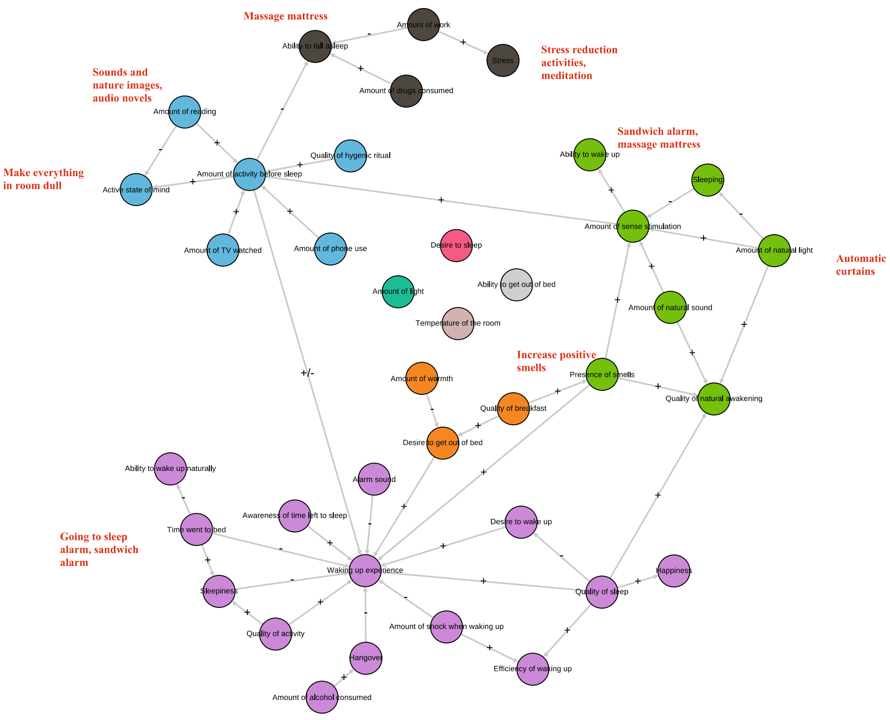

Fig. 5 Map of Group 3 with nodes color-coded according to clusters and ideas highlighted in red

threads that capture the entire time window from "before going to bed" to "waking up the next day". The idea that the group discusses, as the nodes in this cluster emerge, is that of a "sandwich" alarm, one that both reminds the user to go to bed (thus allowing for a sufficiently long sleep) and wakes the user up in the morning.

The other three distinct clusters have a clearer focus:

- The nodes in the blue cluster center on the activities one engages in before going to sleep (e.g., watching TV, reading, and using the phone). Solution ideas are targeted at making these activities "dull" and relaxing, for example by having the user exposed to nature images and listening to audio-novels.
- The nodes in the black cluster relate to one's ability to actually fall asleep once in bed, which might be affected for example by stress, drugs, and anxiety about work to be done. The ideas that emerge in response are, for instance, a mattress that massages the user to sleep and stress-reduction activities like meditation.
- The nodes in the orange cluster focus on one's desire to get out of bed, particularly in relation to the temperature of the bed and and the quality of the breakfast. There were limited solution ideas related to this cluster.
- Finally, the nodes in the green cluster focus completely on the awakening processes, especially with regards to the role of the senses (e.g., smells, lights). Accordingly, related solution ideas focus on engaging with the senses, for instance

through an automatic curtain that allows natural light to come in when it is time to wake up.

This analysis supports the idea that clusters represent different aspects of the problem that the designers are thinking of and paying attention to at different moments during the design session. The significance of this analysis and possible extensions are further addressed in the Discussion.

Discussion

At a high level, we set out to study design activity from a systems perspective, under the assumption that such a viewpoint would provide a general framework to understand design activity. The contribution of this paper is the introduction and preliminary evaluation of a novel protocol analysis approach that uses system mapping as a visualization to code verbal protocols of design. Our research was guided by the following research question: *What can a systems mapping approach to analyzing design protocols tell us about design activity?* The results support our assertion that the contents of the protocols could be approached as a complex network of nonlinear dynamics where groups of interconnected and interrelated ‘parts’ can be studied as a system. Given the exploratory nature of this work, our study raises questions that prompt future research directions. Below, we summarize our contributions and their implications for future research. We also propose areas of inquiry that prompt new ways in which the maps can be further analyzed.

Contributions and Significance

System mapping are a useful thinking tool to help make explicit the structure of the system being studied, including the various “parts” and their interrelationships. In the design context, a system mapping serves to uncover and visualize the designer’s understanding of the complex problem being defined and analyzed, with the aim of identifying leverage points where interventions (or solutions) can be designed [27]. It then follows that maps generated retrospectively based on transcripts of design activity would best capture designers’ work in the problem space.

Tracing Co-evolution and Maturity of Design Process

The temporal analyses on the eight generated maps provide further support for the assumption that these can effectively capture the designer’s activity in the problem space. For all groups, most of the nodes and dynamics were generated in the first half of the session, when the participants were mostly identifying what affected their waking up experiences. Any new additions to the maps tapered off in the second half once their attention turned to ideating and refining generated solution ideas.

One potential implication of this finding, is that cumulative graphs that maintain an increasing slope for a longer portion of the design session indicate that the designers engage in a process of problem–solution co-evolution [28, 29] for longer, demonstrating a more mature design process and higher design expertise [30]. The approach thus has the potential to be used as a means to compare designers across disciplines and/or levels of expertise, as has been previously done with other verbal protocol analysis approaches (e.g., [31, 32]).

Bigger Maps, Better Designs?

If the system mapping captures the designers' activity in the problem space, then the structure of the generated maps can provide a useful way for characterizing the designers' problem analysis activity. Comparing the maps of the eight groups, we found they varied in the number of nodes and system dynamics generated.

The question that emerges is whether groups whose protocols produced larger maps explored the problem space to a greater extent, and whether this points to a higher-quality design outcome. The approach does not presently provide any objective assessments of the quality of the nodes themselves, other than their location in the map, relative to the other nodes. This point is further elaborated on in the next section.

Maps as Signatures of Frames

The maps show promise as a means to capture related cognitive activities such as problem framing [33]. Visual inspection of the maps reveals that the nodes are organized in "hub-and-spoke" clusters, the boundaries of which can be computationally determined through modularity algorithms, which can determine "communities" of related nodes. Inspection of the detected clusters in the map of one of the groups in our study showed that each focused on a particular aspect of the problem, prompting different kinds of solutions that addressed it. We thus believe that the maps provide insight on which aspects of the problem the designers choose to focus on—that is, which problem frames. When combined with temporal analyses of the creation and evolution of these communities over time, the maps have the potential of providing a window into the designers' framing and reframing activity throughout the design session.

When exploring the meaning of the node clusters for one of the groups, we made use of the solution ideas that the group generated to better understand the theme (or frame) of nodes in a cluster. In this preliminary work, we did not devise a systematic way for coding, tracking, and "placing" solution ideas in the maps. However, we believe it would be worthwhile to investigate the relationship between solution ideas and nodes and system dynamics in the map.

In particular, we expect that our approach can shed light on the quality of idea generation. If each cluster of nodes captures a different frame, a question that arises is whether there is a relationship between the characteristics of a cluster (e.g., size and structure) and the quality of the frame in terms of the generated solutions that it prompts. One may hypothesize that a map with many highly populated clusters might be indicative of more *flexibility* [34] during idea generation (the ability to devise ideas that diverge into new and unusual directions) and thus more promising solutions compared to a map with few and/or small clusters. We might also be able to identify which nodes become essential when designers generate solutions.

Future Research

Below we describe a number of future directions for further improving on the approach and expanding on the range of analyses it can afford.

Centrality and Design Fixation

Network analysis methods can be useful for drawing further insights from the maps. For example, centrality metrics can describe the extent to which any node can influence or be influenced by other nodes in the system. Combined with temporal analyses, centrality measures can be used to indicate if, for instance, design fixation is occurring. The approach as described in the Method section only keeps track of when a node or system dynamic is first identified in the transcript. Therefore, all analyses described in this paper are based on the first occurrence [35] of those elements. However, one could also keep track of subsequent occurrences of those nodes and system dynamics; participants sometimes mention the same concepts/topics again later in the session, so subsequent occurrences of previously identified map elements could be noted and tracked.

Mapping Shared Understanding

The approach can also be used for analyzing team collaboration by assigning 'ownership' of a node and system dynamic to the participant from whose verbal utterance it was generated. With this approach, using the map visualizations it may be possible to detect a team's ability to create a shared understanding, or mental model [36], of the problem. The maps might reveal each team member's contribution to building the team's understanding of the problem and the extent to which they build on their own or other team members' ideas. We expect that for those groups who are able to build on each other's nodes and system dynamics, will collectively reach a more comprehensive problem understanding.

Systems Thinking Maturity

Finally, the approach offers appropriate language and tools that can be used to characterize designers' ability to think systemically, by considering the wider complexity of the system and interconnections between parts/issues, a skill highly relevant and useful when solving wicked problems [37]. Given our dataset and the maps generated from the design activity of the eight groups, a question that arises is whether the groups with more nodes and system dynamics might be better able to think systemically. It would be useful to compare and contrast this approach with, for instance, recent research on assessing *systems thinking maturity* through the use of new and improved assessment rubrics [3].

Conclusion

In this paper we have introduced a new approach for analyzing design activity that is inspired by systems thinking approaches. In most protocol analysis studies codes applied to transcripts are typically determined before the process begins. In contrast, our exploratory work uses system mapping as a diagrammatic notation of design conversation that evolves as designers continue to work on the problem.

The approach we have proposed was developed on the basis of an existing body of literature that has been used in many different contexts, like living systems and social networks research. These perspectives offer useful frameworks and metrics for understanding the generated maps of the different systems being portrayed. We have provided a proof-of-concept demonstration of the approach by testing it on verbal protocols collected from eight groups engaged in an early problem analysis and ideation activity. A preliminary analysis of the eight generated maps provides promising results about the usefulness of the approach, especially in capturing a designer's activity in the problem space, and points at an exciting array of research directions for capturing other design processes and phenomena.

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Investigating the Cognitive Processes Involved in Design Ideation Using Psychological Tests

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The cognitive processes involved in design ideation remain poorly understood. To advance knowledge on this issue, we report a study in which 101 Product Design Engineering (PDE) students performed a series of ideation tasks as well as a range of psychological tests assessing different cognitive processes (semantic association, executive functioning, intelligence, mental imagery and divergent thinking). Relationships were then examined between ideation novelty and scores on the cognitive tests. Significant, positive correlations were observed between novelty and associative flexibility, general retrieval ability and fluid intelligence. A significant negative correlation was also found between novelty and inhibition. Finally, multiple regression analysis found that together, the cognitive processes assessed explained 26% of the variance in novelty scores within the sample. The implications of the findings are discussed, along with limitations and directions for future research.

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Introduction

Design ideation i.e. the generation of ideas in response to a design brief, occurs at the early stages of the design process, and is held to be a key determinant of the cost and quality of the final product [1, 2]. The ability to generate novel and feasible concepts during ideation is also thought to be vital to a company's commercial success, as well as for socioeconomic and technological progress more generally [3, 4].

Despite the clear importance of ideation, the cognitive processes that contribute to it remain poorly understood. This can in part be attributed to important shortcomings with existing design cognition research. Scientifically robust theories of design cognition are lacking [5] and a low level of terminological consistency across studies has also been observed [6]. In addition, design cognition research has been criticised for its lack of methodological diversity and over-reliance on small-scale protocol studies. While the protocol method can undoubtedly reveal insightful information about ideation, its resource intensive nature tends to necessitate small samples, thereby limiting generalisability. In addition, many cognitive processes can occur unconsciously and may be difficult to identify through subjective verbal reports.

However, on a more encouraging note, there are signs that positive changes are already underway within the field. For example, increasing methodological diversity can be seen in the growing number of neuroimaging studies conducted in a design setting (e.g. [7, 8]). Nonetheless, at the behavioural level, there remains a need for larger-scale quantitative studies of design ideation employing controlled measures of ideation performance and cognitive processing, and with sample sizes better suited to hypothesis testing and quantitative data analysis.

To address this, in the current paper we report an empirical study (n = 101) examining the relationship between PDE ideation novelty and a range of psychological tests measuring different aspects of cognitive functioning (including semantic association, executive functioning, mental imagery, intelligence and divergent thinking). The rationale of this approach is that a significant association between a given cognitive test (e.g., 2-back memory task) and ideation novelty can indicate that the respective cognitive process (working memory) is involved in the generation of novel design concepts. This method has been widely adopted within the cognitive psychology literature on creativity, and has highlighted the involvement of a range of cognitive processes in creative ideation, including processes that are not necessarily conducive to verbalisation (e.g. semantic association, inhibition [9, 10]). Note also that some studies of this kind have been conducted on design ideation, although they have tended to examine a relatively narrow range of cognitive processes (e.g. [11, 12]).

Existing Behavioral Literature on Ideation

Although a diversity of approaches have been applied to the study of design cognition (case studies, conversation analysis, neuroimaging), protocol analysis is largely viewed as the predominant approach in the field. Two systematic reviews of 47 protocol studies focused on the conceptual design phase (of which ideation is a part) have previously been published by Hay et al. [6, 13]. Based on the latter review, a generic classification of cognitive processes involved in conceptual design was proposed, which included long-term memory, semantic processing, visual perception, mental imagery processing, creative output production and executive functions.

Since then, subsequent work has further extended our knowledge of the cognitive processes involved in conceptual design, including design ideation. In particular, research has continued to highlight the importance of long-term memory retrieval [14, 15]. For instance, Gonçalves and Cash's [14] protocol study suggested that early ideas tend to be generated relatively quickly and automatically, and are often based on the designer's stored conceptual knowledge (i.e. semantic memory) and personal experiences (i.e. episodic memory). In addition, the well-established notion that creative ideas stem from associations between semantically distant concepts [16] has also received support. For instance, in a study analysing designers' conversations during ideation [17], it was found that more creative solutions tended to result from conversations with greater semantic divergence. That is, the semantic relatedness between nouns used tended to become increasingly distant over time.

Focus has also been given to the more top-down, controlled aspects of design ideation. For instance, Ball and Christensen's [18] review of the literature focuses on the concept of meta-cognition, which in a design context refers to how designers monitor their own cognition and develop strategies to navigate ill-structured problems. Examples of such processes include problem definition (e.g., specifying requirements/constraints) and problem framing (i.e., narrowing in on specific aspects of the solution to further explore and develop [19]).

In addition, recent work has emphasised the importance of logical reasoning in ideation [18, 20, 21]. Two key forms of logical reasoning that have been implicated in design ideation are abductive and deductive reasoning. Abductive reasoning involves proposing the simplest explanation for an observation (or set of observations), whereas deductive reasoning involves drawing a specific conclusion based on a series of general statements or premises [22]. Based on protocol evidence, Cramer-Petersen et al. [21] suggest that ideation can be characterised as iterations between abductive-deductive patterns, whereby the designer proposes a general 'frame' or 'perspective' within which to address the problem (abductive), and then evaluates the suitability of that particular frame and solutions generated within it (deductive).

Finally, the relationship between mental imagery and design ideation has continued to receive attention, particularly in the context of sketching. Several accounts within the design literature have emphasised that early-stage sketches often contain a high degree of visual ambiguity, which can stimulate mental imagery processing and lead to novel visual discoveries [23, 24]. This notion was explored by Tseng [25] who had both experts and novices carry out a design task in the presence of visual stimuli. Importantly, the stimuli were derived from actual sketches, and contained varying levels of visual ambiguity. It was found that cues with higher ambiguity were more conducive to the generation of novel concepts, though only in the expert group, suggesting that the ability to utilise visual ambiguity in sketches is acquired through significant experience.

Present Study

The above literature gives a useful insight into the cognitive processes involved in design ideation. However, it remains the case that our existing knowledge of ideation is mainly derived from relatively small-scale protocol studies, which have limitations surrounding generalisability and subjectivity. It is thus important to move beyond protocol analysis as the predominant method in the field, and adopt a more diverse range of methodological approaches and perspectives. In particular, there is a need for larger-scale quantitative studies exploring statistical relationships between ideation performance and psychological tests of cognitive processing. Within this approach, a significant correlation between a given psychological test (e.g., 2-back working memory test) and ideation performance indicates the potential contribution of the corresponding cognitive process (working memory) to design ideation. As discussed, this method offers numerous advantages, including the fact that it is conducive to large sample sizes, and can also shed light on the involvement of more implicit and automatic cognitive processes that are not necessarily capable of being verbalised.

In light of the above considerations, in the present study 101 PDE students performed a series of open-ended ideation tasks as well as a broad range of psychological tests assessing different cognitive processes, including semantic associative processing, executive functioning, intelligence, mental imagery and divergent thinking. The tests were developed within cognitive psychology, and were chosen on the basis of the existing literature on design ideation as well as research on general creativity e.g. [9, 10, 26, 27]. Ideation performance was assessed in terms of novelty, which is regarded as one of the most important measures on which to evaluate early-stage design concepts [28–30]. This likely relates to the fact that novelty is fundamental to virtually all existing conceptualisations of creativity, as well as that fact that the ability to generate novel ideas during ideation has been linked with commercial success and technological innovation [3, 29]. Correlations were used to explore the strength and direction of relationships between ideation novelty and the cognitive tests. In addition, multiple regression was used to examine how much of the overall variance in design novelty could be accounted for by the cognitive tests, as well as to identify which of the cognitive tests independently predicted novelty.

Methods

Participants

A total of 101 individuals participated in the study (54 males, 47 females; mean age = 21.1782, SD = 0.50, range = 18–40). Participants were undergraduate (2nd year or above; n = 76) or postgraduate students of PDE (n = 13), or individuals who had graduated from a PDE degree within 2 years prior to taking part in the study (n = 12) The study was approved by the Department of Design, Manufacturing and Engineering Management Ethics Committee. All participants were reimbursed £30 for taking part in the study.

Tasks and Procedure

After providing informed consent, participants completed a series of cognitive tests (see Table 1) and open-ended ideation tasks in a session that lasted approximately 3 h and 40 min. The order in which the tasks were performed was varied across participants. To mitigate the effects of fatigue, participants were permitted to take occasional breaks throughout the session.

Ideation Tasks

Participants were presented with a set of 10 open-ended ideation tasks, in which they were given up to 6 min to generate and sketch up to three concepts in response to a short design brief (e.g. *Domestic food waste is a serious problem due to global food shortages and socio-economic imbalances. Generate concepts for products that may reduce unnecessary food wastage in the home*). The tasks were a subset of a larger series of tasks used in a previous fMRI study on design ideation [8].

Novelty Assessment Procedure

For the novelty assessment, a subjective scoring method was used whereby three independent raters (R1, R2 and R3) with design expertise assessed concepts on a scale of 1 (least novel) to 7 (most novel). R1 had a masters degree in PDE, with 5 years experience in postgraduate PDE cognition research. R2 held an honours degree in Product Design Innovation and had 5 years industrial experience in product development engineering. R3 held a BSc in Industrial Design Technology as well as 10 years industrial experience and 26 years teaching experience in product design.

Table 1 Cognitive processes examined and their corresponding psychological tests

Cognitive process	Psychological test(s)
Semantic Association: The ability to form associations between concepts stored in memory. Semantic association is widely regarded to be fundamental to creative cognition [16, 31] and has been consistently linked with divergent thinking ability [9, 32]	Associative fluency [31, 33] Associative flexibility [9, 32]
General retrieval ability (Gr): The controlled retrieval of information stored in long-term memory [34]. Gr is most commonly measured using verbal fluency tasks, which require top-down response monitoring and interference management [26]	Verbal fluency [35]
Inhibition: The suppression of a dominant or prepotent response [36]. Higher inhibition is held to facilitate creativity through the suppression of unoriginal or inappropriate ideas [37]. Conversely, however, lowered inhibition has also been linked with creativity [38, 39]	Stroop test [40] Simon test [41]
Updating: Monitoring and updating of information held in working memory [42]	2-back test 3-back test [43]
Visual working memory: Storage and manipulation of visuo-spatial information	Corsi blocks test [44] Visual Patterns test [45, 46]
Fluid intelligence (Gf): Use of logic and abstract reasoning to solve new problems [47]	Advanced Progressive Matrices [48]
Crystallised intelligence (Gc): Breadth and depth of acquired knowledge [34]	National Adult Reading test [49]
Visual mental imagery: Ability to generate and manipulate visual mental images [50]	Vividness of Visual Imagery Questionnaire [51] Paper Folding test [52] Mental Rotations test [53]
Divergent thinking: Generation of multiple responses to an open-ended problem. Divergent thinking tests are widely used as a standardised measure of creativity [54]	Abbreviated Torrance Test for Adults [55]

R1 assessed the full sample of concepts (n = 937), while R2 and R3 assessed all concepts generated in three of the tasks (n = 266; 28.38% of full sample). As a rule of thumb, a 10% subset of the full sample is considered sufficient for inter-rater reliability analyses [56, 57]. Inter-rater reliability between the three raters was acceptable (Cronbach's alpha = 0.762).

In many respects, the rating method used was similar to the widely applied consensual assessment technique (CAT [58]). Consistent with the CAT, raters were asked to assess the concepts according to their own subjective definition of novelty. They were also required to rate participants' outputs relative to one another. However, unlike the CAT method, they could also consider products that already exist when making judgements. In addition, the CAT typically involves all judges rating all concepts in the sample. However, this was not feasible here due to the large sample size and high volume of concepts produced.

Results

Correlations Between Novelty and Cognitive Processes

Pearson's correlations were examined between all measures in the study and are displayed in Table 2. Note that a few of the measures had a small number of missing values due to some participants not completing the tests (Simon task, n = 1; 3-back task, n = 1; Visual Patterns task, n = 2). Novelty was positively and significantly correlated with associative flexibility (r = 0.249), general retrieval ability (r = 0.288) and fluid intelligence (r = 0.208). A significant, positive correlation was also observed between novelty and the Simon effect (r = 0.226). However, since higher Simon effect scores indicate lower inhibition, this actually indicates a negative relationship between novelty and inhibition. All of the above effect sizes were generally in the weak to moderate range. Correlations between design novelty and all other measures were non-significant (all $p > 0.05$).

Variance in Novelty Scores Accounted for by the Cognitive Processes

Having explored correlations, it was then examined how much variance in design novelty could be explained by scores across all of the cognitive measures. To do this, a multiple regression analysis was conducted with design novelty as the dependent variable (DV) and all of the cognitive test scores as predictors. However, the 2-back was not included due to its high correlation with 3-back (r = 0.755), since overly high correlations between independent variables in regression analysis can cause issues with interpreting findings [59].

The overall model was significant, $R^2 = 0.260$, $F(14, 83) = 2.084$, $p < 0.021$. This suggests that overall, scores on the cognitive tests accounted for 26% of the variance in novelty within the sample. Results for each predictor, including the unstandardised coefficient (B), standard error of the coefficient (SEB), standardised coefficient (β) and significance level are presented in Table 3.

Design novelty was significantly and positively predicted by associative flexibility (B = 0.050, SEB = 0.023, β = 0.342, $p = 0.028$) and Simon effect (B = 0.004, SEB = 0.002, β = 0.213, $p = 0.039$), again the latter suggesting a negative relationship between inhibition and novelty. The predictors Gr (B = 0.040, SEB = 0.021, β =

Table 2 Descriptive statistics and Pearson's correlations for all measures

	M	SD	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
1. Design novelty	3.27	0.61	1															
2. Associative fluency	12.21	3.64	0.184	1														
3. Associative flexibility	14.02	4.13	0.249*	0.665**	1													
4. Gr	11.78	3.42	0.288**	0.327	0.432**	1												
5. Simon effect	23.20	30.71	0.226*	−0.018	−0.069	0.040	1											
6. Stroop effect	88.76	69.54	−0.077	0.058	0.129	−0.046	−0.104	1										
7. 2-back	0.85	0.17	−0.114	0.118	0.125	0.071	0.048	0.050	1									
8. 3-back	0.77	0.14	−0.096	0.041	0.044	0.041	−0.012	0.083	0.755**	1								
9. Gf	25.08	5.05	0.208*	0.094	0.046	0.249*	0.087	−0.129	0.093	0.086	1							
10. Gc	111.35	4.84	0.020	0.113	0.334**	0.275**	0.091	−0.095	0.037	0.060	0.221*	1						
11. VPT	9.99	1.72	0.005	−0.003	0.031	0.225*	−0.080	0.063	0.192	0.261**	0.357**	0.168	1					
12. Corsi blocks	6.43	1.24	−0.086	−0.081	−0.094	−0.151	0.105	0.145	−0.094	−0.020	0.020	0.081	0.204*	1				
13. PFT	14.92	3.16	−0.005	0.207*	0.209*	0.068	0.080	0.066	0.271**	0.318**	0.332**	0.193	0.228*	0.114	1			
14. MRT	17.26	5.10	−0.096	−0.051	0.119	0.206*	−0.066	−0.063	0.073	0.163	0.319**	0.245*	0.314**	0.136	0.352**	1		
15. VVIQ	56.73	9.46	−0.043	0.042	0.030	−0.018	−0.025	−0.002	−0.186	−0.141	0.056	−0.138	−0.081	−0.152	−0.255*	−0.099	1	

(continued)

Table 2 (continued)

	M	SD	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
16. ATTA	64.06	7.83	0.052	0.365**	0.494**	0.239*	−0.189	0.170	0.017	−0.050	−0.018	0.081	−0.050	−0.058	0.155	−0.025	0.057	1

VPT, Visual patterns test; PFT, Paper folding test; MRT, Mental rotation test; VVIQ, Vividness of visual imagery questionnaire; ATTA, Abbreviated Torrance test for adults. **, Correlation significance at the 0.01 level; *, Correlation significance at the 0.05 level

Table 3 Unstandardised coefficient (B), Standard error of the coefficient (SE_B), Standardised coefficient (β) and significance level for each predictor of design novelty

	B	SE_B	β	p
Associative fluency	−0.014	0.023	−0.085	0.526
Associative flexibility	0.050	0.023	0.342	0.028
Gr	0.040	0.021	0.226	0.058
Simon effect	0.004	0.002	0.213	0.039
Stroop effect	0.000	0.001	−0.037	0.723
Three-back	−0.421	0.468	−0.094	0.370
Visual patterns task	0.003	0.040	0.008	0.943
Corsi blocks	−0.004	0.051	−0.009	0.931
Gf	0.027	0.014	0.221	0.055
Gc	−0.027	0.014	−0.209	0.063
Paper folding task	−0.012	0.023	−0.062	0.606
Mental rotation task	−0.018	0.013	−0.149	0.194
Vividness of visual imagery	−0.009	0.007	−0.139	0.171
Divergent thinking	−0.007	0.009	−0.089	0.437

0.226, $p = 0.058$) and Gf (B = 0.027, SEB = 0.014, β = 0.221, $p = 0.055$) were also approaching significance. All other predictors were non-significant ($p < 0.05$).

Discussion

The cognitive processes involved in design ideation remain poorly understood. The current study investigated this issue by exploring relationships between ideation novelty and psychological tests assessing different cognitive processes. It was found that novelty was significantly and positively correlated with associative flexibility, general retrieval ability (Gr) and fluid intelligence (Gf); whereas a significant negative correlation between novelty and inhibition was observed. Additionally, a multiple regression model found that together, the cognitive processes significantly explained 26% of the variance in novelty, with associative flexibility and inhibition emerging as significant independent predictors in the model. In the following sections, we discuss each of the cognitive processes in turn and what the findings suggest about their relationship (or lack of relationship) with design ideation. In addition, reflection is given on the fact that a relatively low portion of the variance in novelty was accounted for by the cognitive processes, suggesting that there are many other factors influencing novelty that were not assessed here.

Semantic Association

A significant, positive correlation was observed between novelty and associative flexibility. This aligns with a number of findings within the psychology literature reporting positive correlations between semantic associative ability and divergent thinking performance [9, 32]. In the design literature, the current findings are consistent with a number of behavioural studies employing a role for semantic association [2, 17], as well as neuroimaging studies reporting activations in brain regions previously linked to semantic memory e.g. [7, 60]. Overall, the current findings reinforce the well-established notion that semantic memory is fundamental to the generation of novel ideas [16].

Executive Functions

Relationships were examined between novelty and three executive functions i.e., broad retrieval ability, inhibition and working memory. Findings relating to each will now be discussed in turn.

Broad Retrieval Ability (Gr)

A significant, positive correlation was observed between ideation novelty and broad retrieval ability (Gr), i.e. the controlled retrieval of information stored in long term memory [34]. Gr tasks are regarded to be executively demanding in that successful performance requires managing interference from various sources (e.g., previous/unsuitable responses) as well as strategically searching through and switching between semantic categories in order to retrieve relevant responses [26]. Gr thus likely supports ideation through strategic memory search, management of interference from various sources (e.g. inappropriate ideas) as well as switching between strategies [9, 26].

Inhibition

The results revealed a negative relationship between novelty and inhibition (as measured by the Simon Effect). This contradicts recent accounts and findings from psychology suggesting that inhibition is required during creativity in order to suppress highly accessible but unoriginal responses, allowing more novel ones to be retrieved [37]. The current findings are more consistent with the alternative view that cognitive disinhibition is favourable to the generation of novel ideas [38, 39].

For instance, Martindale [57] argues that under states of low attentional control and disinhibition, spreading activation across semantic networks is increased, thereby facilitating access to more remote and novel semantic associates. While the current findings may provide some support for this, it is important to highlight that no association was observed between novelty and the Stroop task in this study (which also measures inhibition). As such, the suggestion that reduced inhibition is beneficial for design ideation should be regarded as preliminary and worthy of further investigation.

Working Memory

There was no evidence for any relationship between novelty and the measures of working memory in the study, including updating and visuospatial working memory. This contrasts with findings within both the creativity [27] and design [61] literature observing positive associations between ideation performance and working memory capacity. However, it should be noted that a number of studies, like the current one, have not observed any relationship between working memory and creative ideation [62, 63]. This could suggest that at the very least, the ideation-working memory link is complex and potentially influenced by one or more moderator variables (e.g. task duration; number of requirements/constraints).

Intelligence

Relationships were examined between novelty and two key forms of intelligence i.e., fluid intelligence (Gf) and crystallised intelligence (Gc). With regards to Gf, this was significantly and positively related to novelty. This supports existing behavioural work suggesting that logical reasoning is involved in design ideation, e.g. [13, 21]. In addition, Gf may support the generation of effective strategies during ideation, as is thought to be the case in more general creative cognition [64]. In contrast to Gf, there was no evidence for any relationship between novelty and Gc. Thus, while having an extensive knowledge base has been shown to be beneficial for general creativity [65], the current results suggest this is not important for the generation of novel design concepts.

Mental Imagery

Running contrary to the widely held view that mental imagery is a fundamental process in design ideation, no correlations were observed between novelty and the mental imagery tests. This could suggest that the mental imagery-design relationship has been overstated by previous research. However, we suggest that it would be premature to dismiss the importance of mental imagery at this stage. One possibility is that mental imagery processes are engaged during ideation, but do not relate to the novelty of concepts generated. There are however, a number of other performance outcomes that mental imagery might be associated with, such as feasibility, aesthetic value, and elaboration (i.e. amount of detail in the sketch). Thus, there are several avenues for future research to explore the potential outcomes that do relate to mental imagery.

Divergent Thinking

Interestingly, the study found no relationship between design novelty and divergent thinking (assessed by the ATTA). Thus, while divergent thinking tasks are argued to give an indication of one's creative potential [54], the current results suggest that they may have limited predictive validity in a design context. This finding may offer support to critics of divergent thinking, who have suggested that the creative processes that occur across different domains are too diverse and complex to be measured by generic divergent thinking tasks [66, 67]. Similarly, they align with the view that there are fundamental differences between divergent thinking and design ideation, which render the former unsuitable as a measure of design ideation ability [68].

Variance in Novelty Accounted for by the Cognitive Processes

As well as identifying what cognitive processes were associated with ideation novelty, it is also important to consider the strength and independence of the relationships observed, as well as the overall portion of variance accounted for by the cognitive processes. Among the processes significantly correlated with novelty, it is notable that these were generally of weak effect size, ranging between $r = 0.208$ (Gf) and $r = 0.288$ (Gr) and thereby suggesting only modest associations between these processes and novelty. Furthermore, the multiple regression analysis revealed that overall, the cognitive processes assessed accounted for 26% of the variance in novelty. This highlights that there are many factors contributing to the variance in design novelty beyond the cognitive processes assessed here. This may include factors such as personality, domain-knowledge, motivation, other relevant cognitive processes (e.g. episodic memory), in addition to sociodemographic features such as the age, sex and degree of design experience of the participants.

Limitations

There are a number of limitations with the current study that merit discussion. Firstly, it is important to recognise that there are key differences between ideation as it was conducted in the study and ideation as it is carried out in practise. For example, in practice there may be less strict requirements in terms of generating a specific number of concepts within a given time limit. This limitation relates to the broader criticism that is often levelled at highly controlled, lab-based studies of design cognition—namely, that findings are lacking in ecological validity with respect to design as it occurs ‘in the wild’ [69]. Trade-offs between methodological control and ecological validity are a key challenge for design cognition and neurocognition research, and future work is needed to develop approaches that can more appropriately balance these two aspects.

A second limitation relates to the high number of cognitive tests examined. While this approach has allowed for a broad assessment of the cognitive abilities involved in design ideation, it has a disadvantage in that it increases the likelihood of observing a significant correlation by chance. Note, however, that since the processes significantly correlating with novelty were also significant or near-significant in the regression analysis (which adjusts for the other regressors), this suggests that the observed relationships are robust. A related concern worth highlighting is that some of the measures were conceptually highly related with one another. This is arguably problematic for regression analysis, which assumes that regressors are independent of one another. Again, however, it does have to be recognized that among the cognitive measures, only the 2-back and 3-back tests were correlated to a degree that is generally considered problematic (hence removal of the 2-back). As such, we considered this limitation to be a minor one.

A final limitation is that, due to the highly time and resource intensive nature of the novelty assessment procedure, it was only possible to examine one outcome measure (novelty). As highlighted, novelty is regarded to be a key measure on which to evaluate early-stage design concepts. However, several other key measures exist (e.g. feasibility, variety) and it will be important for future research to investigate the cognitive processes associated with such measures. This will lead to a more comprehensive understanding of the common and distinct cognitive processes contributing to these different aspects of ideation.

Conclusion

PDE ideation is widely regarded to be a critical phase of the design process and a key driver of economic and technological advancement. The cognitive processes involved in this activity, however, remain poorly understood. In part, this can be attributed to the lack of robust theories of design cognition, as well as poor terminological consistency across studies and an over-reliance on the protocol method. To advance knowledge in this area, the present study used an approach that has been widely applied in the cognitive psychology literature on creativity, and which arguably addresses many of the shortcomings associated with more commonly applied methods. Specifically, 101 PDE students carried out a set of ideation tasks as well as a variety of psychological tests assessing different cognitive processes. Relationships were then examined between ideation novelty and scores on the cognitive tests.

The results of the study suggested that ideation novelty was associated with associative flexibility, general retrieval ability, fluid intelligence and decreased inhibition (as measured by the Simon effect). By contrast, working memory, mental imagery, divergent thinking, and Stroop inhibition were not found to be significantly correlated with novelty. Multiple regression analysis indicated that overall, scores on the cognitive tests accounted for 26% of the variance in novelty scores. This highlights that there are likely many other factors contributing to the generation of novel design concepts, such as domain knowledge, personality and other cognitive processes. Future research should explore the influence of these other factors.

While the current approach has the potential to greatly extend our knowledge of the cognitive basis of design ideation, its usage remains uncommon in the literature. More studies employing this method are needed to extend the current findings, for instance, by exploring the cognitive processes associated with other performance outcome measures (e.g. feasibility), and whether the cognitive processes implicated vary at different levels of expertise. In addition, this approach could also be used to explore how cognitive processes interact during ideation e.g. by using moderation analysis. Overall, larger-scale quantitative studies of design cognition can build on, challenge and extend insights derived from the existing protocol work. Furthermore, findings can be integrated with the emerging neuroimaging literature on design ideation in order to develop more scientifically robust neurocognitive models of the ideation process. Finally, in conjunction with other approaches, the findings may contribute to the development of new ideation techniques and computational support tools for designers, as well as the more general advancement of education programs for design students.

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Design Neurocognition

Brain and Behavior in Engineering Design: An Exploratory Study on Using Concept Mapping

Mo Hu, Tripp Shealy, John Gero, Julie Milovanovic, and Paulo Ignacio Jr

To explore the connection between brain and behavior in engineering design, this study measured the change in neurocognition of engineering students while they developed concept maps. Concept maps help designers organize complex ideas by illustrating components and relationships. Student concept maps were graded using a pre-established scoring method and compared to their neurocognitive activation. Results show significant correlations between performance and neurocognition. Concept map scores were positively correlated with activation in students' prefrontal cortex. A prominent sub-region was the right dorsolateral prefrontal cortex (DLPFC), which is generally associated with divergent thinking and cognitive flexibility. Student scores were negatively correlated with measures of brain network density. The findings suggest a possible neurocognitive mechanism for better performance. More research is needed to connect brain activation to the cognitive activities that occur when designing but these results provide new evidence for the brain functions that support the development of complex ideas during design.

Introduction

A holistic design approach requires designers to develop a systems point of view [1, 2]. This means understanding the complex and dynamic relationships between components of the problem [2, 3]. Too often, engineers tend to isolate elements of a complex problem and design to optimize these individual elements [4, 5]. Design

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methods and tools that help open designers to see the entire system, rather than the individual pieces, holds the potential to improve their design outcomes.

Concept mapping is one approach to help designers think holistically about components of systems and their relationships. It can improve the engineering design process by helping designers connect new concepts with existing information [6]. Concept mapping works by organizing and graphically representing components and their relationships [7]. Concept maps begin with a main idea and then branch out to show how that main idea is related to other ideas, drawing connections between concepts at various hierarchical levels and from different categories.

Concept maps are also used as an educational tool because they help students learn complex systems [8]. For example, when teaching students about sustainability [9, 10]. Concept mapping coincides with constructivist learning processes. Learners can attain new knowledge by integrating new ideas or concepts with existing ideas that are illustrated within a concept map [6]. However, how connections between ideas are formed in the brain through concept mapping is not well understood. The amount of cognitive effort used for concept mapping certainly plays a role but where this effort occurs in the brain and how brain regions work together to create new concepts and connections is not well known. Better understanding designers' neurocognition when they are constructing concept maps and how this correlates with their performance can provide new indicators for design.

The study presented in this paper measured designers' neurocognition when they developed concept maps, their concept map scores, and the correlation between these two measures. Multiple methods for scoring concept maps are often used to assess designers' ability to think in systems [10, 11]. The most common is counting the number of concepts, cross-links, and the level of hierarchies represented on the maps [1]. Using this technique provides three measures to compare with designers' brain activation. A neuroimaging technique called functional near-infrared spectroscopy was used to capture brain activation when students were drawing a concept map for an engineering design problem. This study provides the correlations between these components of concept maps and their brain activation.

Background

Concept mapping provides an approach to visualize complexities and the interactions between concepts early in the design process [12]. The current understanding of how concept mapping improves design is it creates multiple retrieval paths in the brain for accessing new concepts and information [13]. However, this understanding is based predominantly on observational studies measuring design cognition through think aloud protocols, interviews, and the evaluation of products to infer changes in designers' brains [14, 15]. A limitation of these traditional approaches is the lack of objective measurements of the underlying mechanism of neurocognition.

Methods from neuroscience offer an approach to measure neurocognitive activity during engineering design [16]. This additional layer of information can help explain how tools and techniques, like concept mapping, create novel connections in designers' brains and how these connections correspond with designers generating new concepts. The neurocognitive function that supports a designers' ability to recognize complex relationships and how they use this to create new knowledge is under explored.

Prior literature suggests that concept mapping elicits greater activation in the prefrontal cortex, the region of the brain generally associated with cognitive functions that are involved with designing [11]. What is less understood is how this activation is related to performance. How does ability to recognize complex relationships correlate with cognitive effort? If concept mapping opens new retrieval paths in the brain, is this expressed as more connected brain regions? Establishing a connection between designers' brains and their minds can provide the foundation for future tools and new measures of design effectiveness. The research presented in this paper contributes to this aim by characterizing the neurocognition of designers while concept mapping and how changes in their brain are related to outcomes. The following section outlines the multiple techniques that are often used to observe designers' brain behavior.

Using fNIRS to Explore Neurocognitive Activation and Brain Network

Multiple techniques are available to measure neurocognition, such as functional magnetic resonance imaging (fMRI) [17], electro-encephalography (EEG) [18], and functional near-infrared spectroscopy (fNIRS) [19]. Each technique has its pros and cons. fMRI provides excellent spatial resolution through whole head scanning, but requires participants to lie down in a closed environment without much mobility [20]. EEG has the best temporal resolution, but it is harder to pinpoint the brain region where electrical activity occurs [21]. fNIRS offers relatively good resolution in both space and time, but it is usually limited to measuring activations in the human cortex rather than the whole brain [22].

Considering the nature of engineering design and concept mapping, fNIRS was used in this study because it provided participants a more realistic design environment than fMRI with relatively good spatial resolution of participants' prefrontal cortex. fNIRS measures the change of oxygenated (oxy-Hb) and deoxygenated hemoglobin (deoxy-Hb), also called blood oxygenation level dependent (BOLD) response. BOLD response is a proxy for brain activity [23]. An increase in oxy-Hb typically mirrors more neuronal activity and implies the allocation of resources and nutrients by the cerebrovascular system [24].

The prefrontal cortex (PFC) was the brain region of interest in this study. The PFC is the neural basis of working memory and higher-order cognitive processing, such as sustained attention, reasoning, and evaluations [25]. Based on anatomy and function, the PFC is divided into several sub-regions, including the dorsolateral PFC (DLPFC), ventrolateral PFC (VLPFC), medial PFC (mPFC) and orbitofrontal cortex (OFC),

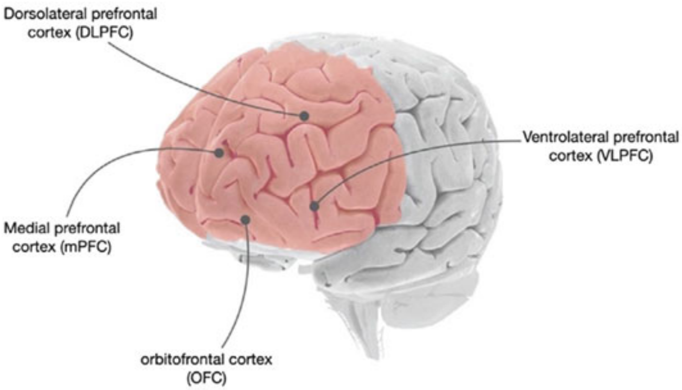


Fig. 1 Prefrontal cortex and its sub-regions [28]

shown in Fig. 1. These sub-regions contribute to different aspects of the cognitive processing in the PFC, and asymmetric cognitive functions are usually identified in the two brain hemispheres [26, 27].

There are several types of analysis used to understand neurocognitive data in neuroimaging studies [29], such as activation analysis (change of activation level) [30], network analysis (functional connectivity among different regions) [28], and interpersonal analysis (activation synchronization between two collaborating subjects) [31]. Activation analysis and network analysis have been used in prior design neurocognitive studies to describe changes in the brain of individual designers [28, 29]. Activation analysis usually compares the activation variables extracted from the BOLD response, such as mean, the area under the curve, kurtosis, time to peak, slope, or the beta coefficients from the general linear models between different subjects or under different conditions [29]. Network analysis calculates the functional correlation and develops the network among the brain regions of interest [29]. Numerous network features, such as network density, clustering coefficient, and efficiency, can be calculated using graph theory to characterize the neural coordination between different brain regions [32].

Brain networks provide an approach to explore functional connectivity and information processing in the brain [33]. Central regions, or nodes, in the brain may facilitate functional interaction and act as a control for information flow as it interacts with many other brain regions [34]. Specific regions or nodes maybe be important, what is not known is whether the size of the functionally connected regions in the brain (i.e., density, clustering coefficient) is correlated to performance.

Brain networks have been used to explore underlying neural correlates of creativity [35]. Yet, little is known about brain functional connectivity during concept generation. Design neurocognition has focused primarily on brain activation [36, 37] more than functional connectivity. The aim in this study was to observe both brain activation and functional connectivity and measure how these are correlated with designers' performance when creating concept maps.

Research Questions

The aim of the research presented in this paper was to understand how neurocognition is related to performance when concept mapping. The specific research questions are:

(1) What is the relationship between concept mapping performance and neurocognition?
(2) What is the relationship between concept mapping performance and neuronetwork coordination?

Methods

Experiment Design

The study was part of a larger project that explored the effects of concept mapping on engineering concept generation. Here we report on the correlation between the concept map scores and neurocognition when developing their concept maps. The Institutional Review Board at Virginia Tech approved the project. Participants were recruited from engineering courses at Virginia Tech. A total of 33 engineering graduate and undergraduate students completed the concept mapping experiment.

Prior to the experiment, engineering students were briefed and trained to use concept maps. This pre-experiment training included a 4-min video introducing concept maps and drawing a concept map to learn and practice how to do it. Engineering students were then outfitted with the fNIRS cap, as shown in Fig. 2a (Shimadzu LIGHTNIRS model). Change in oxygenated hemoglobin (oxy-Hb), a proxy for neurocognitive activity [23], was measured using this fNIRS cap. Figure 2b illustrates the placement of light sensors and channels according to the international 10–20 placement system. The 22 channels captured the change in oxy-Hb in the prefrontal cortex (PFC), covering multiple sub-regions in the PFC.

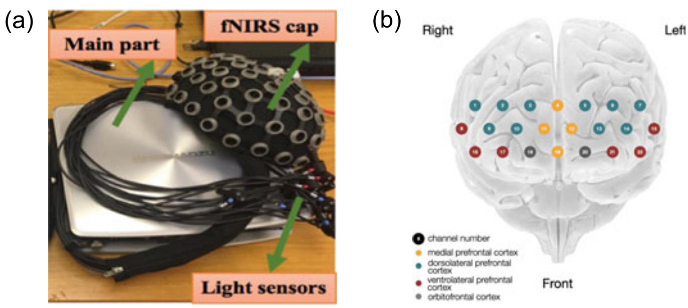


Fig. 2 **a** fNIRS equipment, and **b** prefrontal cortex channel placement

Once the fNIRS instrument began recording change in oxy-Hb, students were instructed to complete a word tracing task prior to concept mapping. The change in oxy-Hb while word tracing was later used as a baseline for activation in their PFC and subtracted from the change in oxy-Hb when developing their concept maps. Participants were then instructed to create a concept map. The instructions were to *Create a concept map illustrating all of the mobility systems on campus. The average time spent on this task is 10 min, but you have as much time as you need to do it. Hit the space bar when you are done reading this prompt and are ready to begin developing your concept map.*

Participants were given as much time as they needed to create their concept maps. PsycoPy was used in the experiment to provide engineering students with timed instructions [38]. The average time length for concept mapping lasted 8.48 min (SD = 4.38 min).

Data Analysis

Each hand-drawn concept map was digitized and all concepts and relationships were coded using the tool CMAP-PARSE [39]. This is a frequently used and previously developed method for scoring concept maps. A limitation of this approach is its quantitative focus. It works by counting the number of concepts (NC), the level of highest hierarchies (HH), and the number of crosslinks (NCL) between different categories [10]. A concept map score (CMS) was determined using Eq. (1). More details about the scoring method can be found in [10]. Each of the variables (NC, HH, NCL, and CMS) were used as an indicator of concept mapping performance. The higher the CMS score the better the performance.

$$\mathrm{CMS} = \mathrm{NC} + 5 * \mathrm{HH} + 10 * \mathrm{NCL} \tag{1}$$

To eliminate noise and motion artifacts, fNIRS's raw data were processed using a bandpass filter (0.01–0.1 Hz, third-order Butterworth filter) and independent component analysis with a coefficient of spatial uniformity of 0.5. The parameters in these steps were selected based on prior research [40, 41]. Filtering was conducted using Shimadzu's fNIRS software. Two out of 33 participants were removed due to bad signals. Baseline correction and z transformation were applied to normalize the data between subjects.

Neurocognitive data were analyzed using two approaches: activation analysis and network analysis. Both are standard approaches to understanding design neurocognition [28, 29]. The activation analysis focused on the change of oxy-Hb in different brain regions when concept mapping. The positive area under the oxy-Hb curve (AUC) when concept mapping (illustrated as the colored area in Fig. 3) was used as a proxy for cognitive load since AUC takes both activation level and time into account. Prior research has also demonstrated that AUC provides a high level of accuracy when classifying the level of cognitive load [42, 43]. The AUC was calculated for each subject when they were developing their concept maps.

Network analysis was used to calculate brain functional connectivity. Pairwise activation (i.e., oxy-Hb) synchronization among the 22 channels for each participant was calculated and represented in a Pearson correlation matrix. A threshold (0.75 was used in this study) was applied to transform the correlation matrix into a binary matrix. Channel pairs with the value "1" in the matrix suggest the high functional connectivity between the two brain regions. The connectivity is represented as an edge linking the two channels in the network figure. Figure 4 presents the process of developing a brain network from the oxy-Hb response. More details on brain network calculations can be found in [28, 32]. Then network features including density, clustering coefficient, and efficiency, were calculated for each participant.

To address Research Question (1), Pearson correlation analysis was performed using the 31 participants that had adequate signal data comparing their concept map performance scores (including each of the concept map variables NC, HH, NCL, CMS) and their neurocognitive activation (AUC) in their prefrontal cortex. To

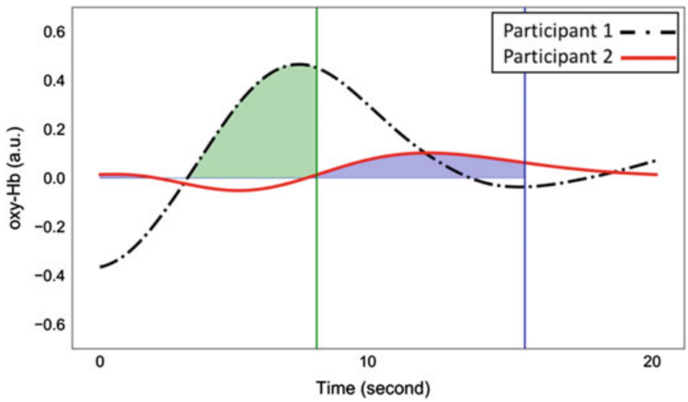


Fig. 3 An example of the positive area under the curve (AUC), where the first vertical lines represent a change in stimuli and the second vertical line represents the end of the task

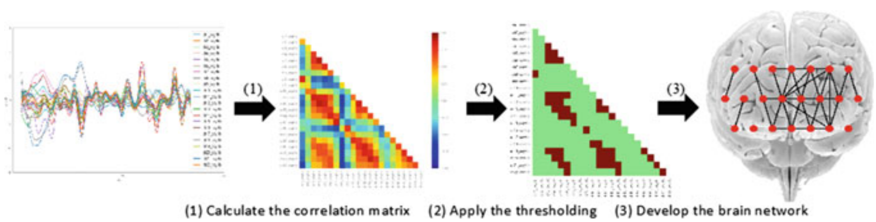


Fig. 4 The process of creating brain network graphs, which is a proxy for functional coordination in the prefrontal cortex

address Research Question (2), Pearson correlation analysis was performed using the 31 participants' concept map performance scores (including the concept map variables NC, HH, NCL, CMS) and network features (density, clustering coefficient, efficiency).

Results

The mean and standard deviation of the number of concepts (NC), highest hierarchy (HH), number of crosslinks (NCL), and concept map scores (CMS) averaged from participants are shown in Table 1. Here, the average concept map score is 89 with 21 concepts, 4 hierarchies, and 4 crosslinks.

Examples from two participants are used to visualize the concept map, activation, and brain network coordination. One of the example participants had a relatively lower CMS (39) and the other had a relatively higher CMS (131) compared to the mean of 89. These participants' concept maps are illustrated in Fig. 5.

Average activation area under the curve (AUC) in the prefrontal cortex (PFC) and the heat map illustrating AUC for both participants is illustrated in Fig. 6. Their brain network features, and brain network graphs are included in Table 4.

The participants with higher performance in concept mapping (i.e., a higher CMS) showed higher cognitive activation (i.e., a higher AUC value). The example participant, who had the high CMS of 131, elicited an AUC value of 2.33. The example participant, who had the low CMS of 39, elicited an AUC value of 1.88. These results were common across participants and suggest a potential relationship between concept mapping performance and neurocognitive activation represented by AUC.

While participants with higher performance in concept mapping (i.e., a higher CMS) showed higher cognitive activation (i.e., a higher AUC value), they also showed a sparser brain network with fewer complexities (i.e., lower values in network features) compared to participants with lower performance in concept mapping. The two example participants are shown in Table 2 and their results are similar to the remaining participants. These results suggest another potential relationship between concept mapping performance and brain network features. The better the concept map performance, the higher the AUC, but sparser the brain network.

Table 1 Students' average concept mapping performance scores

	NC	HH	NCL	CMS
Mean	21.3	4.6	4.5	89.0
Standard deviation	8.72	2.93	5.44	63.40

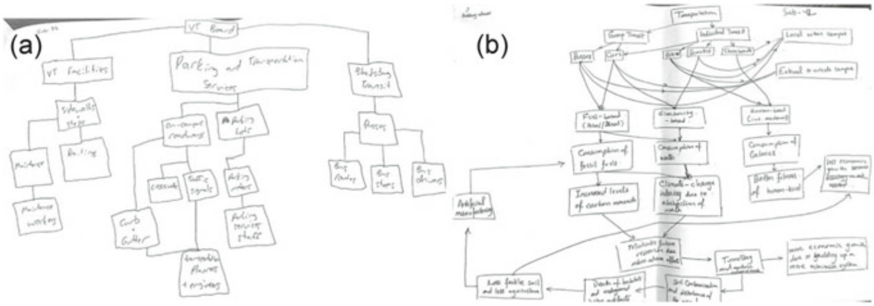


Fig. 5 Examples of concept maps with **a** a low Concept Map Score (CMS) of 39 and **b** a high Concept Map Score (CMS) of 131

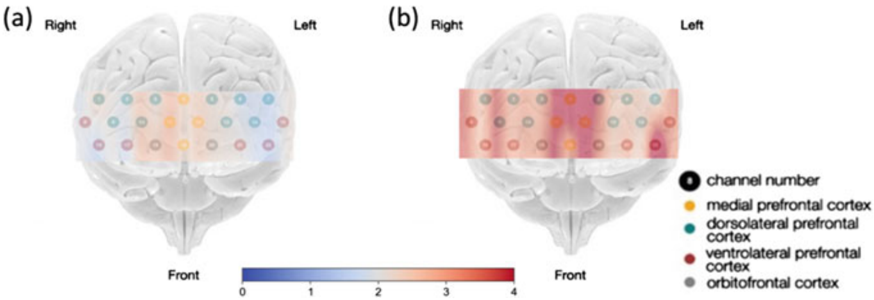


Fig. 6 Example of participants change in AUC: **a** An AUC score of 1.88 for a participant with a low CMS and **b** an AUC of 2.33 for a participant with a high CMS

Table 2 Network features for two participants when developing concept maps

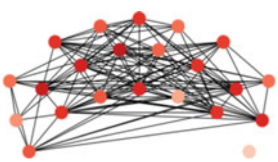
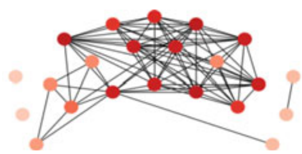
Network	Participant with a lower CMS	Participant with a higher CMS
Density	0.75	0.29
Clust. Coef.	0.87	0.64
Efficiency	0.88	0.55
Graph		

Table 3 Pearson correlation coefficients between brain activation and concept mapping performance (NC is the number of concepts, HH is the highest hierarchy, NCL is the number of crosslinks, and CMS is the concept maps score; *Note* * denotes $p < 0.05$, ** denotes $p < 0.001$)

Brain regions	NC	HH	NCL	CMS
PFC	0.391*	0.035	0.685**	0.650**
Right PFC	0.427*	0.085	0.738**	0.712**
Left PFC	0.353	0.024	0.630**	0.595**
Right DLPFC	0.392*	0.087	0.756**	0.723**
Left DLPFC	0.339	0.077	0.651**	0.624**
Right OFC	0.565**	0.130	0.463*	0.506*
Left OFC	0.453*	−0.011	0.520*	0.507*
Medial PFC	0.348	0.121	0.561*	0.558*
Right VLPFC	0.433*	0.089	0.695**	0.677**
Left VLPFC	0.237	0.036	0.468**	0.443*

Students' Neurocognitive Activation Is Positively Correlated with Their Concept Mapping Performance

Pearson correlation analysis was conducted to better test the relationship between concept mapping performance, cognitive activation, and network features. Concept map performance was measured by the number of concepts (NC), highest hierarchy (HH), number of crosslinks (NCL), and concept maps score (CMS). Each of the variables was compared to sub-regions within the PFC. NC had a significant positive relationship with brain activation across the PFC, specifically, the right PFC, the right dorsolateral PFC (DLPFC), the right orbitofrontal cortex (OFC), the left OFC, and the right ventrolateral PFC (VLPFC). NCL was positively correlated with brain activation in the PFC and all sub-regions. Considering NC weighs most in the CMS, CMS shows a similar positive correlation with brain activation in the PFC and other significant sub-regions. The HH shows no significant correlation with brain activation. The Pearson correlation coefficients are included in Table 3. The most significant correlation between CMS and AUC was in the right DLPFC. These results are also illustrated in Fig. 7a.

Students' Brain Network Features Are Negatively Correlated with Their Concept Mapping Performance

Significant negative correlations were identified between concept mapping performance and the multiple network features among the 31 participants. As Table 4 suggests, correlations between clustering coefficients with HH, NCL, and CMS are significant but negative. Other correlations between network features and concept

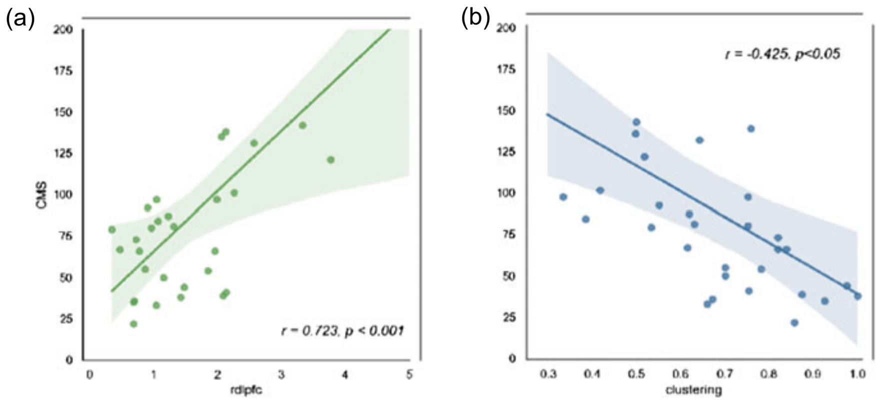


Fig. 7 Significant positive correlation between **a** CMS and brain activation and **b** significant negative correlation between CMS and clustering coefficient

Table 4 Pearson correlation coefficients between network features and concept mapping performance

Network features	NC	HH	NCL	CMS
Density	−0.231	−0.320	−0.289	−0.354
Clustering coefficient	−0.128	−0.404*	−0.370*	−0.425*
Efficiency	−0.218	−0.327	−0.235	−0.307

Note * $p < 0.05$; $p^{**} < 0.001$

mapping performance are also negative but not statistically significant. The most significant correlation between the clustering coefficient and CMS is visualized in Fig. 7b.

Discussion

Neurocognitive activation and the functional network of students' prefrontal cortex (PFC) were different for students with higher and lower concept map scores. Students with higher concept map scores elicited significantly higher overall cognitive effort (i.e., brain activation measured as the positive area under the oxy-Hb curve, or AUC) in their PFC. The PFC plays a critical role in sustaining focused attention and performing executive functions [25]. Higher AUC in the PFC among high concept map achievers is consistent with prior studies from other fields that also measured behavioral performance or task completion [44]. However, activation in the PFC may not always be synonymous with performance. Rather, it may be a better proxy for mental effort [44]. Novices, for example, tend to exert more mental effort for a similar level of task completion as an expert [45].

Designing is more complex than just task completion and this may have an effect on patterns of neurocognitive activation. For instance, novice versus expert designers tend to approach design problems differently [46] and this may also be reflected in brain activation. For example, when brainstorming, first-year engineering students elicited higher brain activation in a region generally associated with divergent thinking whereas senior engineering students, with more experience brainstorming, recruited higher activation in their brains in a region generally associated with uncertainty processing and self-reflection [30].

The most significant differences between students with high and low concept map performance was in their right dorsolateral PFC (DLPFC) and medial PFC. A significant positive correlation was found between the AUC in these sub-regions and the number of concepts and crosslinks that the student designers developed. The right DLPFC is often associated with divergent thinking and cognitive flexibility [47]. This finding echoes those of a prior neurocognitive study that have also found concept mapping elicited higher brain activation in the DLPFC [11]. The medial PFC is often involved in making associations [48]. This cognitive function provides a possible explanation for the positive correlation between AUC in the medial PFC and the number of crosslinks, since crosslinks represent associations between different categories of concepts.

While the increased activation in the right DLPFC and medial PFC was positively correlated with concept map performance, network density, clustering coefficient, and efficiency was negatively correlated with concept mapping performance. This might suggest that new retrieval paths for accessing concepts and making associations between these concepts may not be reflected in the complexity of the brain network (i.e., density and clustering coefficient). Less global coordination across the PFC and greater localized activation within specific sub-regions like the DLPFC and medial PFC may lead to better design performance [11].

These results also present new questions about what happens in designers' brains and how this may affect their designs. For instance, how might these results differ with expert designers? The student designers in this study were not experts in systems thinking, which likely contributed to the positive correlation between cognitive activation and performance. More variability may occur among design experts who may have a higher degree of systems thinking ability than the students or more experience and knowledge to make associations between concepts. Another question is how these student designers' brains may change as their ability to create concept maps improves. A possible explanation is the activation in their right DLPFC, and medial PFC, increase more quickly as they become familiar with this type of design activity and train their brain to perform well on the task. Future research can begin to test this assumption and explore how other tools and techniques shape both brain and designer behavior.

There are several limitations that need mentioning. This study focused on previously established scoring methods to assign concept maps a score. A preliminary analysis of the contents and quality can be found in [49]. The study presented in this paper also only measured the neurocognitive activity in the PFC. This region of interest was selected because of its importance in engineering design and concept generation [28]. Other brain regions are required for this type of cognitive task and maybe equally important for engineering design (e.g., parietal cortex) [11, 50]. However, whole brain scans come with a trade-off in portability and realism in replicating engineering design in an experiment. The sample size of 31 subjects produced good statistical power and met the average sample size of 28 subjects suggested in a systematic review [29], but a future study may consider replicating the experiments with a larger sample size.

Conclusion

Significant brain-behavior correlations were observed when student designers were using concept maps during engineering design. Concept mapping performance, measured using the traditional scoring method, is positively correlated with cognitive activation in the prefrontal cortex (PFC), especially the right dorsolateral PFC. This region is generally associated with divergent thinking and cognitive flexibility. In contrast, concept mapping performance was negatively correlated with functional connectivity across the prefrontal cortex. These opposed relationships might suggest that concept mapping relies more on activation in a specific region, specifically the right DLPFC, rather than coordination between PFC sub-regions.

Understanding how concept mapping performance correlates with neurocognition can begin to help inform pedagogy and design practice for eliciting the underlying neurocognitive patterns that help promote performance. More qualitative-quantitative analysis is also needed to expand how performance of concept maps is being measured. The approach used in this study to measure performance relied on the concept map scores, which were derived using the number of concepts, the level of highest hierarchies, and the number of crosslinks between different categories. This approach did not adequately account for the novelty or quality of the ideas. Future research can consider these additional measures and how they may relate to patterns of neurocognition. In addition, these findings may differ among expert designers compared to novices.

The research reported here presents one aspect of the development of the neural underpinnings of design activity. It forms part of the triangulation for measuring design output (the design), design cognition (the mind) and design neurocognition (the brain). The findings from this research open new questions about how brain behavior and design behavior are related, how this may vary across designers, and what this means for design education. Evaluating a design remains fraught with subjectivity, where the criteria for measurement are not yet fully agreed upon, let alone how to measure those criteria. Measuring design cognition is better developed with several approaches whose results potentially map onto each other. It still contains a mixture of subjective and objective measurements but measuring brain activations during design activities provides an objective result that is independent of the measurer. There is still considerable research needed to connect brain activations and their resultant networks to the cognitive activities that occur during designing. Methods for analyzing brain activity measurements themselves require further development if they are to capture the higher order cognition involved in designing.

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EEG Microstate Characteristics in Product Conceptual Design: Increased Time Coverage of Microstate Class Related to the Default Mode Network

Koji Koizumi, Fukashi Mikami, Kazutaka Ueda, and Masayuki Nakao

In product conceptual design, designers need to produce creative ideas while considering various factors such as the product's function, structure, and behaviour. Which brain activity is more characteristic during product conceptual design compared to when working on general creativity tasks? In this study, we used EEG microstate analysis and compared the brain activity of twelve male students during product conceptual design and general creativity tasks. The EEG was clustered into four typical microstate classes, and the microstate parameters were compared between conditions. As a result, the time coverage of microstate class C suggested to be related to the default mode network, was significantly higher during product conceptual design when compared to that during general creativity tasks. Our findings indicate that product conceptual design may activate semantic memory and devote more time to internal attention and mental simulation. This provides valuable insights into understanding the neural basis of product conceptual design.

Background/Motivation

In the field of cognitive neuroscience, many efforts to elucidate the neural basis behind the production of creative ideas have been made. Much of the research has focused on the cognitive processes behind creativity, namely divergent thinking and convergent thinking. Divergent thinking is the process of generating many ideas or solutions to a problem [1], and the alternative uses task (AUT) [1] is one of the representative tasks to assess this ability. Convergent thinking, on the other hand, is the process of finding a single best idea or solution to a problem [1], and the remote associate task (RAT) [2] is one of the representative tasks to assess this

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ability. To date, neuroimaging studies have clarified the contribution of multiple brain networks to creativity [3]: the default mode network (DMN) supports spontaneous thought such as semantic memory retrieval and mental simulation; the executive control network (ECN) supports deliberate cognitive control such as attentional shift and goal maintenance; and the salience network supports the dynamic switching between the DMN and the ECN.

Creativity is also necessary for product design. Especially, how creativity is demonstrated in the conceptual design, which is the most upstream stage of the product design process, will determine the future of the product. Hence, it is academically meaningful to unravel the neural basis for the creative process of product conceptual design. However, it is not easy to apply existing cognitive neuroscience findings as to the neural basis for product conceptual design because designers need to consider a wide range of matters such as functions, structures, and behaviours required for a product [4]. Thus, it is important to clarify the specificity of the neural basis of the product conceptual design.

To date, various brain activity measurement methods such as functional magnetic resonance imaging (fMRI), functional near-infrared spectroscopy (fNIRS), and electroencephalography (EEG) have been used in design studies [5]. In particular, the increasing number of studies using EEG, due to its usability and high temporal resolution, has made a significant contribution to the field. For example, the beta and gamma band EEG powers have been associated with the design activities [6, 7], and the open-ended design has been characterised by higher alpha power in the temporal and occipital regions [8]. The activation of ventral and dorsal streams during visual attention and the activation of prefrontal, frontocentral, and parietooccipital regions during their visual association have been reported using EEG [9]. Gender commonalities and differences in brain activity of professional designers during design tasks have been reported [10], and a study of industrial designers and mechanical engineers [11] reported higher neurophysiological activation during the open-ended sketch design compared to the problem-solving layout design. Temporal analysis of frequency band power has revealed increased theta, alpha, and beta band power in the open-ended sketch design [12]. As various cognitive processes are involved in the product conceptual design [13], and the cognitive state changes over time, analysis utilising the high temporal resolution of EEG, such as the study of Vieira et al. [12], would be useful in understanding the neural basis of creative process.

Microstate analysis that segments EEG signals into 60–120 ms metastable states is another analysis method making use of the high temporal resolution of EEG [14]. Four typical microstates with different physiological meanings have been reported in numerous studies [15]. Britz et al. [16] suggested that microstate class A is related to verbal/phonological system, microstate B to the visual system, microstate C to the DMN, and microstate class D to the dorsal attention network. To contradict this, Milz et al. [17] reported that the higher coverage of microstate class A during visualisation and the higher coverage of microstate class B during verbalisation. Further research is needed to elucidate this contradiction. Nevertheless, microstate analysis is a promising method for exploring the neural basis of product conceptual design because it can estimate cognitive states by making good use of temporal brain activity information. Previous design studies [18, 19] have used the microstate parameters to quantitatively assess effort, fatigue, and concentration during conceptual design. Jia et al. [20] used microstate analysis and reported that the DMN was more active during idea evolution and the cognitive control network was more active during idea evaluation. In a recent study, they reported a prevalence of microstate classes C and D during idea generation and idea evaluation, but the relationship between the conditions of idea generation and idea evaluation remains unclear [21].

As described so far, our understanding of the neural basis of product conceptual design, which requires creativity, has deepened by the results of numerous EEG design studies. However, in order to clarify the neural activity specific to creativity in product conceptual design, it is necessary to investigate how it differs from the general creativity assessed by commonly used creativity tasks. In a preliminary study, Nguyen et al. [7] compared brain activity in intuition-based and more complex, creative designs. However, they used a modified version of a general creativity task, which is difficult to interpret as brain activity in product conceptual design.

Aims and Hypotheses

This study aims to investigate the brain activity specific to product conceptual design. To that end, we used microstate analysis to capture the temporal dynamics of brain states and compare participants' brain activity during product conceptual design and general creativity tasks, in divergent thinking and convergent thinking. Our results contribute to elucidating the neural basis of product conceptual design.

In product conceptual design, it is necessary to consider various matters such as functions, structures, and the behaviours required for products, using the knowledge stored within the designer's memory. Thus, we hypothesised that the parameters of microstate class C would increase during product conceptual design compared to during general creativity tasks.

Method

Participants

The minimum sample size was estimated from a priori power analysis using G*Power 3.1.9.7 (two-way repeated measures ANOVA; effect size $f = 0.4$; $\alpha = 0.05$; $1 - \beta = 0.8$; number of groups = 1; number of measurements = 4 (2 (product conceptual design /general creativity task) × 2 (divergent/convergent thinking). The results showed that a sample size of 10 was adequate to attain reliable data. Twelve healthy male students (22.8 ± 0.8 years old, all right-handed) participated in the experiment. They all belonged to the mechanical engineering department and had taken classes on engineering design in the past. The research was approved by the Research Ethics Committee of the Graduate School of Engineering of the University of Tokyo (approval number: KE20-55). Participants were informed of the study's purpose, and they provided their consent in writing.

Experimental Design

This experiment aimed to investigate the brain activity specific to product conceptual design. However, interpretation of the microstate classes has not been established (e.g., the relationship between micro-state classes A/B and language/visual functions [16, 17]). Therefore, we also conducted non-creativity tasks based on Milz et al. [17]. We first compared the results of non-creativity tasks with each other like Milz et al. [17], interpreted the thinking modalities of the microstate classes obtained from our sample, and then used them to discuss the results of the creativity task. The rest condition (Rest) was placed at the beginning and end of the experiment. During REST, participants were asked to relax for 60 s while looking at a fixed viewpoint in the centre of the monitor. Six tasks were conducted, and the flow of one problem for each task is shown in Fig. 1a.

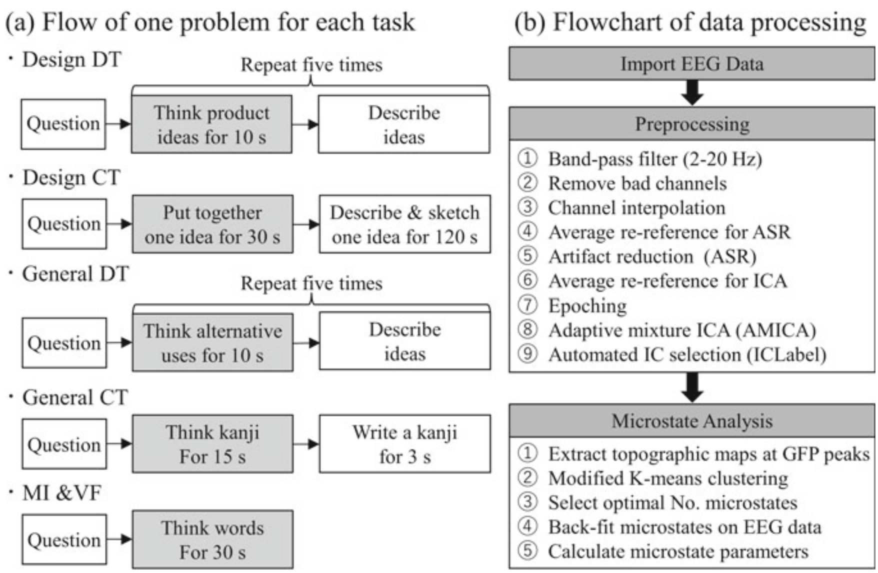

Fig. 1 **a** Flow of one problem for each task. The periods highlighted were extracted for EEG analysis. **b** Flowchart of data processing. DT, divergent thinking; CT, convergent thinking; MI, manipulation imagery; VF, verbal fluency

(1) ***Product conceptual design task requiring DT (Design DT)***

We translated the ideation task focused on open-ended problems used in Hay et al. [22] into Japanese and selected five problems that are familiar to Japanese people (e.g., designing a product concept that would reduce unnecessary food waste at home under conditions of global food shortages and socioeconomic instability). After a problem sentence was presented on the monitor, the participants were asked to think of as many ideas as possible for 10 s while looking at the fixed viewpoint in the centre of the monitor. After that, they were asked to describe all ideas they came up with on the answer sheet. The process was repeated five times for each design problem. In later EEG analysis, 10 s of thinking periods were extracted as the epoch target. The epochs for which there were no responses in the description period were omitted from the epoch analysis.

(2) ***Product conceptual design task requiring CT (Design CT)***

The participants were asked to put together a single product concept for 30 s, looking at the multiple product idea concepts written out in the Design DT. They then described and sketched that product concept on the answer sheet in two minutes. In later EEG analysis, 30 s of thinking periods were extracted as the target epoch.

(3) ***AUT as a general divergent thinking task (General DT)***

Five commodities (a rubber balloon, socks, a brick, a can and a CD-ROM) were selected as the objects for the five problems of thinking of as many unusual uses as possible for the objects [1]. The task flow was similar to that of Design DT. In later EEG analysis, 10 s of thinking periods were extracted as the epoch target. The epochs for which there were no responses in the description period were omitted from the epoch analysis.

(4) ***RAT as a general convergent thinking task (General CT)***

We selected 12 problems from the Japanese version of the RAT [2, 23]. In this task, a total of six kanji characters, three on top and three on the bottom were presented on the monitor. The participants were asked to think of a second kanji forming three two-kanji words that made sense with the top three kanji as the first character. The participants were asked to think of the second kanji for 15 s while looking at the six kanji presented. They then wrote the second kanji they came up with on the answer sheet. In later EEG analysis, 15 s of thinking periods were extracted as the target epoch. The epochs for which there were no responses in the answering period were omitted from the analysis.

(5) ***Manipulation imagery task (MI) as a non-creativity visual imagery task***

We translated the manipulate task used in Hay et al. [22] into Japanese and selected five familiar problems to the Japanese people (e.g., At construction sites, vehicles and equipment of various sizes perform various functions. Produce detailed mental images of construction vehicles or equipment in which selected features are rotated/resized.). After a problem sentence was presented on the monitor, the participants were asked to produce a detailed mental image for 30 s while looking at the fixed viewpoint in the centre of the monitor. In later EEG analysis, 30 s of mental imaging periods were extracted as the target epoch.

(6) ***Verbal fluency task (VF) as a non-creativity task requiring verbal ability***
VF task measures how many words beginning with a specified letter can be spontaneously generated within a time limit. The five hiragana characters ("ko", "ka", "ki", "shi" and "a") were selected for the five problems. After a hiragana character was presented on the monitor, the participants were asked to imagine as many words as possible for 30 s while looking at the fixed viewpoint in the centre of the monitor. In later EEG analysis, 30 s of imaging words periods were extracted as the target epoch.

The order of tasks was counterbalanced among the participants in the experiment under the restriction that DT was followed by CT (Design DT −> Design CT/General DT −> General CT). To reduce the impact of participant fatigue on the results, a break was taken after every two tasks. The EEG measurement took approximately 1 h 45 min per participant.

EEG Data Acquisition and Processing

EEG signals were recorded using the BrainAmp DC (Brain Products) and Brain Vision Recorder (Brain Products) at a sampling rate of 500 Hz. The active electrodes of the ActiCap (Brain Products) were located at 32 positions over the whole head according to the International 10–20 system (Fp1/2, F7/8, F3/4, Fz, FT9/10, FC5/6, FC1/2, T7/8, C3/4, Cz, CP5/6, CP1/2, TP9/10, P7/8, P3/4, Pz, O1/2, and Oz). The ground electrode was Fpz, and the reference electrode was FCz.

The data were analysed offline using MATLAB 2021b and EEGLAB version 2021.1. Flowchart of data processing is shown in Fig. 1b. Using the FIR filter, the EEG signals were band-pass filtered between 2 and 20 Hz. The channels exhibiting flat signals for longer than 5 s and the channels poorly correlated to the surrounding channels (less than 0.8) were automatically removed. The removed channels were interpolated using a spherical spline interpolation algorithm. EEG data were then re-referenced to the common average reference. Electrooculographic (EOG) and electromyographic (EMG) artefacts were reduced using the Artifact Subspace Reconstruction (ASR) method. The ASR threshold was set at 10 standard deviations with all other parameters turned off. EEG data were then re-referenced to the common average reference again for independent component analysis (ICA). EEG data epochs during rest (60 s $\times$ 2 epochs), design DT (10 s $\times$ number of answered epochs), design CT (30 s), general DT (10 s $\times$ number of answered epochs), general CT (15 s $\times$ number of answered epochs), MI (30 s $\times$ 5 epochs) and VF (30 s $\times$ 5 epochs) were extracted. Consecutively, adaptive mixture ICA (AMICA) was applied to each epoched EEG data and ICLabel version 1.3 was used to label the independent components (ICs) into seven categories (brain, muscle, eye, heart, etc.) automatically. Finally, the EEG data were reconstructed using only ICs corresponding to the brain.

The Microstate EEGlab toolbox (MST 1.0) was used for microstate analysis. First, a total of 1000 EEG topographical maps at the peak of global field power (GFP) were randomly extracted for each participant and concatenated within each condition. The GFP was calculated as the standard deviation across all electrodes at a given moment based on Eq. (1).

$$GFP(t) = \sqrt{\frac{\sum_{i=1}^{N_E}(v_i(t)-\overline{v}(t))^2}{N_E}}\# \tag{1}$$

N_E denotes the number of electrodes. $v_i(t)$ is the electric potential of the EEG signal at the electrode i at time instant t. $\overline{v}(t)$ is the average electric potential at time instant t. Secondly, based on the extracted EEG maps at the GFP peaks, the modified K-means clustering algorithm was applied to identify the microstate classes. We set the number of microstates to cluster the EEG data into two to eight microstate prototypes. The number of random initialisations was set to 50, and the maximum number of iterations was 1000. The optimal number of microstates classes for each condition was selected by minimising the cross-validation criterion (CV) [24] and maximising the global explained variance (GEV). CV calculated as Eq. (2) is related to the residual noise, and the goal is to minimise the value of CV.

$$CV(K) = \widehat{\sigma}^2\left(\frac{N_E-1}{N_E-1-N_K}\right)^2\# \tag{2}$$

$$\widehat{\sigma}^2 = \frac{\sum_{t=1}^{N_T}\left(V(t)^T V(t)-\left(V(t)^T\cdot\Gamma_k(t)\right)^2\right)}{N_T(N_E-1)}\# \tag{3}$$

$\widehat{\sigma}^2$ is an estimator of the residual noise variance. N_K is the number of microstate classes. N_T is the number of time samples. $V(t)$ is a $N_E \times 1$ vector consisting of the electric potential at time instant t. $\Gamma_k(t)$ is a $N_E \times 1$ vector representing the prototypical map for the k-th microstate class at time instant t. GEV is a measure of how well the given microstates explain the variance across the data and calculated as:

$$GEV = \frac{\sum_{t=1}^{N_T}(GFP(t)\cdot Corr(V(t),\Gamma_k(t)))^2}{\sum_{t=1}^{N_T}GFP(t)^2}\# \tag{4}$$

The optimal number of microstate classes was five for the VF condition and four for all other conditions. Therefore, the number of microstate classes was defined as four for each condition. To compare the conditions, the microstate classes were sorted and labelled as A, B, C, and D according to Michel & Koenig [15]. Then, the global microstate classes of topographical maps were calculated by averaging the classes of topographical maps for each class over all conditions. The four global microstates obtained in this manner were fitted back to all the EEG data. In this back-fitting process, each original EEG topographical map was assigned to the class of the global microstate it was the most similar with. To temporally smooth the microstate sequences, small segments of microstate less than 30 ms were rejected and changed to the next most likely class. The temporal smoothing was done until no microstate segments were smaller than 30 ms. For each condition, each participant, each epoch, and each microstate, the following parameters were calculated; duration: the average length of time that each microstate remains stable when it occurs; occurrence: the average number of times that each microstate occurs per second; coverage: the percentage of the total recording time covered by each microstate. The calculated parameter values of a microstate were averaged among epochs within the same participant. Firstly, microstate parameters between rest, MI, and VF conditions were extracted and compared to the results of Milz et al. [17]. Then, the microstate parameters of the four creativity conditions were compared.

Statistical Analysis

Statistical analyses were conducted using R version 4.1.2. Paired *t*-tests were performed to compare the microstate parameters for the three non-creative conditions. A total of three $2 \times 2 \times 4$ repeated measures analyses of variance (rmANOVA) tests were conducted on the three microstate parameters. In each rmANOVA test, the manipulated factor was the Type of creative thinking (Design or General), the manipulated factor was the thinking Process (DT or CT), and the measured factor was the microstate Class (A, B, C, or D). The significance level was set to $\alpha = 0.05$. Partial eta squared estimation of effect sizes ($\eta_P{}^2$) was estimated, and its confidence intervals were calculated using a 2000-replication bootstrap. When a significant interaction between factors was observed, the simple main effect test was performed for Type $\times$ Class and Process $\times$ Class interactions. Post-hoc paired *t*-tests were conducted with Holm- Bonferroni correction.

Results

The obtained four microstate maps were characteristically consistent with the four typical microstate maps reported in many previous studies [15]. The global topographical maps of the four microstate classes and those in each condition were shown in Fig. 2.

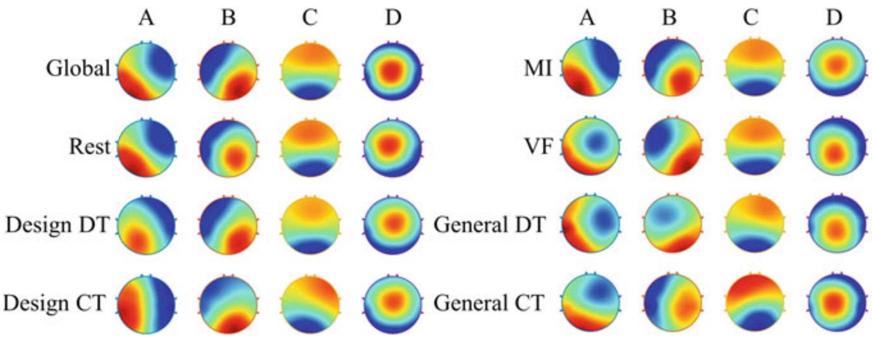

Fig. 2 The four microstate classes for across conditions (global) and in each condition. DT, divergent thinking; CT, convergent thinking; MI, manipulation imagery; VF, verbal fluency

Changes of Microstate Parameters in Non-Creative Conditions

The results of paired *t*-tests revealed a significant decreased occurrence of microstate class C during VF compared to MI ($t\,(11) = -4.465$, $dz = 1.289$, $p = 0.001$, 95% CI [−0.120, −0.353]), significantly decreased occurrence of microstate class D during MI compared to Rest ($t\,(11) = -4.169$, $dz = 1.203$, $p = 0.002$, 95% CI [−0.105, −0.339]), and a significant decreased in the coverage of microstate class D during MI compared to Rest ($t\,(11) = -4.025$, $dz = 1.162$, $p = 0.002$, 95% CI [−0.009, − 4.025]). On the other hand, the coverage of microstate class C was significantly increased during MI compared to Rest ($t\,(11) = 4.360$, $dz = 1.259$, $p = 0.001$, 95% CI [0.054, 0.018]).

Table 1 summarises all the changes and trends ($p < 0.05$, $p < 0.10$, no correction for multiple testing based on Milz et al. [17]) in the microstate parameters between the three conditions (MI, VF, and Rest). In Table1, the cells of the results consistent with Milz et al. [17] were shaded in orange, and inconsistent results were shaded in blue.

Table 1 Microstate parameter changes between MI, VE, and Rest

Conditions	Duration				Occurrence				Coverage			
	A	B	C	D	A	B	C	D	A	B	C	D
MI → VF		**↗**					**↘**	**↗**			**↘**	↗
Rest → MI			**↗**	↘	**↘**	↘	**↗**	**↘**			**↗**	**↘**
Rest → VF			**↗**									

Differences at $p < 0.10$ are depicted by arrows; arrows for $p < 0.05$ are in bold (no correction for multiple testing like Table 5 in Milz et al. [17]); arrows for corrected $p < 0.05$ (Holm-Bonferroni correction) are in red. ↗ microstate parameter increases. ↘ microstate parameter decreases. Cells of the results consistent with Milz et al. [17] were shaded in orange, and inconsistent results were shaded in blue. MI, Manipulation Imagery; VF, Verbal Fluency

Changes of Microstate Parameters Among Creative Conditions

Duration

The means and the standard deviations of microstate duration of each task are shown in Table 2. The ANOVA result is shown in Table 3. The interaction effects of Type × Process and Type × Class were significant and the effect sizes were small. The simple main effect test revealed that there was statistically non-significant difference between Design and General in each microstate class. There was a significant interaction effect of Process × Class. The simple main effect test revealed that microstate class C had a longer duration during DT compared to CT ($F(1,11) = 16.379$, $p = 0.002$, $\eta_P^2 = 0.598$, 95% CI [0.259, 0.752], $\eta_G^2 = 0.164$). Post-hoc paired *t*-test revealed a statistically non-significant increase during Design DT compared to Design CT and a significant increase during General DT compared to General CT (Table 4).

Table 2 Means and standard deviations of microstate duration of each task

Microstate class	Mean ± Standard deviation (ms)			
	Design DT	General DT	Design CT	General CT
A	68.390 ± 3.249	69.335 ± 2.688	69.094 ± 4.117	70.694 ± 2.964
B	68.350 ± 3.716	68.707 ± 3.395	67.689 ± 3.308	70.173 ± 3.845
C	84.277 ± 11.024	82.533 ± 9.209	77.348 ± 6.324	75.056 ± 6.586
D	71.952 ± 4.090	71.491 ± 4.623	70.214 ± 3.999	73.203 ± 4.347

DT, divergent thinking; CT, convergent thinking

Table 3 ANOVA result of microstate duration

Source	*df*	*F*	*p*	η_P^2	η_P^2 95% CI	η_G^2
Type (design or general)	1	1.026	0.333	0.085	[0.000, 0.609]	0.012
Process (DT or CT)	1	3.828	0.076	0.258	[0.012, 0.550]	0.011
Class (A, B, C, or D)	3	14.435	0.000*	0.568	[0.363, 0.723]	0.396
Type × Process	1	7.629	0.019*	0.410	[0.038, 0.741]	0.003
Type × Class	3	4.439	0.010*	0.288	[0.028, 0.568]	0.011
Process × Class	3	8.979	0.000*	0.449	[0.161, 0.636]	0.057
Type × Process × Class	3	1.136	0.349	0.094	[0.001, 0.260]	0.003

$^*p < 0.05$. DT, divergent thinking; CT, convergent thinking

Table 4 Microstate class C duration change between DT and CT

Conditions	*t* (11)	*dz*	*p* (corrected *p*)		95% CI
Design DT → Design CT	3.056	0.882	0.011 (0.077)	↘	[1.939, 11.920]
General DT → General CT	4.433	1.280	0.001 (0.008*)	↘	[3.765, 11.190]

Differences at $p < 0.10$ are depicted by arrows; arrows for $p < 0.05$ are in bold (no correction for multiple testing like Table 5 in Milz et al. [17]); arrows for * corrected $p < 0.05$ (Holm-Bonferroni correction) are in red. ↗ duration increases. ↘ duration decreases. DT, divergent thinking; CT, convergent thinking

Occurrence

The means and the standard deviations of microstate occurrence of each task are shown in Table 5. The ANOVA result is shown in Table 6. The interaction effect of Type × Process was significant and its effect size was very small. There was no significant interaction effect for Type × Class and Process × Class.

Table 5 Means and standard deviations of microstate occurrence of each task

Microstate class	Mean ± Standard deviation (times/s)			
	Design DT	General DT	Design CT	General CT
A	3.128 ± 0.322	3.207 ± 0.298	3.299 ± 0.363	3.305 ± 0.338
B	3.155 ± 0.267	3.175 ± 0.251	3.407 ± 0.202	3.240 ± 0.235
C	3.889 ± 0.305	3.809 ± 0.352	3.824 ± 0.263	3.688 ± 0.310
D	3.373 ± 0.317	3.415 ± 0.285	3.446 ± 0.266	3.543 ± 0.370

DT, divergent thinking; CT, convergent thinking

Table 6 ANOVA result of microstate occurrence

Source	*df*	*F*	*p*	η_P^2	η_P^2 95% CI	η_G^2
Type (design or general)	1	0.545	0.476	0.047	[0.000, 0.400]	0.001
Process (DT or CT)	1	4.803	0.051	0.304	[0.020, 0.598]	0.010
Class (A, B, C, or D)	3	12.547	0.000*	0.533	[0.296, 0.714]	0.378
Type × Process	1	6.305	0.029*	0.364	[0.012, 0.719]	0.002
Type × Class	3	2.624	0.067	0.193	[0.013, 0.322]	0.010
Process × Class	3	2.821	0.054	0.204	[0.013, 0.513]	0.018
Type × Process × Class	3	0.664	0.580	0.057	[0.001, 0.172]	0.003

*$p < 0.05$. DT, divergent thinking; CT, convergent thinking

Coverage

The means and the standard deviations of microstate coverage of each task are shown in Table 7. The ANOVA result is shown in Table 8. The interaction effect of Type × Class was significant and its effect size was small. The simple main effect test indicated that the coverage of microstate class C was higher during Design compared to General (F (1,11) = 8.611, p = 0.014, $\eta_P{}^2$ = 0.439, 95% CI [0.032, 0.792], $\eta_G{}^2$ = 0.028). Post-hoc paired t-test revealed a statistically non-significant increase during Design CT compared to General CT and a non-significant increase during Design DT compared to General DT (Table 9).

The interaction effect of Process × Class was significant and its effect size was medium. The simple main effect test was applied and showed that the coverage of microstate class B was higher during CT compared to DT (F (1,11) = 13.089, p = 0.004, $\eta_P{}^2$ = 0.543, 95% CI [0.124, 0.773], $\eta_G{}^2$ = 0.073). Post-hoc paired t-test revealed a statistically non-significant increase during Design CT compared to Design DT and a non-significant increase during General CT compared to General DT (Table 9). On the other hand, the coverage of microstate class C was higher during DT compared to CT (F (1,11) = 9.116, p = 0.012, $\eta_P{}^2$ = 0.453, 95% CI [0.028, 0.757], $\eta_G{}^2$ = 0.116). Post-hoc paired t-test revealed a statistically non-significant increase during Design DT compared to Design CT and a non-significant increase during General DT compared to General CT (Table 9).

Table 7 Means and standard deviations of microstate coverage of each task

Microstate class	Mean ± Standard deviation (%)			
	Design DT	General DT	Design CT	General CT
A	21.411 ± 2.578	22.256 ± 2.344	22.926 ± 3.686	23.404 ± 3.028
B	21.545 ± 2.294	21.821 ± 2.334	23.115 ± 2.384	22.798 ± 2.492
C	32.741 ± 5.347	31.476 ± 5.354	29.684 ± 4.160	27.783 ± 4.442
D	24.303 ± 3.194	24.447 ± 3.324	24.275 ± 3.092	26.016 ± 3.719

DT, divergent thinking; CT, convergent thinking

Table 8 ANOVA result of microstate coverage

Source	*df*	*F*	*p*	$\eta_P{}^2$	$\eta_P{}^2$ 95% CI	$\eta_G{}^2$
Type (design or general)	1	0.000	1.000	0.000	[–, –]	0.000
Process (DT or CT)	1	0.000	1.000	0.000	[–, –]	0.000
Class (A, B, C, or D)	3	14.685	0.000*	0.572	[0.343, 0.748]	0.462
Type × Process	1	0.000	1.000	0.000	[–, –]	0.000
Type × Class	3	3.676	0.022*	0.250	[0.028, 0.465]	0.010
Process × Class	3	6.079	0.002*	0.356	[0.079, 0.631]	0.041
Type × Process × Class	3	0.771	0.519	0.066	[0.001, 0.153]	0.002

*p < 0.05. DT, divergent thinking; CT, convergent thinking

Table 9 Microstate coverage change between conditions

Microstate class B					
Conditions	*t (11)*	*dz*	*p* *(corrected p)*		*95% CI*
Design DT → Design CT	1.725	0.498	0.112 (0.450)		[−0.004, 0.019]
General DT → General CT	2.344	0.677	0.039 (0.233)	↗	[0.001, 0.019]
Microstate class C					
Conditions	*t (11)*	*dz*	*p* *(corrected p)*		*95% CI*
Design DT → General DT	1.575	0.455	0.144 (0.861)		[−0.005, 0.030]
Design CT → General CT	2.556	0.738	0.027 (0.214)	↘	[0.003, 0.035]
Design DT → Design CT	2.381	0.687	0.036 (0.255)	↘	[0.002, 0.059]
General DT → General CT	3.049	0.880	0.011 (0.088)	↘	[0.010, 0.064]

Differences at $p < 0.10$ are depicted by arrows; arrows for $p < 0.05$ are in bold (no correction for multiple testing like Table 5 in Milz et al. [17]); arrows for * corrected $p < 0.05$ (Holm-Bonferroni correction) are in red. ↗ coverage increases. ↘ coverage decreases. DT, divergent thinking; CT, convergent thinking

Discussion

Herein, we used microstate analysis to investigate the brain activity specific to the product conceptual design. In the first half of the microstate analysis section, we compared non-creative conditions and found that the occurrence and coverage of microstate class C were significantly higher, while the occurrence and coverage of microstate class D were significantly lower during the manipulation imagery. In the second half of the main microstate analysis section, as hypothesised, we found that the coverage of microstate class C was significantly higher during the product conceptual design compared to the general creativity tasks. Additionally, the duration and coverage of microstate class C were higher and the coverage of microstate class B was lower during divergent thinking compared to convergent thinking.

Interpretation of the Thinking Modalities of Each Microstate Class Following the Results of the Non-Creativity Task (Rest, MI, and VF)

First, we used Milz et al. 's [17] experiment as a reference to compare the microstate parameters in a non-creative experiment, but we differed from them in that the participants had their eyes open. Seitzman et al. [25] reported that whether the eyes are open or not affects all microstate class parameters. Therefore, it is possible that the discrepancy between the present results and those of Milz et al. [17] is due to the open/closed state of the eyes, while the agreement between our results and theirs is a feature that is not affected by the open/closed state of the eyes.

The non-significant decrease in the occurrence of microstate class A during MI compared to Rest may be due to increased visual processing and decreased verbal processing during MI [16]. In other words, a decrease in the parameters of microstate class A may be related to increased visual processing. However, Milz et al. [17] argued that microstate class A is observed more during visualisation, reflecting activation of the left posterior hub that triggers suppression of connected left hemisphere regions associated with language processing. This discrepancy arises the need for further study.

The non-significant decrease in the parameters of microstate class B during MI compared to the other conditions supports the suggestion of Milz et al. [17] that the right posterior source of microstate class B reflects the activation in the right-posterior hub. This leads to the triggering suppression of the connected right hemisphere regions associated with visuospatial processing. In other words, the decrease in the parameters of microstate class B may be related to the increase in visual processing.

For microstate class C, both MI and VF showed a non-significant increase in the duration compared to Rest. Although the increase during MI seems to contradict the report of Milz et al. [17], this may be due to the difference in the visual imagery task used. In contrast to Milz et al. [17], who presented participants with images immediately prior to visual imagery, the current experiment was designed to make participants evoke visual imagery from their memory without showing them pictures. Additionally, considering that the design of the present VF task involved retrieving a word with a certain initial hiragana letter from one's memory, increased duration of microstate class C may reflect memory retrieval, which is the process of long-term memory retrieval. Pascual-Marqui et al. [26] estimated that the anterior and posterior cingulate cortices, the main hubs of the DMN, are the sources of microstate class C. Additionally, the posterior cingulate cortex has been suggested to be associated with memory retrieval [27]. In our study, MI showed increased occurrence and coverage compared to Rest and VF. Considering that in MI, the participants imagined their manipulation of the features of the object, increased occurrence and coverage of microstate class C may reflect the activation of semantic memory and the increase of internally directed attention and mental simulation. Several previous studies have suggested a relationship between microstate class C, DMN and semantic memory

[28, 29]. The DMN is closely related to internal attention and mental simulation [3, 30]. These findings of previous studies support our consideration.

For microstate class D, the higher levels of both occurrence and coverage for VF and Rest compared to MI can be attributed to the difference in the frequency of attentional switching. During MI, participants pay attention to a single image object to be manipulated. In contrast, during VF, they recall words starting with a specific single letter one after another, so attention shifts frequently occur between words. As for Rest, which was significantly higher than MI, it is also consistent with a previous report that microstate class D, which has reflexive aspects of attention and focus switching, can appear more frequently during Rest compared to goal-directed tasks [16].

The following summarises the interpretation of the thinking modality of the microstate parameters obtained in this study.

- Decreased microstate classes A and B parameters may reflect an increase in visual processing.
- Increased duration of microstate class C may reflect an increase in memory retrieval.
- Increased occurrence and coverage of microstate class C may reflect the activation of semantic memory and an increase in internal attention and mental simulation.
- Increased occurrence and coverage of microstate class D may reflect an increase in attention switching.

Differences in Microstate Parameters Between the Creativity Tasks

The coverage of microstate class C closely related to DMN was significantly higher during the Design than the General tasks, especially in CT (Table 9). The DMN plays an important role in generating ideas, including semantic memory retrieval and internal attention in creative thinking [3]. In a previous design study [9], the activation of DMN has been reported when designers engage visual associations closely related to visual retrieval, imagination, and mental simulation. Furthermore, increased alpha band power, which is strongest in the frequency range of microstate analysis (2–20 Hz), has been found during creative idea generation [31] and related to top-down processing or heightened internal attention in convergent and divergent thinking [32]. Design research has also suggested a link between the generation of design concepts and EEG alpha rhythm [8, 12]. Based on the findings from these previous studies and the interpretation of increased microstate class C coverage in the previous section, it can be inferred that semantic memory was more activated, and internal attention and mental simulation were increased in Design CT compared to General CT.

The General CT (RAT) is a common closed-end convergent thinking task that produces one correct answer to a problem [2]. The Design CT also requires a convergent thinking process in terms of putting together multiple ideas into one design concept. On the other hand, Design CT is also an ill-defined or open-ended problem in generating the final product conceptual design, requiring free thinking about which product concepts to combine, how to put them together, and what to do with the physical structure and behaviour to satisfy the required functions. Like this Design CT, design problems are typically ill-defined or open-ended [33, 34]. In this respect, in Design CT, greater activation of the DMN, which is closely associated with semantic memory, internal attention, and mental simulation, is reasonable and can be considered a distinguishing characteristic compared to General CT. It is also possible that, in Design DT, semantic memory was more activated, and internal attention and mental simulation were more increased than in General DT, in that various matters such as product function, structure and behaviour had to be considered. However, there was no significant difference in the coverage of microstate class C, which needs further validation.

Regardless of the Type (Design or General), the microstate class C was higher during DT compared to CT for both duration and coverage (Table 9). Our result is consistent with the results of design studies that reported an increase in microstate class C parameters during idea generation and idea evolution [20, 21]. Activation of the DMN in divergent thinking has been previously reported in many creativity studies [3, 35], supporting the present results. Furthermore, the α-band power, which is strongest in the target frequencies of microstate analysis, is characterized by top-down processing and memory processes such as the efficient combination of unrelated semantic information [31]. In design research, increased EEG alpha power in open-ended design problems has previously been reported [8, 12], and the DMN is also related to visual association [9]. Furthermore, it has been suggested that the ECN, which acts in opposition to the DMN, is activated in tasks that require externally directed attention, such as relational integration and working memory [3]. Both Design CT and General CT had in common that they required external attention to objects: multiple product concepts for Design CT and kanjis for General CT. From the findings of previous studies and the interpretation of the microstate parameters of class C in the previous section, it can be inferred that semantic memory was more activated, and internal attention, memory retrieval, and mental simulation were increased during DT than in CT.

Additionally, in this study, it was found that the coverage of microstate class B was higher during CT than in DT. The interpretation of microstate class B in the previous section and the previous report of negative association between microstate class B and activation of the extrastriate cortex [16] suggest that visual processing increased more in DT than in CT. In creativity research, the activation of the extrastriate cortex has been reported during the AUT [36]. Furthermore, visual attention is closely related to extrastriate cortex and can bias the selection of information objects, such as specific features or locations [37]. In this respect, visual attention is critical for creativity [9], and it can be considered that DT, which requires as many ideas for objects as possible on the subject of commodities or products, prompted more attention to visual imagery than CT, resulting in decreased microstate class B coverage. In Design CT, participants were thinking about a product concept. On the other hand, in General CT, they were thinking about a kanji. This difference could be the reason why the difference in microstate class B coverage between DT and CT was not as large in Design condition as General condition.

Finally, for the three parameters of microstates, the effect size of Process × Class was larger than that of Type × Class, suggesting that the thinking process (divergent vs convergent) has a greater impact on EEG microstates than the type of task (conceptual design vs general creativity task).

Conclusions

Herein, for the purpose of capturing specific brain activity during product conceptual design, we used EEG microstate analysis and compared participants' brain activity during product conceptual design and general creativity tasks. The results showed the higher coverage of microstate class C related to the DMN during product conceptual design and suggested the possibility of activated semantic memory, and increased internal attention and mental simulation.

However, due to the small sample size, biased gender balance, and fixed sequence of the experiment tasks (DT followed by CT) of this study, further research is required in order to test this hypothesis. Additionally, the present study is limited to mentioning the results of the comparison of microstate parameters across tasks. It is left for future behavioural analysis to understand the designer's cognitive state based on the responses obtained during product conceptual design.

Nevertheless, this paper shows that microstate analysis is useful in identifying brain activity specific to product conceptual design, particularly characterised by more activation of the DMN than general creativity tasks. These results provide important insights for elucidating the neural basis of product conceptual design.

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Neurophysiological Responses to Biophilic Design: A Pilot Experiment Using VR and EEG

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This pilot study explores the effects of biophilic design on university students' neurophysiological responses in virtual classrooms through measuring relative alpha and beta power using EEG in two different display conditions: a conventional computer display and an immersive VR Head-Mounted Display. Seventeen male undergraduate students from both a design major and a non-design major in their twenties at Yonsei University participated. Seven different biophilic design cases were presented as visual stimuli to participants in the two different conditions. Results of ANOVA analysis revealed significant main effects of condition and hemisphere in the relative alpha power. Results revealed there is significant interaction effect between case and major as well as between condition, case, hemisphere, and major in relative beta power. Results showed statistically significant differences in some electrodes of both relative alpha and relative beta measurements between some cases when presented in the computer display. In the VR presentation, differences were found only in the relative beta in some electrodes. This study has the potential to contribute to building evidence-based design strategies for improving biophilic design environments.

Background

Biophilic design has a positive effect on human mental health and well-being [1]. Especially during the COVID-19 pandemic, physical and mental health became critical considerations. Most students spend the majority of their time indoors and some suffer from depression and psychological stress [2]. The natural environment plays

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a positive role in anxiety reduction and attention restoration [3, 4]. In the education environment, biophilic learning spaces can have a positive impact on student success [5]. Beyond self-reporting and physiological and cognitive measurements [6–8], an understanding of how biophilic design influences students' neurophysiological responses can lay a foundation for evidence-based design [9–11].

In the previous literature investigating the effects of biophilic indoor environments, physiological methods were used to measure stress and anxiety levels by monitoring heart rate variability, heart rate, skin conductance levels, blood pressure and cognitive and productivity performance by recording eye-tracking, blood pressure, galvanic skin response, and heart rate in the workplace [12–15]. However, few studies explored the effects of biophilic design on the students' brain physiological responses in learning spaces. This study seeks to better understand the neurophysiological response to biophilic design in an educational environment. It uses electroencephalography (EEG) combined with virtual reality (VR) to study a cohort of students' brain's reaction to biophilic design elements in both an immersive and a non-immersive environment.

Brain responses, measured using EEG, have the potential to increase our understanding of the relationship between human behavioral response and design elements [16–18]. EEG records the electrical activity of the brain using electrodes placed on the scalp. In EEG signals brain waves are found in the frontal, parietal, temporal, and occipital cortex [19]. Empirical studies focusing on EEG-specific experiments have not been widely explored utilizing VR technology [20–24].

To measure brain responses, the frequency band results acquired from EEG signals have been widely used. Khushaba et al. [25] assessed the brain response to product design using an Emotiv EPOC wireless EEG headset with 14 channels. In the five principal frequency bands, Delta, Theta, Alpha, Beta, and Gamma, results showed that EEG power spectral activities occurred mainly in the frontal (Delta, Alpha and Beta), temporal (Alpha, Beta, Gamma), and occipital (Theta, Alpha, and Beta) regions when participants showed their preferences related to product design [25]. For quantifying the visual aesthetics of a product, [26, 27] used an integrated approach of EEG and eye-tracking. The results of the brain response showed that a low aesthetic product evoked significantly weakened relative alpha power and enhanced relative gamma power [27].

In design research, EEG was also used to study designers' cognitive and affective states [16]. EEG is used to measure neurophysiological activation while designing and problem-solving [18, 28] and brain activity of industrial designer in constrained and open design [17]. However, EEG studies to understand users' brain responses and design neurocognition to architectural environments are still at the early stage. This present study focuses on neurophysiological responses measuring Relative Alpha and Relative Beta power while students visually experience biophilic learning spaces.

Aims

This pilot study aims to explore the effects of biophilic design on neurophysiological responses in an educational environment. We investigate the following research questions:

(i) What are the differences in students' relative alpha and beta power in seven virtual classrooms (i.e., one non-biophilic base classroom and six different designs enhanced with direct/indirect biophilic design elements?
(ii) What are the differences in students' relative alpha and beta power when viewing a virtual classroom in two different representations: a conventional computer display and an immersive VR Head-Mounted Display?
(iii) What are the differences in relative alpha and beta power of students' major (design and non-design majors) when viewing virtual classrooms?

Method

The research questions are examined using two different representation conditions (1) computer display, and (2) VR HMD. In this study, each participant explored all seven cases of experimental stimuli in randomly assigned order. In this within-subjects design, we statistically compare relative alpha and beta power when experiencing non-biophilic and biophilic designs of the same classroom. The experimental procedure was pre-tested prior to this study.

Participants

We recruited 23 healthy, male students via an online recruitment system from June to July in 2021 in Seoul, South Korea. All qualified participants were undergraduate students from various majors who were right-handed, had normal or corrected to normal vision and no report of neurological impairment. Participants voluntarily signed up for the experiment with a $20 compensation. Due to the COVID-19 pandemic restrictions, the arrangement of the number of participants was adjusted, and all participants were asked to wear a face mask during experiments. The study was approved by the Institutional Review Board of Yonsei University and all participants signed the consent form before the experiment.

Some participants did not fully complete the VR experiment because of the motion sickness and dizziness. Results are based on the remaining seventeen subjects aged in their 20 s (mean = 21.34, SD = 1.44) who completed the experiment and post-surveys and interviews. The data of four participant was not completely collected due to unstable electrical connection. Valid EEG data was acquired from thirteen subjects (six design majors and seven non-design majors) used for statistical data analysis.

Environmental Simulation

We simulated seven three-dimensional virtual classrooms: one case to replicate an existing university classroom setting and the other six cases with different biophilic design elements for the same classroom. A representative classroom of a physical university teaching spaces was virtualized, and the classroom was chosen from a building at the Yonsei University. The dimension of the classroom used as the stimulus is 7.6 m (W) × 11.5 m (D) × 2.7 m (H) and the layout and 3D model are shown in Fig. 1.

Two different representation conditions were used to display the rooms: a computer monitor display and a VR HMD. The computer monitor used in this study was an iMac, 27-inch screen with a resolution of 5120 × 2880. The HMD device used was the Oculus Quest 2 and it provides LCD screen resolution of 1832 × 1920 per eye. In a computer display, two perspective rendering images were shown, and a real-time VR-walkthrough content was displayed in Oculus' HMD for each stimulus. The stimuli are modeled in VR by using Rhino (version 6.0) in advance and rendered in real-time by using Twinmotion (version 2021.1).

We displayed seven different cases: Case 1 non-biophilic classroom as a control setting, Case 2 a biophilic design with the direct integration of nature and Cases 3 to 7 with the indirect application of natural elements. Design elements and attributes are inspired and applied based on a theory of biophilic design [9]. Apart from biophilic interventions, all seven classrooms were identical, with the same room size, layout, and furniture for seven virtual classrooms to allow for case by case comparisons. The biophilic design elements were applied to areas of wall, floor, and ceiling as shown in Fig. 2.

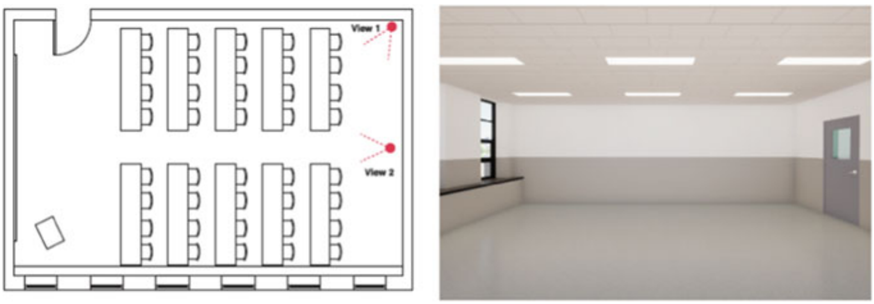

Fig. 1 Classroom layout and 3D model

Case	Description	View 1	View 2
1	Non-biophilic design: Existing classroom (control setting)		
2	Biophilic design to outdoor: Greenery view		
3	Biophilic design to wall treatment (1): Green plant wall at window side		
4	Biophilic design to wall treatment (2): Green plant wall with a whiteboard		
5	Biophilic design to floor treatment: Wood material		
6	Biophilic design to wall and floor treatment: Green plant wall and wood material		
7	Biophilic design to ceiling treatment: Organic (wavy) patterned structure		

Fig. 2 Seven cases of virtual classroom

Experiment Procedure

Each experiment was conducted individually with a researcher and took approximately one hour in total. A timeline summary of the procedure is shown in Fig. 3. Prior to conducting the experiment, each participant signed a consent form approved by the IRB.

All participants were informed of the step-by-step introduction and precautions of the experiment. Each participant sat on a chair comfortably in a laboratory setting and wore the EEG equipment. A researcher confirmed that each electrode was attached

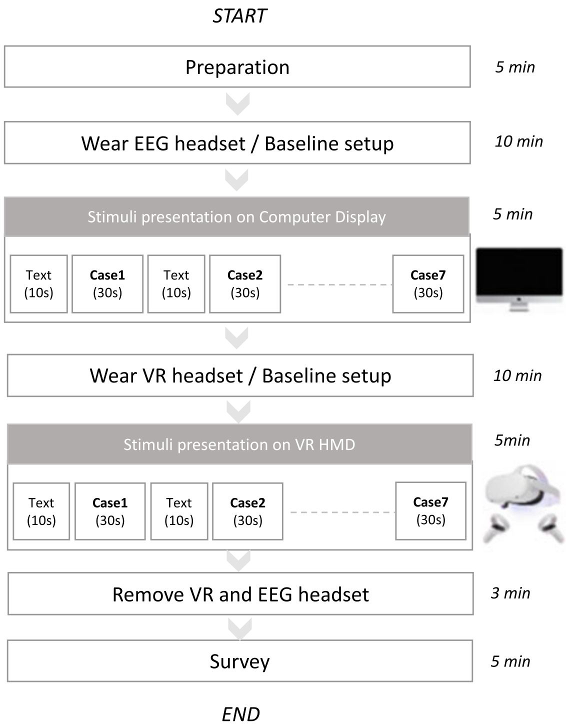

Fig. 3 Experiment procedure

to the participant's scalp. When the impedance of all electrodes attached fell below 1, a researcher examined the status of EEG data recording.

Each participant experienced two different settings in sequence as shown in Fig. 4: firstly, two perspectives of 3D rendering on a computer monitor display and secondly, VR-walkthrough content using an Oculus' Head-mounted display. In both settings, participants were exposed to seven cases of the experimental stimuli randomly assigned. Each visual stimulus was shown for 30 s to collect EEG signals. To provide a break time in-between, a white screen with the display of text was presented for 10 s. If needed, extra time was given to the participants before presenting the next stimulus. After participants completed the sequence of two settings, participants were compensated and exited the lab.

Data Collection and Processing Methods

Data was collected between August 15 to August 30, 2021, at Yonsei University. The experiments were performed between 10:00 am and 16:00 during working days in a laboratory room with the necessary conditions for the EEG experiment, such as lighting, humanity, and temperature.

Fig. 4 Experiment setup (left: computer display condition, right: VR HMD condition)

EEG signals was recorded using a research-grade wireless dry electrode EEG headset (model name: DSI-24, Wearable Sensing, USA), Fig. 5. Electrodes are positioned according to the 10–20 International System. 19 sensors at 10–20 locations are Fp1, Fp2, Fz, F3, F4, F7, F8, Cz, C3, C4, T3, T4, T5, T6, P3, P4, Pz, O1, O2.

EEG activity was measured by the monopolar derivation method from a total of 19 electrodes. The participants' EEG signals underwent the16 bits AD (Analog–Digital) conversion with sampling at 300 Hz and was recorded in the computer in a frequency passband of 0.003–150 Hz. The measured EEG signals (raw data) were collected by a real-time data collection software, DSI-streamer (ver1.08.44, Wearable Sensing, USA), and converted the output in CSV file using the time series analysis program TeleScan (ver3.29, LAXTHA Inc, South Korea), and then analyzed.

This study used Fast Fourier Transformation (FFT) and Power Spectrum Analysis (PSA). Noise caused by body movement, facial muscle activity, swallowing artifacts were removed. The criteria of the low- and high-frequency filters were set at 0.5 and 50 Hz. Eye movement and blink artifacts were filtered using the principal component analysis (PCA) method. As denoising criteria, the amplitude of a subject's eye movement is measured while the subject's eyes are open and the amplitude is larger than

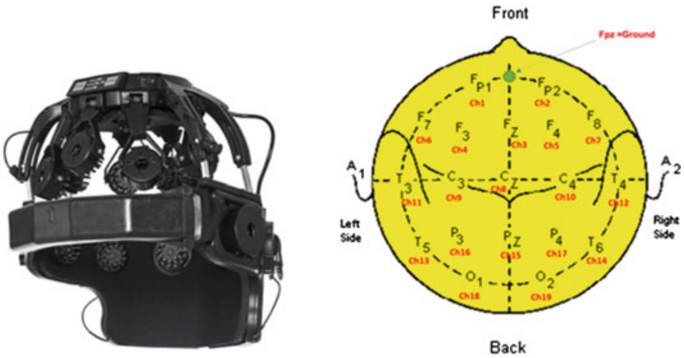

Fig. 5 EEG cap and electrode locations of Wearable Sensing DSI-24

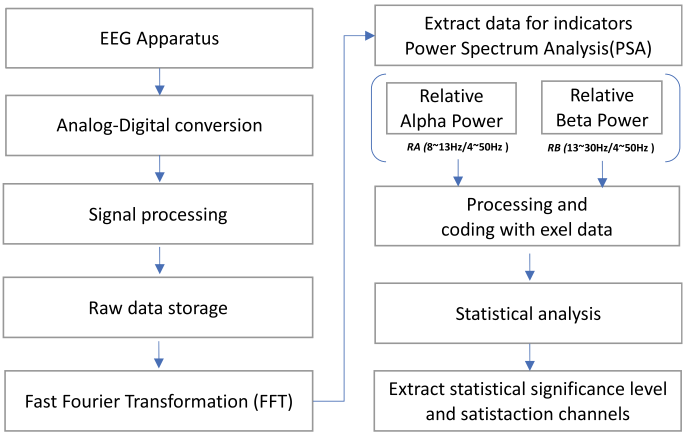

Fig. 6 EEG data collection and processing pipeline

the subject's existing size, it is considered as an outlier during VR EEG measurement and removed, and only the cleaned data was used for data analysis. In addition, data with greater than 50 Hz frequency occur more than 50% of the time were excluded.

FFT transforms the EEG signals into the frequency domain. It is used to covert raw data to extract the Relative Theta (RT), Relative Alpha (RA), Relative Theta (RT), Relative Beta (RB) and Relative Gamma (RG). Frequency was set to RT (4–8 Hz/4–50 Hz), RA(8–13 Hz/4–50 Hz), RB (13–30 Hz/4–50 Hz), and RG(30–50 Hz/4–50 Hz). Among EEG data collected from the 19 electrodes, we analyzed eight electrodes: Prefrontal (FP1, FP2), Frontal (F3, F4), Parietal (P3, P4), Occipital (O1, O2). EEG data was acquired in a total of 7 cases, respectively, for computer monitor display and VR HMD. In this study, we analyzed the change of power spectrum in RA and RB to assess students' brain behaviors in response to seven cases in two different representation conditions. Figure 6 illustrates the flow of EEG data collection and the processing pipeline.

Data Analysis Methods

All valid EEG signal data from thirteen participants was used for statistical analysis. Statistical analyses were carried out using Jamovi (ver.1.6). This paper focuses on frequency bands to assess if there were significant differences in the eight electrodes (FP1, FP2, F3, F4, P3, P4, O1, O2) of RA and RB between the non-biophilic base case and the six other cases with different biophilic design elements: between a computer display presentation and VR head-mounted display. An assumption of the normality in all groups was tested using the Shapiro–Wilk test and the outcome data was normally distributed permitting the use of parametric tests.

Based on the design of the experiment, statistical analyses were performed using a repeated measures ANOVA with case (non-biophilic and multi biophilic design), condition (computer display, VR), hemisphere (left, right) as within-subject factors and major difference as between subject factor. Partial Eta Squared ($\eta p2$) was calculated to measure of effect size. Th magnitude of differences indicates large effects ($\eta p2 \geq 0.14$), medium effects ($\eta p2 \geq 0.06$), and small effects ($\eta p2 \geq 0.01$). Furthermore, post-hoc analysis with Bonferroni correction was performed to determine which of the multiple groups had a significant difference.

To compare the non-biophilic and six different biophilic design individually, paired samples T-test was carried out to verify significant differences of the RA and RB power measurements between non-biophilic and biophilic design cases (i.e., Case 1–Case 2; Case 1–Case 3; Case 1–Case 4; Case 1–Case 5; Case 1–Case 6) when presented in the computer display and VR. A p-value < 0.05 was considered statistically significant.

Analysis of Results

From statistical analysis using repeated-measures ANOVA, we found significant main effects and significant interaction effects between multiple factors: condition (computer display and VR), hemisphere (left and right), case (a non-biophilic case and multiple biophilic cases) as within-subject factor and major (design and non-design) as a between-subjects factor. Table 1 summarizes the results.

We found significant main effects of condition ($p < 0.001$) and hemisphere ($p < 0.05$) in RA. No significant main effect was found for the between-subject factor major in RA. This study revealed that the display condition had a large effect size ($\eta p2 = 0.38$) whereas the hemisphere had a small effect size ($\eta p2 = 0.006$) in RA. Post hoc test analysis showed that higher RA appeared in computer display condition and left hemisphere appeared across all cases, Table 2. Comparisons of hemisphere and condition per case in relative alpha power are illustrated in Fig. 7.

No significant main effect of condition and hemisphere was found and for the between-subjects factor major in RB. However, results indicated there is significant interaction effect ($p < 0.001$) between case and major in RB. A significant interaction effect ($p < 0.05$) between condition, case, hemisphere, and major was found for RB.

Table 1 Significant main effects from the repeated measures ANOVA

Freqency band	Relative alpha	Relative beta
Condition	<0.001*	–
Hemisphere	<0.05*	–
Case × major	–	<0.001*
Condition × case × hemisphere × major	–	<0.05*

Note * $p < 0.05$

Table 2 Post hoc comparisons in relative alpha power

Comparison	Mean difference	SE	df	t	pbonferroni
Condition (computer display-VR)	0.08044	0.01797	12.00	4.477	0.0008
Hemisphere (left–right)	0.00857	0.00330	12.00	2.591	0.0236

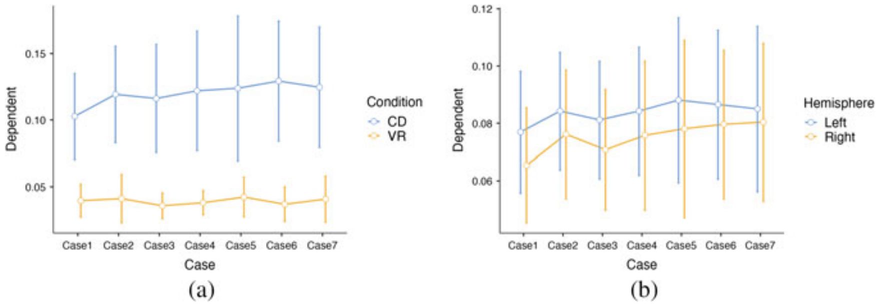

Fig. 7 Comparison in **a** condition **b** hemisphere and per case in relative alpha power

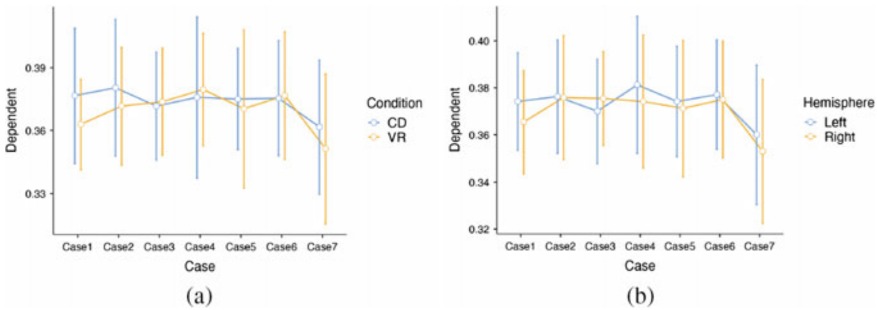

Fig. 8 Comparison in **a** condition and **b** hemisphere and per case in relative beta power

The significant interaction effect between case and major in RB showed a small effect size ($\eta p2 = 0.34$). Comparing condition and hemisphere, higher RB exhibited in Case 1 and 2 in the computer display condition and in Case 2 and Case 3 in the right hemisphere. Figure 8 presents comparisons of hemisphere and condition per case in relative beta power.

Effect of Biophilic Design on Relative Alpha (RA) Power

This study compared a non-biophilic and six different biophilic designs individually using paired T-test. The result of RA power showed significant differences only between Case 1 and Case 2; Case 1 and Case 6 in the computer display. There were no significant differences in other paired cases in VR. Table 3 summarized paired cases that showed significant differences (p-value < 0.05) across eight electrodes in a computer display condition.

The circled points on the electrodes, depicted in Fig. 9, represent statistical differences in brain mapping. There were significant differences in RA power between Case 1 and Case 2 across FP1 ($t = -3.237$; $p < 0.05$), FP2 ($t = -2.635$; $p < 0.05$), F3 ($t = -3.167$; $p < 0.05$) and F4 ($t = -2.889$; $p < 0.05$). The significant difference occurred mainly in the prefrontal lobe and frontal lobe. The result showed that RA in Case 2 was higher than RA in Case 1 across FP1, FP2, F3, F4, P3, P4, O1, and O2. Higher RA power values mainly were dominant in the occipital and parietal lobe than prefrontal and frontal lobe. Highest RA value in Case 2 was found in P3 (Mean = 0.189, SD = 0.120) and O2 (Mean = 0.172, SD = 0.119).

As shown in Fig. 10, there are significant differences between Case 1 and Case 6 across F3 ($t = -2.212$; $p < 0.05$), P3 ($t = -2.450$; $p < 0.05$), and O2 ($t = -2.474$; $p < 0.05$). In the VR HMD condition, the results showed that there was no significant difference statistically in RA power. RA power in Case 6 showed a higher value than

Table 3 Cases with significant differences in RA

Case–case (display modality)	Electrode	Mean difference	SE difference	Statistic	df	*p*-value
Case 1–case 2 (computer)	FP1	−0.015	0.004	−3.237	12.00	0.007*
	FP2	−0.013	0.005	−2.635	12.00	0.021*
	F3	−0.013	0.005	−3.167	12.00	0.008*
	F4	−0.012	0.004	−2.889	12.00	0.013*
Case 1–case 6 (computer)	F3	−0.013	0.006	−2.212	12.00	0.047*
	P3	−0.044	0.018	−2.450	12.00	0.030*
	O2	−0.050	0.020	−2.474	12.00	0.029*

Note * $p < 0.05$

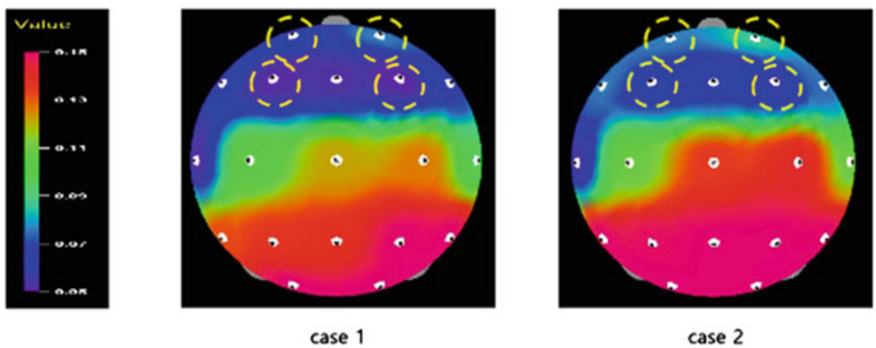

Fig. 9 Brain mapping: Case 1 and Case 2 in the computer display condition

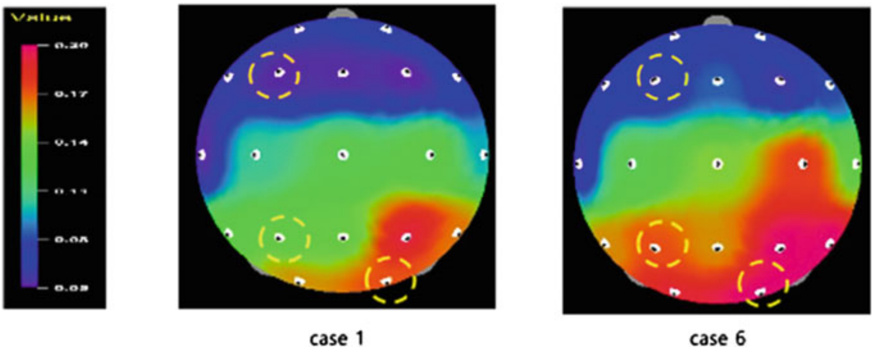

Fig. 10 Brain mapping: Case 1 and Case 6 in computer display condition

RA in case1 across FP1, FP2, F3, F4, P3, P4, O1, and O2. Highest RA value in Case 6 was found in P3 (Mean = 0.223, SD = 0.156) and O2 (Mean = 0.208, SD = 0.168).

Effect of Biophilic Design on Relative Beta (RB) Power

RB results showed significant differences between Case 1 and Case 2; Case 1 and Case 3 in the computer display; between Case 1 and Case 3 and Case 1 and Case 6 in VR, described in Table 4.

In the computer display, depicted in Fig. 11, there was significant difference indicated between Case 1 and Case 2 across F4 ($t = -2.512$; $p < 0.05$). Difference in RB power only occurred in frontal lobe of left hemisphere. The results showed that RB in Case 1 was higher than RA in Case 2 across FP1, FP2, O1, O2. RB in Case 1

Table 4 Cases with significant differences in RB

Case–case (display modality)	Electrode	Mean difference	SE difference	Statistic	df	*p*-value
Case 1–case 2 (computer)	F4	−0.016	0.006	−2.512	12.00	0.027*
Case 1–case 3 (computer)	P3	0.024	0.010	2.391	12.00	0.034*
	O2	0.016	0.007	2.412	12.00	0.032*
Case 1–case 3 (VR)	O2	−0.028	0.009	−3.121	12.00	0.008*
Case 1–case 6 (VR)	FP1	−0.043	0.016	−2.584	12.00	0.023*
	F3	−0.031	0.014	−2.253	12.00	0.043*
	F4	−0.044	0.018	−2.373	12.00	0.035*

Note * $p < 0.05$

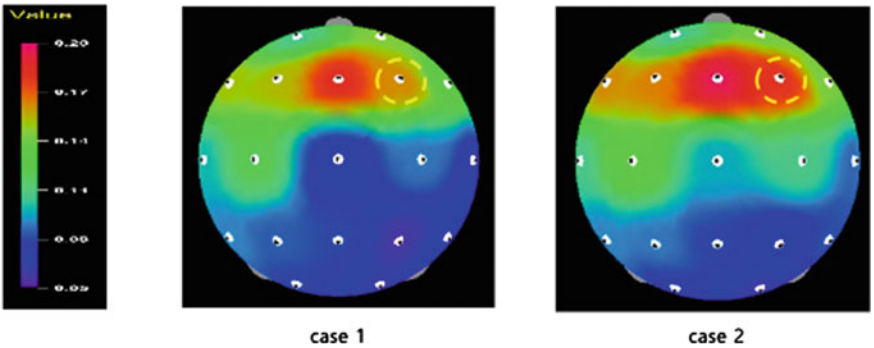

Fig. 11 Brain mapping: Case 1 and Case 2 in computer display condition

was lower than RA in Case 2 across F3, F4, P3, and P4. The highest RA value found in Case 2 and they were dominant in the frontal lobe across F3 (Mean = 0.436, SD = 0.062) and F4 (Mean = 0.446, SD = 0.067).

Between Case 1 and Case 3, significant differences in RB power are found across P3 (t = 2.391; $p < 0.05$) and O2 (t = 2.412; $p < 0.05$). Difference occurred mainly in parietal lobe and occipital lobe. The result of descriptive statistics indicated that RB in Case 1 was higher than RB in Case 3 in area of F3, F4, P3, P4, O1, and O2. However, RB in Case 1 was lower than RB in Case 3 across FP1 and FP2. The highest RB was found in Case 1 across F3 (Mean = 0.424, SD = 0.066) and F4 (Mean = 0.429, SD = 0.063). Figure 12 illustrates differences in RB power.

In the VR condition, the significant differences in RB were between Case 1 and Case 3 and Case 1 and Case 6, shown in Fig. 13. The significant difference indicated between Case 1 and Case 3 only in O2 (t = −3.121; $p < 0.05$). Difference showed only in the right hemisphere. The statistics resulted across eight electrodes, RB power in Case 3 showed higher value than RB in Case 1 except O1 area. The two highest RB

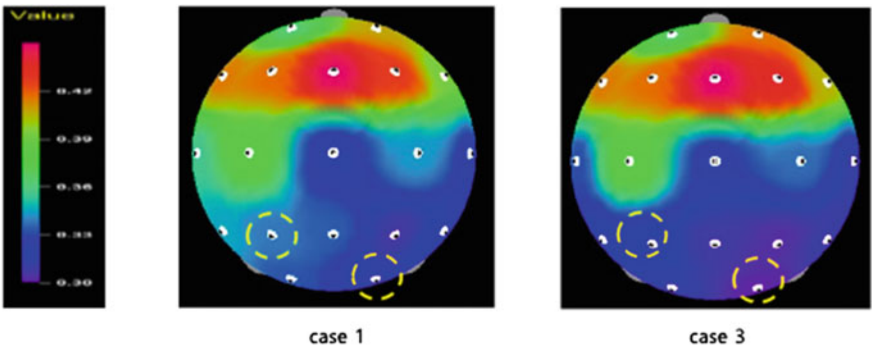

Fig. 12 Brain mapping: Case 1 and Case 3 in computer display condition

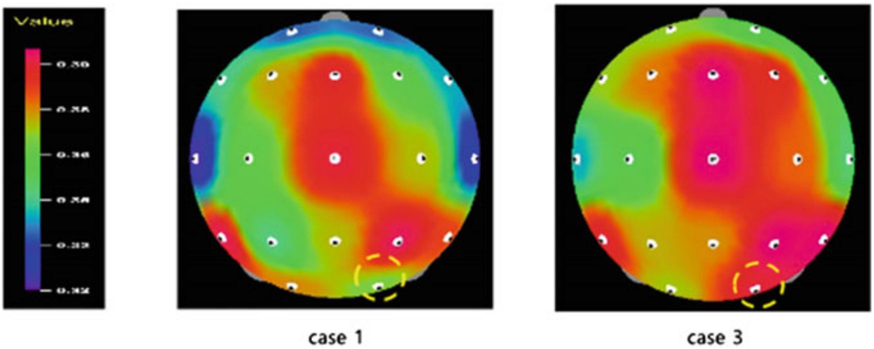

Fig. 13 Brain mapping: Case 1 and Case 3 in VR HMD condition

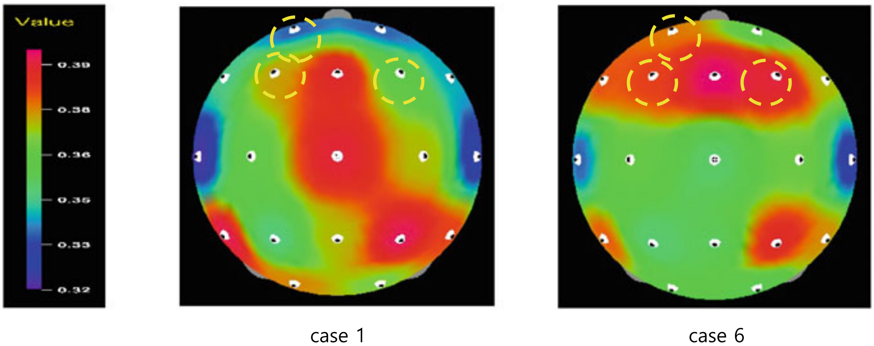

Fig. 14 Brain mapping: Case 1 and Case 6 in VR HMD condition

showed in Case 3 indicated across P4 (Mean = 0.985, SD = 0.066) and O2 (Mean = 0.390, SD = 0.041).

The results, as depicted in Fig. 14, showed that significant difference revealed between Case 1 and Case 6 across FP1 ($t = -2.584$; $p < 0.05$), F3 ($t = -2.253$; $p < 0.05$), and F4 ($t = -2.373$; $p < 0.05$) in VR. It occurred mainly in prefrontal lobe and frontal lobe. The statistics resulted across eight sites, RB power in Case 6 showed higher value than RB in Case 1 except P3 and O2. The two highest RB showed in Case 6 indicated across F3 (Mean = 0.394, SD = 0.049) and F4 (Mean = 0.396, SD = 0.054).

Discussion

We statistically analyzed the differences in students' brain responses by measuring relative alpha and beta power in (i) seven virtual classrooms (a non-biophilic case and multiple biophilic cases); (ii) two different display conditions (computer display and VR); and (iii) design major and non-design group.

Comparing the non-biophilic base case and the six different cases enhanced with biophilic design elements, this study's results showed statistically significant differences in participants' RA power when they viewed stimuli on a computer display. We found a significant main effect of hemisphere in RA and higher RA values exhibited across all cases in the left hemisphere. Each of the electrodes is associated with specific brain regions that aligned 10–20 electrodes placement with Brodmann areas that allows for connection with a range of cognitive functions [29]. The significant differences in RA between non-biophilic and biophilic design classroom occurred across prefrontal and frontal cortex, where cognitive functions are associated planning [30, 31] and attention, information section and performing functions [32].

Alpha power (8–13 Hz) amplitude increases when the subject is relaxed and comfortable, which are dominant in the occipital and parietal lobe during relaxed [33–35]. Our findings supported that higher RA power values mainly occurred in the occipital and parietal cortex. Higher RA values were found in environments integrated with greenery outdoor view and indirectly applied natural design elements on the wall and floor. Similarly, Lei et al. [15] found a significant positive impact of greenery on physiological performance by measuring EEG and higher alpha exhibited indoor workplace with larger greenery coverage. Klimesch et al. [36] showed that the higher alpha band is most sensitive to the encoding and processing of semantic information.

The significant differences in students' RB power were found between the non-biophilic classroom setting and the classrooms with greenery view and green planting wall treatment at the window side in the computer display condition. The higher RB occurred in frontal cortex across F3 in left hemisphere associated with the brain functions of deductive reasoning and semantic processing [37] and F4 in right hemisphere related to goal-intensive processing [38] and search for originality [39]. When experiencing the VR condition, significant differences occurred in the green plant wall treated case as well as in combined cases. For most cases, participants' RB power values during the VR condition were found to be higher than when viewing the same stimulus in the computer display condition. Since participants interacted with the room through a walk-through in VR simulation while standing, this might have caused more mental activity compared to sitting on a chair looking at a monitor.

Beta power (13–30 Hz) is generally produced when the subject is mentally active which is dominant in the frontal region during mental activity [34, 35]. However, it was only partially supported in RB results. The highest RB showed that a combined application of biophilic wall and flooring treatment, indicated in the frontal cortex, which is associated with visuo-spatial information processing [40] and visual attention [41]. In the classroom with a greenery view, the highest RB was indicated in parietal and occipital cortex.

Comparing the two display conditions (computer display and VR), we found significant main effects of condition in RA power measurement. The results of a paired sample t-test for each case between the computer display and VR showed significant differences in some electrodes of all cases in RA and RB. Higher RA appeared in the computer display condition than VR across all cases. In the computer display condition, significant differences were found, with higher RB values in the prefrontal and frontal cortex, associated with cognitive function for coordinating visual spatial memory [42]. Higher RB values were found only in parietal and occipital cortex, in right hemisphere in the VR condition. Although the same cases are represented through different hardware for comparison of two display methods, the distinction in media between still 3D rendering image and VR walkthrough might cause effects on results.

From the analysis of the effects of education major, no significant main effect was found for between-subject factor major in RA and RB. It could be caused by the small sample size in this study. However, this study revealed there is a significant interaction effect between case and major as well as between condition, case, hemisphere, and major. Future studies can investigate education major differences further to gain insight into how to differentiate learning spaces by department at a university.

Conclusion

This pilot study investigated the effects of biophilic design on university students' neurophysiological responses in an educational environment. This paper presented the results of a pilot experiment using EEG and VR and demonstrated a protocol for experiment design for future applications across design domains. One limitation of this study is the relatively low number of participants. Future research suggestions include exploring the effects of differences in gender, culture, and educational background. This paper is also limited by analyzing brain responses measuring only RA and RB powers across the eight electrodes. However, future research will analyze into two ranges (i.e., low and high frequency) in RA and RB powers and explore the correlation between electrodes across prefrontal, frontal, parietal, occipital lobe and will correlate results with Brodmann area and further interpret the meaning of these differences in cognitive terms.

This paper described a study that forms a part of a larger research project to measure neurophysiological, physiological, and emotional responses in biophilic environments. Combining VR, EEG and body sensors has the potential to quantify human experience [43, 44]. In our future study, we will explore experiments by integrating multimodal biometric methods and VR technology. Future research will examine EEG, eye-tracking, and galvanic skin response to measure the effects of biophilic design on human neurophysiological and neurocognitive responses. By bringing direct and indirect natural elements into a classroom, biophilic design aims to cultivate positive emotion and increase mental health and well-being [9]. Not limited to a learning space, such experiments can provide evidence on positive effects of biophilic design on occupants' cognition and emotions in a wide spectrum of indoor environments. This study demonstrated that an immersive VR system is a useful method to represent biophilic design virtually.

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Comparing Designers' EEG Activity Characteristics for Common Association and Remote Association

Yuan Yin, Pan Wang, Ji Han, Haoyu Zuo, and Peter Childs

Design is a principal form of creative output. Understanding creativity can be influential in development aimed at improving the design process. Association, a proxy for creativity, has been studied by neuroscience technology in recent years. However, most of these studies are about which part of the brain or which wave bands are related to the association process. EEG characteristics such as event-related potential (ERP) and EEG signals tendency have not been fully studied. Therefore, this study aims to identify the EEG activities of common association and remote association and compare the differences. The results revealed that the common association was evoked faster than remote association. When common association and remote association processes are evoked, both can lead to a result fast. However, after generating one result, remote association will stop while common association will keep generating more results unconsciously.

Introduction

Design can be regarded as a process to translate ideas into products or prototypes [1, 2]. Creativity is often defined as the ability to imagine or invent something valuable and novel [3]. Creativity and design have tight associations. As a principal form of creative output, design is a tangible display of creativity. In addition, creative ideation is a fundamental process of product design [2]. In a design process, designers tend

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to reformulate problems to identify new knowledge, revise previous solutions and in turn develop an improved solution [4]. After a few iterations of this recursion process, final design ideas are often generated. Creativity has been identified as an important element in this recursion process [4]. In the divergent thinking process of creative design, high creativity levels may also lead to more creative ideas. In addition, researchers have found that the creative ideation process and product design process share some similar brain activity areas such as the left cingulate gyrus [2]. This was an attempt to explain the relations between creativity and design informed from neuroscience perspectives. Therefore, understanding creativity can be influential in development aimed at improving the design process [2].

With the development of neuroscience, applying neuroscience technology (such as functional Magnetic Resonance Imaging (fMRI) and Electroencephalography (EEG)) in creativity areas has been attempted in a number of research studies. Many researchers have found that alpha waves play an important role in creativity [4–7]. Other band waves such as theta and gamma were also related to the creative idea-generation process [8]. Apart from the band wave, researchers also identified which part of the brain is related to the creative idea-generation process. Frontal and parietal regions were thus promoted to have relations with creative idea-generation processes through fMRI and EEG methods [9].

Association is an important cognitive factor in the creative design process. Also, association is considered an ability that is highly related to creativity because novel association may trigger more creativity [10]. Therefore, to better understand aspects of design, it is important to identify creativity. Association is an important cognitive factor related to creativity and is thus a good starting point. Association is related to alpha waves. When creativity includes association processes, the higher alpha waves will be detected in frontal and parietal regions [11].

Association can be divided into remote association and common association [12]. The ability to associate irrelative concepts is considered remote association. The ability to associate relative concepts is considered common association. In a design idea generation process, remote association is often identified to be related to higher creativity [12–16]. This is helpful for divergent thinking processes where creative ideas can be generated. Common association, sometimes is considered a barrier to being creative [17].

Considering that the common association and remote association are the core constituents of association, some researchers have tried to identify the differences between common association and remote association in creative processes through neuroscience technologies. With the help of fMRI, researchers found that remote association tasks included more creative responses compared to common association tasks ($t[101] = 6.58$, $p < 0.001$) [12]. Also, remote association has higher brain activation than common association. However, fMRI is a method that measures brain activity by detecting blood flow. It cannot reflect the wave-band results. To identify the wave band, EEG method has been applied. The results from EEG studies reveals that alpha power is lower in common association compared to remote association [5, 8, 18]. This result is also supported by fMRI studies [19].

Although researchers may agree on alpha waves being related to remote association in creative processes, researchers have not agreed on which part of the brain is related to remote association. A few possible brain areas have been promoted such as the left frontal lobe [19, 20], the left temporal lobe [8], and the right temporal lobe [21].

Although existing studies have identified and compared the neurophysiological characteristics between remote association and common association, the results were mainly focused on the characteristics of remote association [8], which part of the brain was active in association processes, or which band waves were related to association processes. The existing studies have not fully identified other EEG activities such as Event-related potentials (ERPS; a measure that can quantitatively reflect the brain temporal response to a specific cognitive event [4, 8, 22]) and EEG signals tendency on remote association and common association.

To address the gaps, this study aims to identify the ERPS and EEG signals tendency of common association and remote association and compare the differences between them.

Methodology

To achieve the study goals, the study attempts to use the Alternative Uses Task (AUT) and the Object Characteristics Task (OCT), respectively, to identify remote association and common association EEG signals of industrial and product designers.

Participants

The study recruited 30 right-hand Chinese participants [5]. One participant had to be excluded from all data analysis because of technical problems during EEG recording, resulting in a final sample of 29 participants (14 female, 15 male; aged 20–25). All of the 29 participants were industrial design or product design background students, who had experience in designing products and using hand-drawing to express their ideas in the past year.

Tasks

AUT was used to measure the designers' remote association ability in creative processes [5, 20, 23, 24]. Participants were asked to find a remotely related use for each object (such as Umbrella—boat for animals). Considering that remote association may be an unfamiliar expression for participants, participants were asked to "think of a concept for which only a few people would think of" to replace "remote association" [12].

OCT was used to measure the common association ability in creative processes [5, 20]. Participants were asked to find a high-related characteristic for each object (such as Shoes—paired). Considering that common association may be an unfamiliar expression for participants, participants were asked to "report the first characteristic that comes to mind to most people" and use this expression to represent "common association" [12].

Each task included 30 trials. In both tasks, participants were presented with 15 everyday object words and 15 everyday object graphics. In this case, the EEG characteristics which were generated from different thinking forms (images or words) can be removed. Each word or graphic was presented once in each task. The order of the presentation was random. The words and graphics used in AUT and OCT were different.

The words and the description of graphics were collected from Stevens Jr and Zabelina [5]. The corresponding graphics were collected from BaiduImage searching (https://image.baidu.com/) which is a common Image searching method in China. The image which can reflect the described object accurately was selected. The size of the graphics was resized to 500 × 500 pixels.

Procedure

Before the study, participants were given an information sheet and they could ask any questions they have. If there were no questions, they were asked to sign a consent form.

An introduction was then delivered to participants. The introduction included how many trials are included in this study, what the participants need to do, and an example.

Each trial for the AUT task began with a fixation period, presenting a black fixation cross on light grey background jittered between 2 and 5 s. Then, the word or graphic was displayed and remained on the screen for up to 8 s. During the period, participants were asked "based on the word or graphic, think of a concept that only a few people would think of" but not verbalize this. If they found a solution before the timeout, they can hit the "Space" key on the computer keyboard to progress to the next fixation interface. If the 8 s run out, the interface will jump to the next fixation interface automatically.

After the AUT, participants can have a 5-min rest. Then, the OCT started. Each trail of OCT began with a fixation period, presenting a black fixation cross on light grey background jittered between 2 and 5 s. The word or graphic is displayed and remained on the screen for up to 8 s. During the period participants were asked to "based on the word or graphic, report the first characteristic that comes to mind to most people" but not verbalize this. If they found a solution before the timeout, they can hit the "Space" key on the computer keyboard to progress to the next response interface. If the 8 s run out, the interface will jump to the next response interface automatically.

The order of AUT and OCT was random in the study. The whole study took about 15 min to complete. This study was approved by the local ethics committee of the first author institute.

EEG Recording and Equipment

EEG signals were collected using a Neurofax EEG-9200 system with 16 scalp and 2 mastoid Ag/AgCl electrodes mounted according to the 10/20 system. An EEG measurement system, Amplifier, and EEG results viewing software are all included in the system. Impedances of all EEG channels were below 5 kΩ. The data were sampled at 1000 Hz.

Previous studies have found that the activated brain areas of remote association and common association may be the frontopolar cortex [25] or temporal lobe [26]. The 16 channels can cover most of those areas and thus more channels may be not necessary. To be specific, Fp1/Fp2/F7/F8/F3/F4 can report signals in the frontal lobe; T3/T4/T5/T6 can report signals in the temporal lobe. Considering the study is also interested in potential hemispheric differences, the midline electrodes such as FZ, CZ, PZ were not included [23].

The EEG tasks were generated with the help of E-Prime 3.0. All tasks were presented on a computer screen (35.89 × 24.71 cm with a resolution of 2560 × 1600). The data were collected and stored in the Neurofax EEG-9200 system.

EEG Data Analysis

All EEG signals processing was based on MATLAB R2018b (The MathWorks, Inc., Natick, Massachusetts, United States) using EEGLAB. A 50 Hz notch filter has been applied to remove the electrical mains contamination. Then, the signals were passed through a band-pass filter with a pass-band of 0.1–100 Hz [23]. The reference electrodes were placed on the left and right mastoid processes.

Remote association and common association events were marked and extracted from EEG signals. For each event, blink artifacts were removed with the help of ICA. The ERP results for each event were represented by the averaged results of all participants and all event-related-task trials.

Results

Spectral Analysis

For each event, spectral analysis was conducted and the component percent variance was accounted for. The top-five component percent variances were selected and used as the cue to identify which brain areas were activated in the event. The Component number on component percent variances is consistent with the ICA component number. The results showed that for remote association (Fig. 1), Components 1, 5, 6, 2, 3 were top-five component percent variances. For common association (Fig. 2), Components 1, 4, 2, 3, 8 were top-five component percent variances. From the correlated ICA component of remote association and common association, it could be seen that both remote association and common association mainly relate to Fp1 and Fp2 channels areas which is the frontal lobe area.

ERPS Results

After identifying the activated brain areas, the study further analysed the ERPS results of each event. The ERPS results were analysed based on the related activated-brain-area EEG channels (Fp1/Fp2). The remote association's highest ERP was generated at 164 ms while the common association's highest ERP was generated at 95 ms (Fig. 3).

EEG Signals Tendency Results

The EEG signals tendency between remote association and common association were compared. The results are shown in Fig. 4. From comparison of the two association types' EEG signals, it can be seen that after the highest ERPS, the common association's ERPS generated discontinuously during the whole 8000 ms while the remote association's ERPS generated continuously for a short period.

Discussion

This section compares the findings with existing studies, discusses the comparison results, identifies the limitations of this study, and what is expected for future studies.

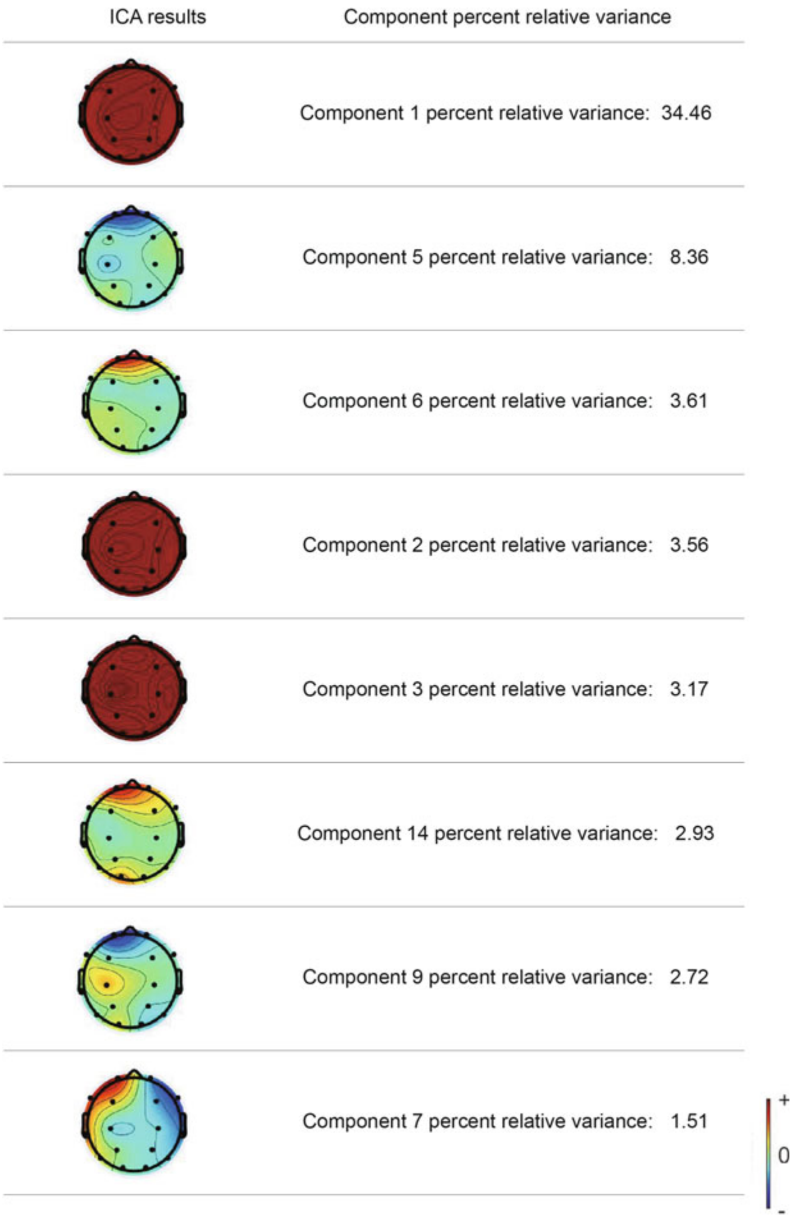

Fig. 1 Remote association task results: the top eight component percent relative variances and their ICA results

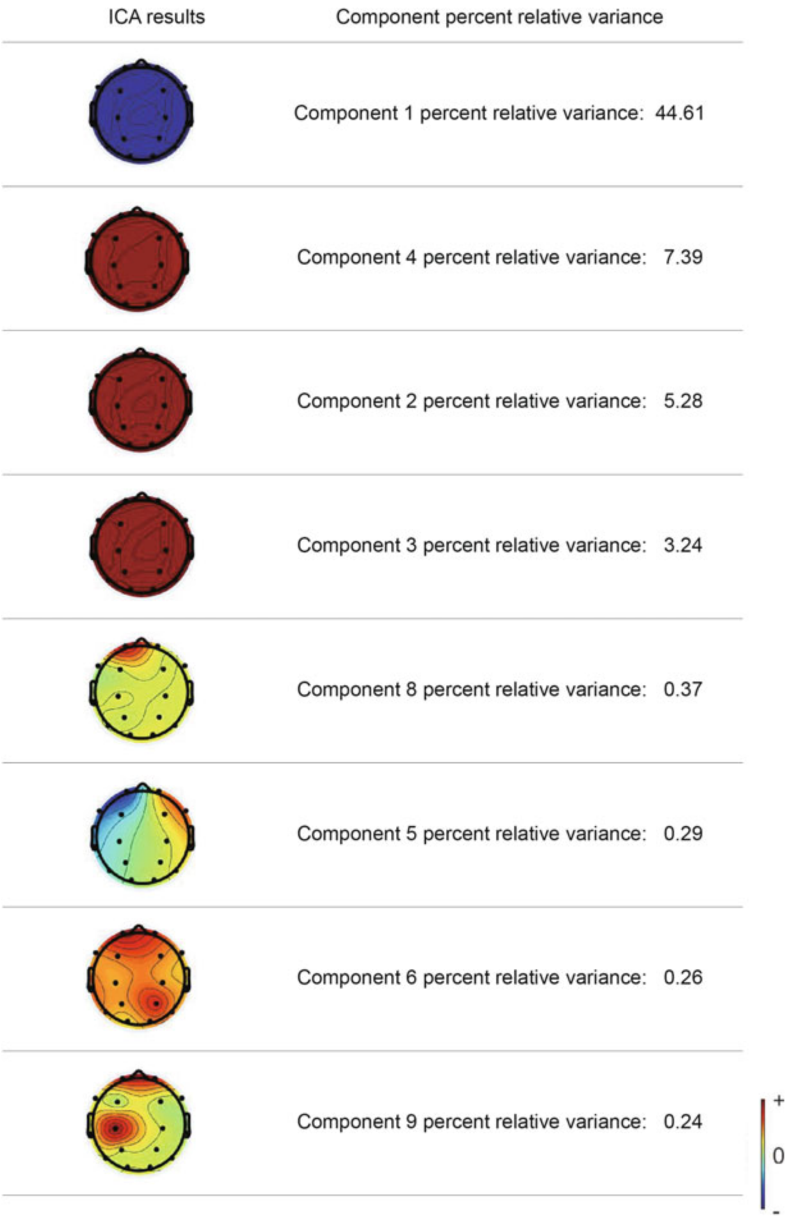

Fig. 2 Common association task results: the top eight component percent relative variances and their ICA results

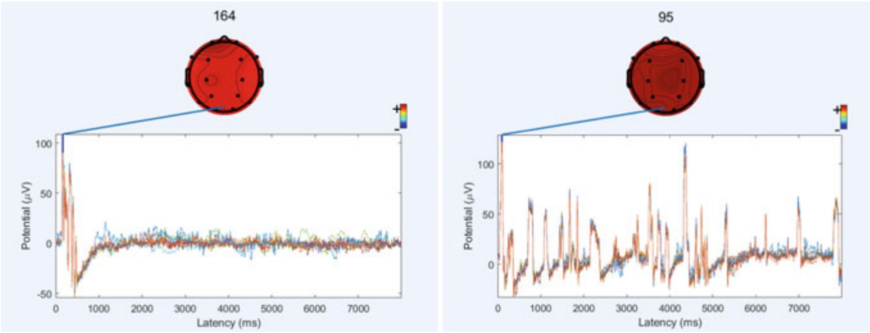

Fig. 3 Left figure: The highest ERP result of remote association on Fp1 channel. Right figure: The highest ERP result of common association on Fp1 channel

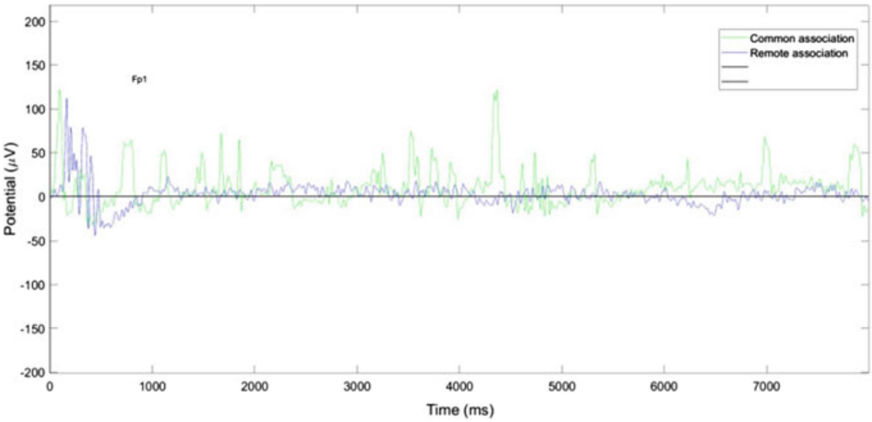

Fig. 4 The comparison results of EEG signals between remote association and common association on Fp1 channels

Compare the Findings with Existing Studies

The results of this study indicated that remote association is related to the frontal lobe and the highest ERPS was at 162 ms. This location result is related to some existing studies [19, 20]. However, the results is inconsistent with some other studies which support that the remote association is related to the left temporal lobe [8], and the right temporal lobe [21].

One possible explanation for this difference is that semantic memory and episodic memory are related to association [20]. When the brain areas related to remote association were activated, brain areas related to semantic memory and episodic memory may also be activated. Semantic memory is related to the activity of the frontopolar cortex [25] while episodic memory is related to the activity of the temporal lobe [26].

Therefore, the identified active brain areas of remote association may also include the active brain areas of semantic memory and episodic memory. This may be the reason why the active brain areas of remote association are different.

Comparing the EEG Activities for Remote Association and Common Association

From the study, both remote association and common association are related to the frontal lobe area. Apart from the similar results between remote association and common association, there are also some different results. For example, the highest ERPS result on remote association is 162 ms while that of common association is 95 ms. ERPS can quantitatively reflect the brain response to a specific cognitive event [22]. Therefore, the results revealed that the participants have a faster response to common association tasks than to remote association tasks [5, 11]. This may indicate the reason why common association is more likely to occur than remote association. When a creative person plans to use remote association to image some creative ideas, common association may occur and interrupt the remote association.

From the comparison, it has also revealed that after the highest ERPS, the common association's ERPS generated discontinuously in the whole 8000 ms while the remote association's ERPS generated continuously in a short period. This indicates that common association will occur swiftly when participants recognize the word or image and they will have a result quickly. Although remote association was evoked more slowly than common association, as long as it occurs, it will get a result quickly. However, the speed to obtain a remote association result is still slower than that of common association.

After generating one result, remote association will end, while common association will keep generating more results unconsciously. Thus, the ERPS of common association is discontinuous and lasted during the whole task period, while the ERPS of remote association is a one-time event in a short period. This further indicates and helps explain why in a creative design process, designers may have more results from common association than remote association. Also, this result indicated that without deliberate control, designers may be less likely to have remote association. In other words, remote association is a conscious cognitive behavior while common association can be regarded as an unconscious cognitive behavior.

These comparison results can also trigger thinking on how to stimulate remote association in a creative design process from cognitive levels. On the one hand, considering the remote association is a one-time cognitive behavior, the remote association stimulation method should be a continuous action. In this way, the continuous stimulation can maintain remote association actively in design for a period of time. On the other hand, considering the common association can occur repeatedly, if remote association can be triggered from each common association period, remote association can also occur repeatedly.

Limitations and Future Research

There are some limitations existing in this study. Firstly, this study only recruited 30 Chinese participants. The participants' culture and age may also affect the EEG results. In the future, more participants from different ages and cultures are expected.

In addition, the study tried to be conducted without any external intervention (such as movement and noise). However, spill-over effects cannot be ruled out completely. In other words, it may be possible that the previous task/trial affected the later task/trial. What the study can do is to limit the spill-over effects by presenting the two tasks in a random order and presenting the trials in each task in a random order. Also, even after denoising, the eyebrows' muscular movement cannot be completely removed from the EEG signals which may bring bias in this study.

Finally, the study was designed to ask participants to think in a remote association or common association way. However, the study cannot identify whether the tasks results of participants were remote association or common association results. Therefore, in the future, the study is expected to add remote association or common association results checking mechanism to further accurately identify whether the participants have a remote association or common association thinking in the related tasks.

Conclusion

Creativity is helpful to generate novel ideas in divergent thinking processes in design. To better understand design, identifying creativity is important. Association as an important cognitive factor related to creativity and is thus a good starting point. An EEG study was designed to identify and compare designers' EEG activities (ERPS and EEG signal tendency) of remote association and common association in creativity.

The results support that the association in creativity is mainly related to the frontal lobe brain area. The comparison results indicated that when common association and remote association processes are evoked in the brain, both of the processes can lead to a result quickly. However, the common association was evoked faster than remote association. Also, after generating one result, remote association will stop while common association will keep generating more results unconsciously. These results further explain why the common association is more likely to occur than remote association from an ERPS perspective.

The results prompt reconsidering association control and stimulation methods in design. To be specific, to stimulate remote association process, continuous stimulation may be needed. Also, one possible direction for future work that could provide insights could focus on whether remote association can be triggered by common association.

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Characterization of Design Brain States Over Time When Using Morphological Analysis and TRIZ

Julie Milovanovic, John Gero, Tripp Shealy, and Mo Hu

In this paper, we explored changes in brain states over time while designers were generating concepts. Participants either used morphological analysis or TRIZ to develop a design concept for two design tasks. While designing, participants' brain activation in their prefrontal cortex (PFC) was monitored with a functional Near Infrared Spectroscopy machine. To identify variation in brain states, we analyzed changes in brain networks. Using k-mean clustering to classify brain networks for each task revealed four brain network patterns. While using morphological analysis, the occurrence of each pattern was similar along the design steps. For TRIZ, some brain states dominated depending on the design step. Drain states changes suggests that designers alternate engaging certain subregions of the PFC. This approach to studying brain behavior provides a more granular understanding of the evolution of design brain states over time. Findings add to the growing body of research exploring design neurocognition.

Introduction

Characterizing the underlying patterns in the brain when engaged in designing [1] and creative thinking [2] offers new knowledge on design thinking and design processes. It also offers a potential to increase the efficiency and objectivity of methods used in design research to measure design cognition [3]. A deeper understanding of brain behavior while designing could lead to the development of a new family of design

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tools based on brain signals, for example, providing designers with neuro-cognitive feedback during design [4].

Prior studies in design neurocognition have tackled the differences between problem-solving and open-ended design tasks [5, 6], the effect of expertise in problem solving [7] and the effect of sketching on neurocognitive behavior [8]. Those studies suggest that problem-solving and open-ended tasks recruit different brain regions [5, 6]. Activation in parietal regions for experts and novices appeared different while design problem solving, that could be related to expertise [7]. Sketching tends to increase Alpha waves that suggests a more relaxed state after drawing [8]. Other research looked at brain activation when providing designers with an input for analogical reasoning by displaying visual stimuli [9]. Temporally, some brain regions are more engaged with inspirational stimuli than without [9]. In this paper, we focus on analyzing brain states over different steps of the design process.

In our prior work, we analyzed designers brain activation using three design techniques while designers ideated [10, 11] and explored changes in brain network over time [12]. The research reported in these previous papers focused on the ideation phase only. They did not include brain behavior analysis of problem identification and analysis, which is an important step of the design process. In a recent paper, we inquired about brain behavior changes during other phases of design like problem identification [13]. The findings from this prior study suggested that the prefrontal cortex was recruited differently depending on the design phase, either concept generation or problem identification.

In the present paper, we build on these prior findings to explore the dynamic functional connectivity of designers' brains while generating concepts with morphological analysis or TRIZ. The motivation for this research was to examine whether specific brain states characterize design cognition processes such as problem identification or ideation. We studied morphological analysis and TRIZ because they induce a structured approach to designing. This way, we could identify design phases and track their related brain behavior. Functional connectivity in the brain was assessed by identifying brain regions that synchronize, meaning that they activate and deactivate concurrently [14]. Co-activation of brain regions could imply information transfer between those regions [15]. Dynamic functional connectivity focuses on analyzing changes in brain states of synchronization over time [16]. The implications of the findings presented in this paper are two-fold: providing new insights about whether the cognitive processes that occur in design can be mapped to brain behaviors, and subsequently, further developing new methods to study design neurocognition.

Background

Two Approaches to Concept Generation: Characteristics of Morphological Analysis and TRIZ

Designers rely on a variety of techniques to assist them in their design process, for instance brainstorming or concept maps. The type of technique influences how designers advance in the design process [17]. In this study we focused on two techniques, morphological analysis and TRIZ. Morphological analysis relies on a two-step process starting with an analytic strategy to decompose the problem followed by a systematic association of partial solutions to sub-problems to stimulate unconscious thoughts [18]. An example of morphological analysis provided by Alexander [19] was a kettle to boil water. The kettle's requirements could be subdivided into design problems related to safety (e.g., able to withstand the temperature of boiling water), use (e.g., easy to grasp when it is hot, easy to store), or maintenance (e.g., easy to clean) [19]. Each sub-problem can be addressed by a sub-solution, for example a plastic handle will solve the 'easy to grasp when it is hot' sub-problem. Each sub-solution is then synthesized into an overall design solution.

TRIZ, or the Theory of Inventive Principles, provides even more structure to the concept generation process, with a set of procedures to generate inventive solutions by defining the problem and looking at existing solution principles, before developing a solution [20, 21]. Using TRIZ, designers first identify contradictions in a design problem, solve the problem at a conceptual level then adapt it to a solution within the context of their specific constraints. The most popular TRIZ tools include the use of the contradiction table to identify contradictions in the design problem. Once contradictions are defined, designers will search for existing principles to address contradictions at a conceptual level. The inventive principles list was built from recurring patterns observed by Altshuller in patented technologies [20]. TRIZ's inventive principles are a set of conceptual solutions for technical problems that drive the process of problem solving and innovation. These inventive principles offer conceptual solutions to conceptual problems defined by the contradiction matrix. With TRIZ, designers seek a match between the problem and the solution at the conceptual level [20, 21]. The last step in TRIZ consists of transforming the conceptual solution into a solution that adapts to the real context of the design brief. In practice, TRIZ is used by professionals to promote innovation rapidly, increase the competitiveness of a company using this approach and adapt to new regulations [22].

In general, more structuredness in the concept generation technique, as in morphological analysis and TRIZ, leads to more reasoning on the design problem [17]. Using one technique or the other has an effect on cognitive processes [17, 23]. Recent studies highlight that concept generation technique implementation also alter brain behaviors [10, 12] that could be related to cognitive processes designers engaged in [13].

Design processes can be analyze by design researchers through a multitude of methods like protocol analysis [24], direct observations or retrospective interviews [25]. In this study, we explored the potential of analyzing brain states to inform our understanding of the design processes.

Using Dynamic Functional Connectivity to Identify Brain States

Higher order cognitive tasks like designing can involve multiple brain regions. Functional connectivity in the brain is assessed by identifying several brain regions that synchronize, meaning that they activate and deactivate concurrently [14]. In other words, two regions can be functionally connected if they have coherent and synchronized dynamics. Brain networks are representations of functional connectivity and stand as useful tools to study complementary characteristics of brain activation during a task [14, 26, 27]. Analyzing static functional connectivity in design tasks provides insights into patterns of brain region synchronization that could be related to specific cognitive tasks [12]. Research in creative cognition studying the whole brain points toward a coordination of two types of networks to generate creative ideas, the default mode network and the executive network [28, 29]. Both networks are associated with creative tasks like ideation: the default network is recruited for mind wandering and imagination while the executive network is engaged during goal directed tasks like problem solving [29].

Recently, the use of functional connectivity over time has provided a new method to describe the fundamental properties of how the brain functions [16]. Using a sliding window approach, the functional connectivity can be measured over time. By applying clustering methods to correlation matrices of brain regions, connectivity states or recurring patterns of region-to-region correlations can describe brain functions and the effect of morphological analysis and TRIZ [16]. Interestingly, the dominance of some brain states, like a cooperation between the default and executive network, correlate with creative personality traits [30].

For design research, an interest in dynamic functional connectivity is twofold. First, such techniques help associate brains states and cognitive function. It provides new knowledge, mapping brain activity and design cognition. Second, it can provide an alternative method to studying design tasks. Instead of solely relying on protocol analysis or direct observations methods to study design cognition [25], brain behavior, for instance EEG microstates, or fNIRS network analysis, might be useful to identify design processes in protocols [3].

Methodology

Experiment Design

Thirty graduate engineering students (all right-handed, 22–26 years old) were recruited to participate in the study. All participants had taken courses in engineering design. None were familiar with TRIZ or morphological analysis so they were given instructions on using these techniques in their design course. Participants were presented with the task and equipped with the fNIRS cap in the lab's experiment room. Each participant generated concepts for the following design tasks: designing an alarm clock for the hearing impaired, and designing a kitchen measuring tool for the blind. They were randomly assigned one design technique to engage in each concept generation task. The order in which design tasks were presented was random. No time limit was given to participants. Students were encouraged to draw their design on paper or write their ideas (Fig. 2). The fNIRS cap is suitable for such tasks thanks to its robustness to movement [31].

Morphological analysis and TRIZ are structured in phases that were tracked during the experiment. For morphological analysis, three phases were monitored. The first phase was for participants to define and decompose the problem. The second phase was to generate multiple sub-solutions to each sub-problem. Participants were invited to generate a morphological chart where sub-functions are associated to a sub-solution. For example, sub-functions of an alarm clock could be to provide a signal to users, adapt to sleeping cycles, or providing time. Examples of sub-solutions that fit those subfunctions, respectively, were to vibrate or emit smell as a signal, identify the users' sleep cycle through heart rate monitoring, and display time through a visual display. The final step was the ideation phase where participants integrated all of the sub-solutions into a coherent final design.

Using TRIZ, participants engaged in four distinct phases. First, participants were asked to read the brief and to define the problem. Then, they used Altshuller's 39 engineering parameters to search for a physical contradiction and well-solved problems that correspond to their specific problem [20]. In this phase, the design problem was set up through parameters such as "the weight of the object", its "shape", "strength" or its "convenience of use". In that stage, the task was to identify physical contradiction related to the function of the object. For example, when designing an umbrella, a bigger size would protect the user better but also make it cumbersome to carry around [21]. Therefore, the size of the object is a physical contradiction.

The third step consisted of adapting some of the 40 inventive principles to solve the current problem. The contradiction matrix provided a list of relevant inventive principles to resolve the contradictions formulated in the previous step, based on the specific parameters selected. These inventive principles provided conceptual solutions. For example, principle 23 about feedback, refers to introducing feedback to improve a process or adapt the feedback according to operating conditions. This principle is found at the intersection of the parameter "productivity" (improving feature) and "loss of information" (worsening feature) in the contradiction matrix.

The final step of the task was the ideation phase where participants generated a solution based on the principle from the contradiction matrix. In the case of the alarm clock, the feedback principle could be applied to the current problem as one could imagine a tactile signal indicating the time to wake up. For both TRIZ and morphological analysis, participants moved through the steps linearly without iteration revisiting previous steps.

Data Collection

Participants were equipped with a function Near Infrared Spectroscopy (fNIRS) cap from the LIGHTNIRS system (Shimadzu Co., Japan Kyoto) with a sampling frequency of 4.44 Hz (Fig. 1a). fNIRS is a tool to measure brain activation by monitoring metabolic demands (oxygen consumption) of active neurons [32, 33], with a penetration depth of about three centimeters. In the fNIRS cap, light is emitted from sources at specific wavelengths (between 700 and 900 nm) into the scalp. The light scatters, before reflecting back to the light receivers. The oxy-hemoglobin (oxy-Hb) and deoxy-hemoglobin (deoxy-Hb) absorb more light than water and other tissue in the brain. The change in the difference between the emitted light and reflected light is used to calculate the change in oxygenated blood using a Modified Beer-Lambert Law.

fNIRS is suited for naturalistic environments. Participants can perform the design task in an upright sitting position [4–6]. Three wavelengths of near-infrared light (780, 805, and 830 nm respectively) were used by this fNIRS system to record a change in participants' oxy-Hb. We only report oxy-Hb due to its relatively higher amplitudes and sensitivity to cognitive activities than deoxy-Hb.

The sensor placement on the fNIRS cap is illustrated in Fig. 1b. We used 16 sensors (eight emitters and eight detectors) located using the 10/20 international systems. The 16 sensors covered the frontal part of the 10/20 system. The eight emitters and eight detectors formed a total of 22 channels. A channel (grey lines in Fig. 1b) is the combination of a light source (red squares in Fig. 1b) and a nearby light receiver (blue squares in Fig. 1b). The 22 channels capture the change in oxygenated cortical blood in the PFC. Multiple sub-regions in the PFC are covered: the dorsolateral prefrontal cortex (DLPFC: channels 1, 2, 3, 9, 10 in the right hemisphere, and channels 5, 6, 7, 13, and 14 in the left hemisphere), the ventrolateral prefrontal cortex (VLPFC: channels 16 and 17 in the right hemisphere, and channels 21 and 22 in the left hemisphere), the orbitofrontal cortex (OFC: channel 18 in the right hemisphere, and channel 20 in the left hemisphere), and medial prefrontal cortex (mPFC: channels 4, 11, 12 and 19) in both hemispheres.

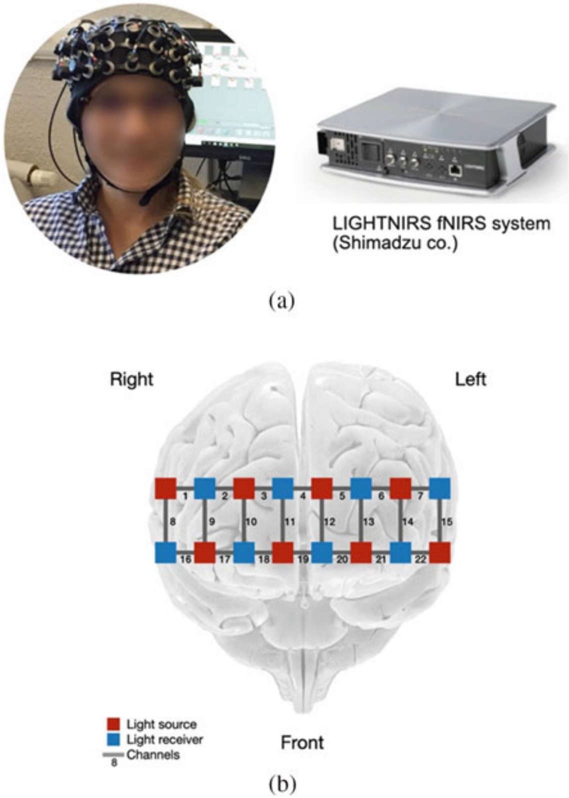

Fig. 1 **a** Participant set up for the experiment. **b** Placement of the fNIRS cap sensors on the prefrontal cortex

Data Analysis

To pre-process the raw fNIRS data, the steps taken were based on previous fNIRS studies [34–36]. Out of the 30 participants, three subjects were removed from the analysis due to bad signals. The remaining fNIRS raw data were processed using a bandpass filter (frequency ranging between 0.01 and 0.1 Hz, third-order Butterworth filter) to remove high-frequency instrumental and low-frequency psychological noise [37]. To remove motion artifacts, ICA (independent component analysis) with a coefficient of spatial uniformity (CSU) of 0.5 was applied. The filtering process was done with Shimadzu fNIRS software. The analysis was based on filtered oxy-Hb, which aligns with previous studies [38, 39]. Oxy-Hb signals were z transformed to normalize the data across subjects before conducting further analysis.

The following steps of the methodology are presented in Fig. 2. After pre-processing the data, each subject data was segmented into a window of 5 s. Functional connectivity was assessed for each window. Functional connectivity is defined as a statistical dependence between the time series of measured neurophysiological signals [14]. In this study, a Pearson correlation matrix between variations in oxy-Hb

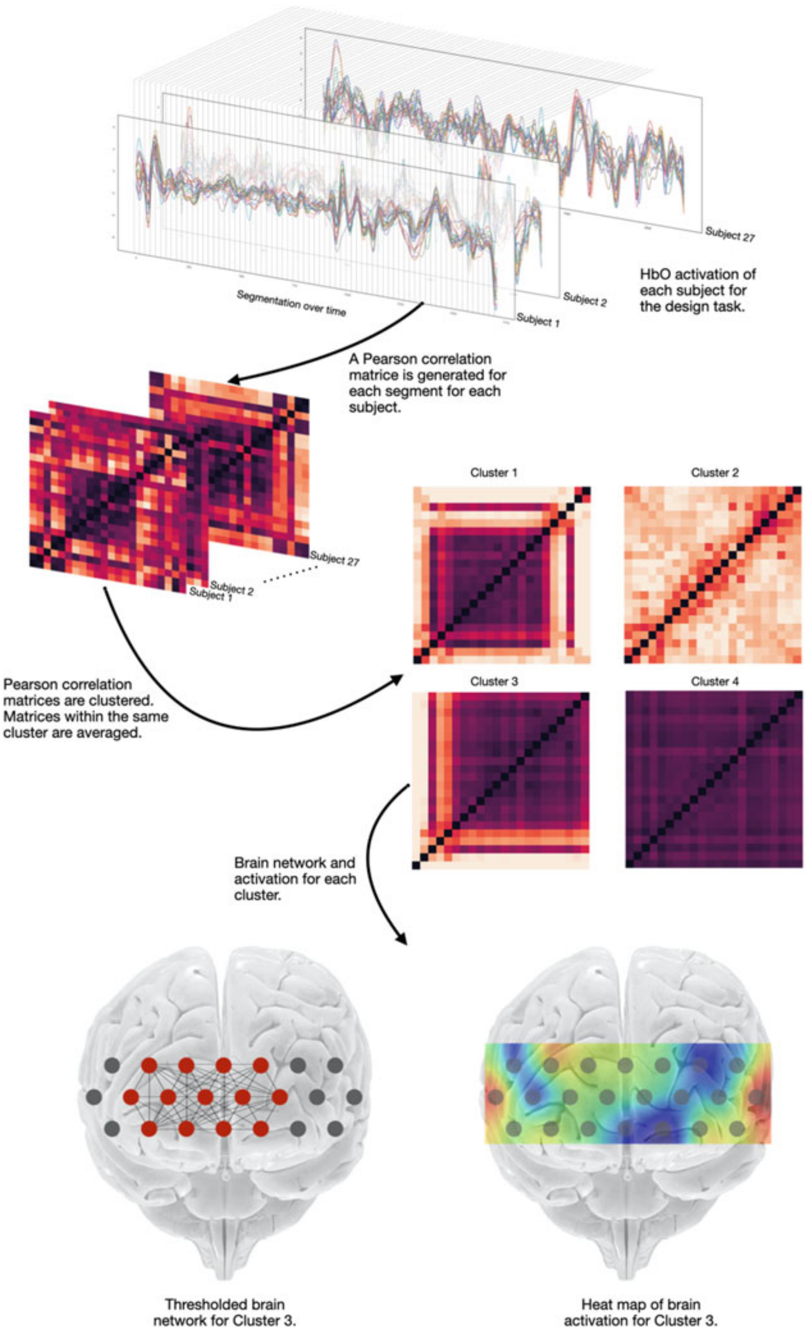

Fig. 2 Steps of the analysis. The brain signals are segmented. For each segment, a Pearson correlation matrix is generated. Matrices are clustered to define brain states. From the average matrix for each state, the network represents coactivation patterns and the activation heatmap inform on higher activation regions

processed signal channels provided an indicator of similarity activation between two channels. It follows methods from prior studies [40–42]. The time window value was selected because it allowed sufficient data points per window to obtain a reliable measure of the Pearson correlation while having enough windows for each morphological analysis or TRIZ phase. Multiple time window durations were tested (including 10 and 15 s) that provided similar results.

For each technique, the matrices capturing coactivation between channels for each participant were generated. Correlation values for two channels range from -1 to $+1$. A value of -1 signified that both channels followed opposite behaviors and $+1$ implies that the channels displayed the exact same behavior. The correlation of activation was evaluated using the segment time of 5 s. In total, 3,862 matrices were produced for the TRIZ dataset and 3,249 matrices were generated for the morphological analysis dataset. The matrices were then clustered using k-means clustering (Scikit-Learn package in Python). The matrices were classified within four clusters that subsequently defined four types of brain networks occurring while designing. We used the Elbow method to define the appropriate number of clusters [43]. Using a threshold on the correlation matrix, a network of the most correlated nodes was generated, i.e., nodes that undergo a similar trend of activation across time. There is no consensus on the particular value for the threshold to be used [14]. A range of plausible global threshold coefficients (incrementally from 0.6 to 0.7) was used in prior studies [15, 44]. In this study, a correlation coefficient of 0.7 was used.

The networks that met the threshold represented potential functional relationships between synchronized activation in different brain regions for each brain state. For each state, we generated a heatmap of the activation of channels to better define each brain state. This part of the analysis was conducted using Python libraries (Numpy, Pandas, and Networkx) (see Fig. 2). To test whether some clusters were particular to one phase in the design process, we compared the distribution of each cluster for each phase. The statistical difference in the distribution of each type of brain state for each phase was compared using t-tests. The data was tested for normality (Shapiro–Wilk test) and variance (using the SciPy package in Python).

Results

Identification of Brain States When Generating Concepts with Morphological Analysis

Students took on average 11 min for the design task using morphological analysis. On average, they spent a few seconds to define the problem, 5 and half minutes to generate multiple sub-solutions and 4 min to generate a final idea.

The cluster analysis identified four brain states during concept generation with morphological analysis. Each state describes a certain degree of synchronization of the PFC sub-regions. The distribution of the four brain states was similar for each of the three design phases of morphological analysis (problem decomposition phase, generation of sub-solution phase and the ideation phase).

The most frequent state was defined by a high coordination of sub-regions within the PFC (see brain network for Cluster 3_{MA} in Fig. 3a). On average, participants entered that brain state for 34.2–37.2% of the time during the design task (Table 1). All the nodes from this brain network state were connected to each other. Most regions within the PFC were activated when designers experienced that state (see brain activation for Cluster 3_{MA} in Fig. 3a).

In one of the states, the channels were not synchronized which implies that sub-regions of the PFC activated in different ways (see brain network for Cluster 1MA in Fig. 3a). In this state, the highest activation occurred in the right part of the DLPFC (dorsolateral PFC) and VLPFC (ventrolateral PFC) as well as in the lower part of the medial PFC (see brain activation for Cluster 1_{MA} in Fig. 3a). This state was the second most frequent state within all three design steps of morphological analysis. It occurred for 36.8% of the time during the problem decomposition phase, 34.5% of the time during the generation of sub-solution and 32.7% of the time during the

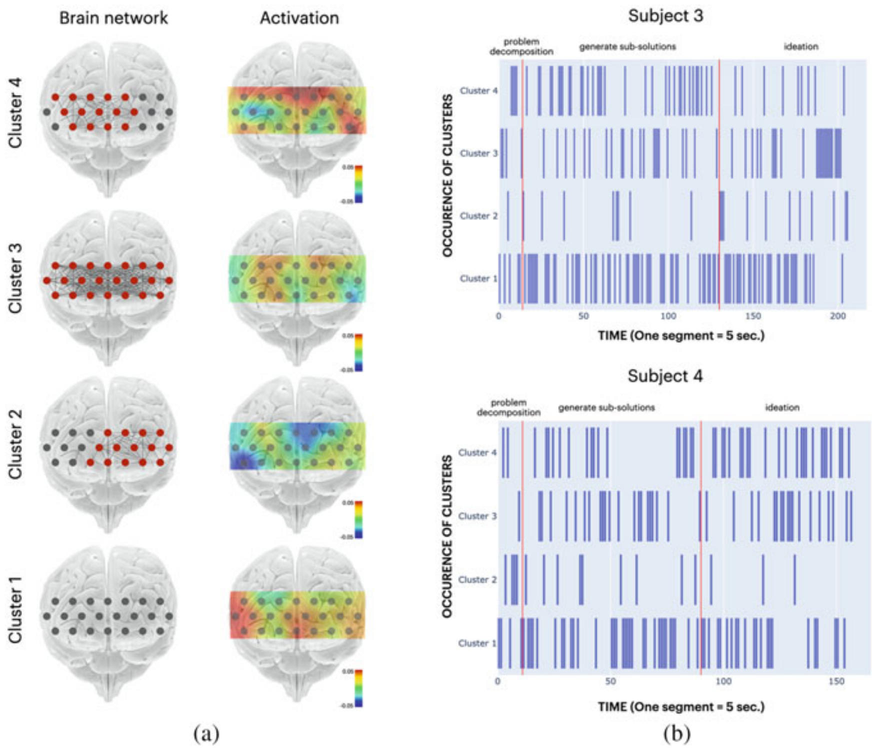

Fig. 3 **a** Representation of the brain network and brain activation in the PFC for each cluster of the morphological analysis concept generation. **b** Example of the occurrence of brain states over time for two subjects

Table 1 Distribution of brain state per phases of morphological analysis

	Problem decomposition %, (SD)	Generate sub-solutions %, (SD)	Ideation %, (SD)
Cluster 1_{MA}	36.8 (31.0)	34.5 (21.0)	32.7 (17.3)
Cluster 2_{MA}	15.8 (16.5)	16.1 (12.8)	18.0 (13.7)
Cluster 3_{MA}	34.3 (34.2)	34.2 (18.7)	37.2 (17.8)
Cluster 4_{MA}	13.1 (15.4)	15.1 (11.6)	12.1 (11.3)

ideation phase (Table 1). Figure 3b provides an example of the occurrence of this state over time for two subjects.

The other two states were characterized by a brain network that connected sub-regions within the medial and the right part of the PFC (see brain network for Cluster 4_{MA} in Fig. 3a) or that connected sub-regions within the medial and left part of the PFC (see brain activation for Cluster 2_{MA} in Fig. 3a). Brain activation for the Cluster 2_{MA} state was mainly in the left DLPFC and VLPFC (see brain activation for Cluster 2_{MA} in Fig. 3a) while the brain activation for the Cluster 3_{MA} state was in the medial part of the PFC.

The occurrence of the identified states over time varied for each subject as exemplified in the timeline represented in Fig. 3b.

Identification of Brain States When Generating Concepts with TRIZ

Students spent 13 min on average generating a concept using TRIZ. They spent about 57 s reading the task and defining the problem, 3 min searching for engineering parameters, 5 and a half minutes searching for inventive principles to adapt to their design problem and 4 min to generate a solution.

Four brain states were identified through the cluster analysis when participants used TRIZ to generate concepts. Cluster 1_{TRIZ} state was one of the most frequent states during the design activity. It occurred between 28.0 and 37.3% of the time depending on the phase (Table 2). This state was characterized by a synchronization of each channel activation, represented by a highly connected brain network (see brain network for Cluster 1_{TRIZ} in Fig. 4a). The highest activation appeared in the medial part of the PFC (see activation heatmap for Cluster 2_{TRIZ} in Fig. 4a). This state was the most frequent in the ideation phase. The occurrence of this state during ideation was significantly higher than during the problem decomposition phase ($t(52) = 2.33$, $p = 0.03$), while searching for parameters ($t(52) = 2.54$, $p = 0.02$) and selecting an inventive principal ($t(52) = 2.05$, $p = 0.049$).

Cluster 2_{TRIZ} state was characterized by a high desynchronization of the PFC sub-regions. The correlation of activation for channels in this cluster was below the network threshold of 0.7 (no edges appear in the brain network for Cluster 2_{TRIZ}, see

Table 2 Distribution of brain state per phases of TRIZ averaged across participants

	Problem definition %, (SD)	Search parameters %, (SD)	Select inventive principles %, (SD)	Ideation %, (SD)
Cluster 1_{TRIZ}	28.0 (21.5)	30.4 (16.2)	32.0 (16.1)	37.3 (20.0)*
Cluster 2_{TRIZ}	40.8 (27.3)	38.8 (21.1)	37.8 (19.6)	35.0 (21.9)
Cluster 3_{TRIZ}	16.8 (17.4)	16.6 (13.5)	16.2 (13.5)	12.6 (10.8)
Cluster 4_{TRIZ}	13.8 (15.2)	14.5 (19.0)	14.2 (17.8)	15.3 (13.6)

[*] Distribution of cluster 1_{TRIZ} for ideation is significantly higher than for the other phases

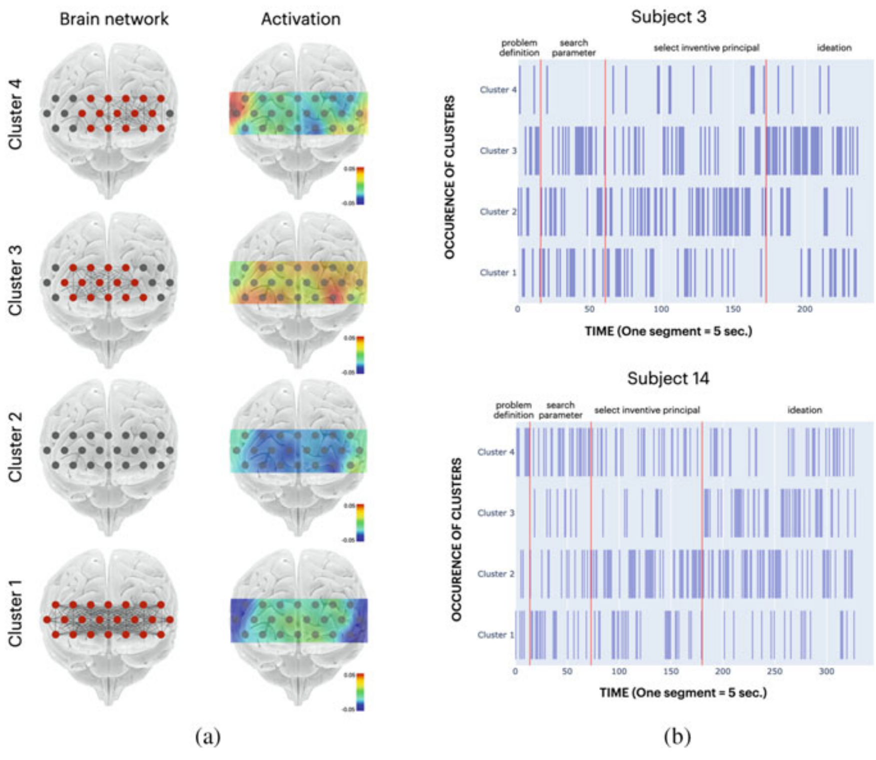

Fig. 4 **a** Representation of the brain network and brain activation in the PFC for each cluster of the TRIZ concept generation. **b** Example of the occurrence of brain states over time for two subjects

Fig. 4a). During this state of desynchronization in the PFC, the PFC was deactivated compared to other states (see activation heatmap for Cluster 2_{TRIZ} in Fig. 4a). On average, participants experienced this brain state between 35.0 and 40.8% of the time (Table 2).

The last two states represented less than 17% of brain states during any phases of TRIZ. Cluster 3_{TRIZ} was characterized by a higher synchronization of the medial and right part of the PFC (see brain network for Cluster 3_{TRIZ} in Fig. 4a). The activation for this state was higher in two channels in the right and left VLPFC (see activation heatmap for Cluster 2_{TRIZ} in Fig. 4a). This state was less frequent during the ideation phase of TRIZ.

The brain state defined by Cluster 4_{TRIZ} was characterized by a higher synchronization of the medial and left part of the PFC (see brain network for Cluster 4_{TRIZ} in Fig. 4a). In this state, higher activation occurred in the left VLPFC and the lateral part of the right DLPFC (see heatmap for Cluster 4_{TRIZ} in Fig. 4a). This state was more frequent in the ideation phase than in any other phase of TRIZ.

For each participant, the four brain states occurred with different frequency and organization within phases. For example, in the timeline representing the occurrence of brain states for two participants (Fig. 4b), we see that subject 3 experienced Cluster 4_{TRIZ} brain state much more frequently than subject 14.

Discussion and Limitations

The analysis of dynamic functional connectivity in the brain of designers provides new insight into the brain states need for generating concepts. Two parallel analyses were carried out to assess brain states when using two different techniques, morphological analysis and TRIZ. The four states that occurred when using each technique are similar. This agrees with our expectations based on cognitive studies that identify similar general cognitive actions in designing [45, 46]. One brain state was characterized by a desynchronization of the PFC (Cluster 1_{MA} state when using morphological analysis and Cluster 2_{TRIZ} state when using TRIZ). It implies that the activation of sub-regions of the PFC were not following similar trends of activation over the time window. This state was the most frequent when using both types of techniques. The average pattern of activation for both states was different between techniques: in morphological analysis, higher activation occurred in the left and medial on the PFC while for TRIZ, we observed a deactivation of the PFC with bilateral activation in the lateral part of the PFC.

Another dominant brain state was characterized by a synchronization of all the sub-regions in the PFC (Cluster 3_{MA} state when using morphological analysis and Cluster 1_{TRIZ} state when using TRIZ). This state corresponds to an activation of the whole PFC in both cases. Only for TRIZ was this state significantly more frequent in the ideation phase compared to the other phase.

The other two states suggest a synchronization of the medial and left part of the PFC (cluster 2 state when using morphological analysis and cluster 4 state when using TRIZ) or the medial and right part of the PFC (cluster 4 state when using morphological analysis and cluster 3 state when using TRIZ).

In design cognition studies, concept generation phases are qualified by similar yet different cognitive effort [17]. Therefore, we expected brain state dominance to better characterize the concept generation phase, as previously demonstrated in an EEG study that analyzed microstates [3]. The results from the study presented here clearly demonstrate a variation of brain state over time, but falls short in relying on those states to inform cognitive processes. These results could imply that although cognitive processes are different over time when designing (focusing on problem identification versus ideation), brain functional connectivities are alike. This does not directly align with previous findings in design neurocognition that suggest a change in behavior depending on the phase of a concept generation tasks [5, 13].

These results could also be a consequence of limitations of the experimental setting. In a recent study on identifying microstates while designing [3], the EEG microstate dominance over time accounted for the switch in cognitive tasks. In this previous study, cognitive tasks were analyzed based on video protocol analysis while in our study, the phases were preset and tracked during the task. This could have led to an inaccurate segmentation of the design task into phases that do not correspond to cognitive tasks. To lift that limitation, future work should measure protocol analysis and brain state analysis concurrently.

Only the PFC was monitored during our tasks. Brain networks are usually assessed at the whole brain level (see default mode network and the executive network [28, 29]). In [3], the microstates were found based on the whole brain electrical behavior. This could provide an explanation for our results: brain activation in the PFC could be similar for each phase of the concept generation process but its functional connectivity to other regions of the brain could differ. In an ongoing study, we are collecting designers' brain behavior for the whole brain. Our future work will focus on applying a similar methodology to whole brain activation data to overcome the current limitation of the study presented here.

Conclusion

In this paper, we explored the dynamic functional connectivity of the brains of designers (engineering students) while generating concepts to two different design tasks: designing an alarm clock for the hearing impaired, and designing a kitchen measuring tool for the blind. For each task, participant used a design technique to help them with concept generation. For one of the tasks, they applied morphological analysis while for the other they developed a solution following the TRIZ approach. Each technique is structured in phases such as problem identification, generating subsolutions or ideation. Brain behaviors was monitored to assess activation patterns over time. Functional connectivity explores whether two distinct brain regions synchronize (activate/deactivate in similar patterns). Our results highlighted four similar brain states that designers experienced when generating concepts with morphological analysis and TRIZ. Contrary to our expectations, each brain states occurred in each phase of the concept generation process. Nonetheless, analyzing the dynamic functional connectivity of designers' brain behavior while designing offers a potential better understanding of design neurocognition. Our study was limited to the PFC, which could explain the lack of correlation between brain states and design cognition phases. The findings from this study will serve as inputs for future research in that direction. Better understanding of design neurocognition provides the foundation for design tools based on neurofeedback [4], a direction worth exploring in the future [47].

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Learning and Design

Representing Design Cognition Through 3-D Deep Generative Models

Başak Çakmak and Cihan Öngün

This paper aims to explore alternative representations of the physical architecture using its real-world sensory data through Artificial Neural Networks (ANNs), which is a simulated form of cognition having the ability to learn. In the project developed for this research, a detailed 3-D point cloud model is produced by scanning a physical structure with LiDAR. Then, point cloud data and mesh models are divided into parts according to architectural references and part-whole relationships with various techniques to create datasets. A Deep Learning Model is trained using these datasets, and new 3-D models produced by Deep Generative Models are examined. These new 3-D models, which are embodied in different representations, such as point clouds, mesh models, and bounding boxes, are used as a design vocabulary, and combinatorial formations are generated from them.

Background

The present research aims to use physical world structures to be decoded by various information processing methods to explore representations of design cognition. The methodology used in this research is based on Artificial Neural Networks (ANNs), more specifically, Deep Generative Models. Therefore, in this section, 3-D Deep Generative Models and related works in the field of design computing are discussed in order to distinguish the specific contribution of this research to the field.

Generative Models aim to generate new data from the same distribution of given training data. With the advancements in Artificial Neural Networks, Deep Generative Models are proposed, which can outperform the previous studies. Generative Adversarial Networks (GAN) [1] consists of 2 different Artificial Neural Networks that play

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an adversarial minimax game against each other; Generator G and Discriminator D. The Generator aims to generate novel realistic samples, and the Discriminator tries to distinguish between real and fake samples. At each iteration, Discriminator gets better at identifying fake samples, and the generator, using the feedback from the Discriminator, generates more realistic samples to fool the Discriminator. GANs are one of the state-of-the-art Generative Models and are highly used in all kinds of generative tasks. AutoEncoders are encoder-decoder models which are used in the Artificial Neural Networks field. They are used for encoding the data into reduced dimensions and then decoding it to get the input data again. The aim is to represent the data in lower dimensions, extracting important features and learning underlying structures in the data with minimum error.

In the existing research, Zhang [2] used 3-D models for training GAN. The study translates 3-D modes into 2-D images to use in the system. Various popular Generative Models, such as Pix2Pix [3] and CycleGAN [4], were used in the research. In this alternative application of Neural Style Transfer, the aim was to create a 3-D form by positioning 2-D outputs in different directions. Zhang [2] aimed to generate 3-D models with StyleGAN [5], which is a state-of-the-art Generative Model that was trained with the reconstruction of 3-D models in various complex concepts. It was mentioned that the 3-D model is composed of changing images, and these images were used as a dataset to create new 3-D models on various complexity levels of input. In one of the researches on Deep Generative Models, using a dataset that included house plans that have a specific architectural character, GAN was used to generate new plans that had the features of this architecture [6].

Liu et al. [7] produced 3-D model parts that have a reference to specific architectural styles, further combined to create more complex models that have various design references. After that, rendered images were used as a database for GAN. The image results were presented in the environments according to their concepts. In another study, Peng et al. [8] worked on a dataset, including parts of 3-D models, to decode architectural space using Machine Learning and Computer Vision. These models were the buildings of renowned architects. It was expected to recognize specific local compositions in these partial models to produce new compositions. Images of model parts were used for training a Neural Network, and new 3-D configurations were created by post-processing on 2-D output.

Point clouds are a set of unstructured points in a 3-D coordinate system that represents real-world 3-D objects. It is mostly used in robotic applications and 3-D scanners like LiDAR. It is the most used capturing technique to digitalize real-world structures. To calculate the similarity of point clouds for reconstruction, Chamfer Distance is used [9]. It is a nearest neighbor distance metric for point sets. It is permutation invariant to work on unordered sets. Bidgoli and Veloso [10] used an AutoEncoder for point clouds to provide a new generation of 3-D objects. They mentioned the advantages of using point cloud for 3-D representations in Machine Learning because it allows producing samples both by using a digital model and by scanning physical objects using LiDAR Scanners.

In this research, a GAN is used to generate new samples from the learned architectural character encoded in a physical structure. Also, an AutoEncoder is used in this study to learn and encode the common style of input samples. Since we aim to learn from the information of design cognition using a real-world structure, we choose to work on point clouds instead of other 3-D representation methods such as Polygonal Meshes or 3-D Voxels. In most of the existing works, 2-D generative models were used due to the difficulties encountered in 3-D processing in Machine Learning (ML). The present research examines the production of the design cognition, which is the built-in architecture, in detail to explore its alternative representations. The study uses generative models in a 3-D environment during the process of automation to decode the real-world data and investigates the morphology that creates a character by conscious design decisions.

Aims

Design elements come together by conscious design decisions to provide the morphology that creates a specific character. This computational design research is problematized by questioning how well this character can be learned. The design, which is formed by the combination of elements, encodes design decisions within the whole as well as in its parts. In this study, a design context is investigated by producing alternative representations transforming the information of the physical structure.

In this study, an architectural design is examined with its point cloud geometry produced with LiDAR Scanner. This data provides the coordinate of every single point of the building within its context. The point cloud and mesh model of the architectural structure are manipulated and transformed to produce datasets and operate through information processing systems. By processing these datasets with Artificial Neural Networks, which is a simulated form of cognition having the ability to learn [11], the relationship between the cognitive processes and design (itself part of the real-world) is examined within a computational environment. This research aims to answer the following questions:

- What data types and representations can be used for the analysis of the physical structure to generate alternative representations?
- How should architectural structures be transformed while creating data sets in order to decode the design features in real-world structures?
- What are the information processing models suitable for decoding the information of design cognition in physical structure?
- How can information processing models designed with this approach be used in the production of alternative representations?

Significance

This research will provide an alternative generative design method by the use of 3-D Deep Generative Models. The study uses the building parts of an architectural context for providing the generation of a specific design vocabulary. Recent studies in the field are seen to bypass the information in the 3-D contexts, which is difficult to collect and process, to enhance Machine Learning techniques that process mainly 2-D and abstract data such as drawings or photos. The present approach hence distinguishes itself with the analysis of real-world data, providing for the ability to process the parts of a 3-D model with ML to make spatial generations. To the best of our knowledge, using a single real-world structure with its sensory data and investigating the alternative representations is a novel approach in the field. In the data analysis experiments, the production of datasets to be processed with ANNs by transforming real-world structures according to the design process and references is discussed. In the methodology part, the design of a 3-D Deep Generative Model with these datasets is described in detail. The study encourages the application of data analysis experiments and the designed Generative Model on different datasets and contexts in future research. It enables the developed system to be experienced in a specific case and sheds light on the research for generative processes of representation. This study will therefore convey an understanding of spatial representation for future research to innovate the current strategies for the use of ML models in design research.

Project

The approach underlying this descriptive research is experienced in a project. This project creates a platform for the study to be tested and examined qualitatively in a chosen context by the use of 3-D Deep Generative Models and the use of datasets in various forms as mesh models and point cloud models. The data collection for the project is conducted from primary sources of the chosen context, The Faculty of Architecture at Middle East Technical University (METU). Original drawings of the chosen context are provided by the METU Directorate of Construction and Technical Services. The LiDAR Scanner model was developed by the Photogrammetry Laboratory of the Faculty of Architecture at METU, and mesh models are our own production. The stages of the project are described in the workflow diagram in Fig. 1.

Concept

This research experiments to process design context with ML using point cloud data directly obtained from the physical environment. In order to analyze the design character in the 3-D contexts and to investigate its use for alternative representations

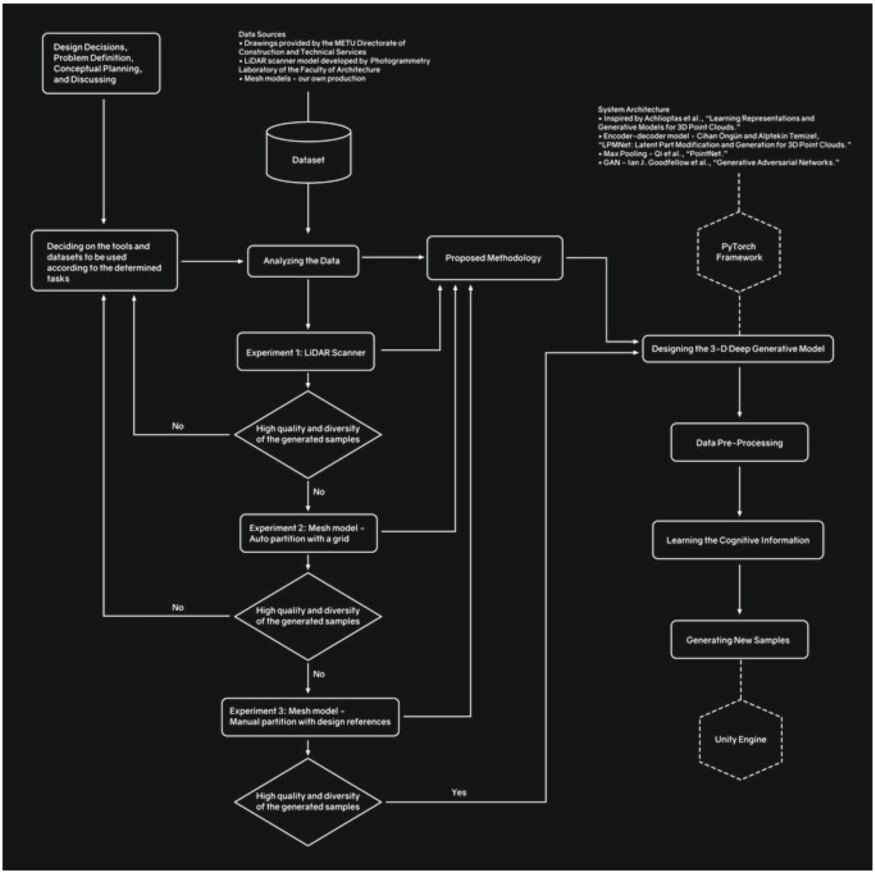

Fig. 1 Workflow diagram

through ML, a 3-D model is deconstructed and processed. Then the new 3-D models produced by the ML model are examined. Different combinations of design elements are selected, and spatial parts are analyzed through 3-D Deep Learning algorithms. For this purpose, the ML model is trained by using 3-D parts of the design system to analyze the information about the features of the whole system encoded in the parts. Later, a Generative Model is used to produce new samples reflecting a representation of design cognition. The conceptual representations of the process of designing the ML model via 3-D parts of the model and the decoding of the design system are displayed in Fig. 2.

Fig. 2 The conceptual representations of designing the ML model via 3-D parts

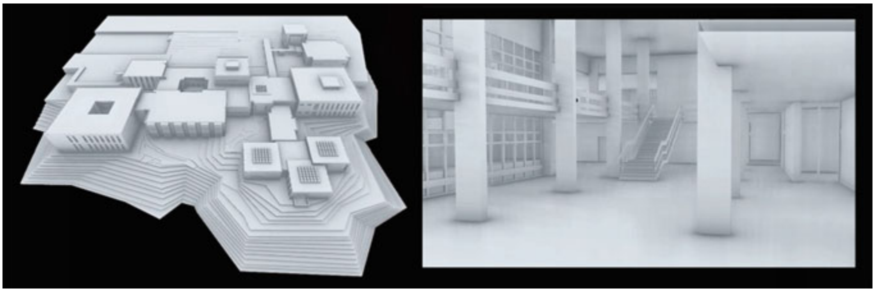

Fig. 3 3-D mesh model of the Faculty of Architecture at METU

Context

The feature sought in the chosen context is its inclusion of meaningful and repetitive combinations of design elements that express a strong character. In this study, the Faculty of Architecture at Middle East Technical University (METU) is used as context. There is a visible strong articulation of the solids that make up the design composition, which would benefit the study, and the required data could be obtained from primary sources. The views from the 3-D mesh model of the building that is produced for the project are shown in Fig. 3.

Analyzing the Data

The research also has a story about its data collection and processing stages, and these stages, which lasted for months, constitute a survey process that should be explained on its own. In the project, the transformation of design data for use in ANNs is tested with different experiments based on architectural references and volumetric

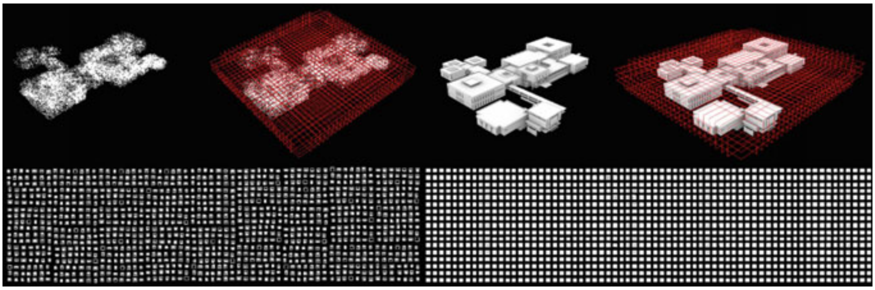

Fig. 4 Dividing the 3-D point cloud model and mesh model into 3-D sub-units

relationships reflecting the design process. These experiments are briefly mentioned below.

Experiment 1: LiDAR Scanner

The selected design context was scanned with the LiDAR Scanner tool, which uses laser pulses to detect the distance of an object's surface. In this way, a highly detailed 3-D point cloud model was created for the chosen building. LiDAR provides the coordinate values of all the details of the building in real dimensions. This data was divided into smaller 3-D sub-units that allowed detailed analysis of semantic information (see Fig. 4). ML model was trained with the sub-units of this 3-D point cloud model. Using the real scans can help to decode the underlying system of the design process and provide experimental results on real-world data.

The LiDAR data has some problems regarding the uniformity and density of the points. The point density is higher near locations where the LiDAR device is located. This causes a non-uniform distribution of the points among the 3-D model. This also creates visible dense circles around the LiDAR device on the point cloud. ML systems tend to learn dense areas better than sparse areas. Thus, it may cause problems regarding reconstruction and generation quality. An extra pre-processing step (spatially uniform point sampling) is applied to make LiDAR data more uniform.

Experiment 2: Mesh Model—Partition with a Grid

At this stage, the mesh model was partitioned with a 3-D grid (see Fig. 4). This is a basic process to partition the buildings with respect to the given part count. These parts were used for training the ML model. When the results were examined, some generated models were very similar or as same as some parts in the dataset. When a dataset, which consists of elements that are similar to each other, is used for training a Generative Model, the model starts to memorize the elements in the dataset and repeat them instead of understanding the hierarchical relationships of these elements and making new productions. Also, this automatic splitting causes unrelated and semantically unrealistic parts, such as unconnected parts or elements from different spaces. The produced parts do not follow a meaningful pattern or a useful representation. The ML model imitates the dataset by generating unconnected or semantically meaningless parts. This method reduces the quality and diversity of the generated samples.

Experiment 3: Partition with Design References

After experimenting with partitioning using a grid, we create the dataset with logical partitions according to the references of design elements that carry the semantic representation of the design process. With this approach, the whole building was divided into parts gradually, and the results were analyzed at each stage. First, the building was divided into 250 main parts that refer to the whole volume. Later, these 250 pieces were split into 500 pieces with references within themselves. Finally, all parts were brought together, and the parts were transformed into 1000 sub-parts containing different relational combinations to allow the machine to focus more on the details. Datasets that are gradually divided into sub-spaces according to design references are displayed in Fig. 5. The dataset consists of both meaningful parts with a semantic representation and uniform distribution of points and surfaces.

Methodology

The methodology of the study is inspired by Achlioptas et al. [12]. First, the data is pre-processed to feed the network, as explained in Data Pre-processing Section. The data is fed to an encoder-decoder for learning the underlying structure of input samples. Then, a GAN is used to generate new samples from the learned structure. The encoder-decoder and the GAN models are explained in Learning the Underlying Structure Section and Generating New Samples Section, respectively. All implementations are done with the PyTorch framework on an Nvidia RTX 2070 GPU and are imported into the Unity Engine. The proposed methodology of the study is demonstrated in Fig. 6. And the system architecture is visualized in Fig. 7.

Data Pre-Processing

The selected building is modeled in 3-D format. After partitioning the building model as explained in Analyzing the Data Section, there are 250, 500, and 1000 parts in

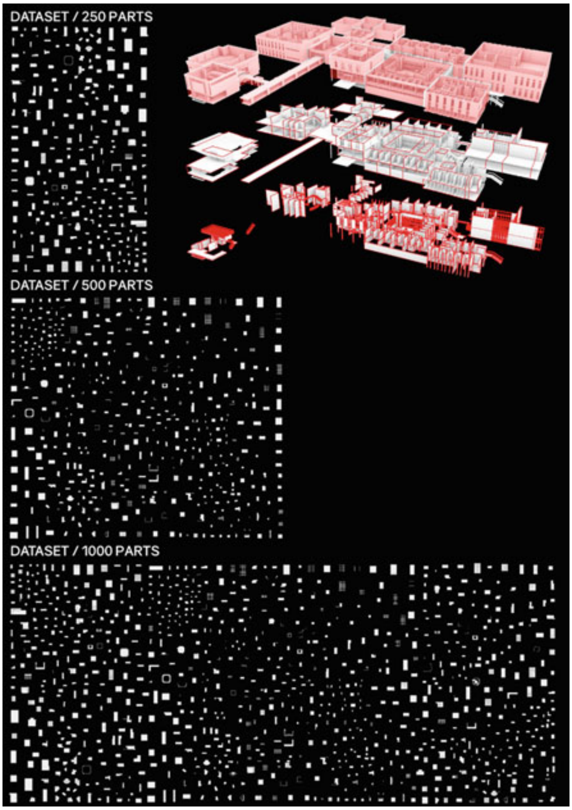

Fig. 5 Partitions according to the references of design elements

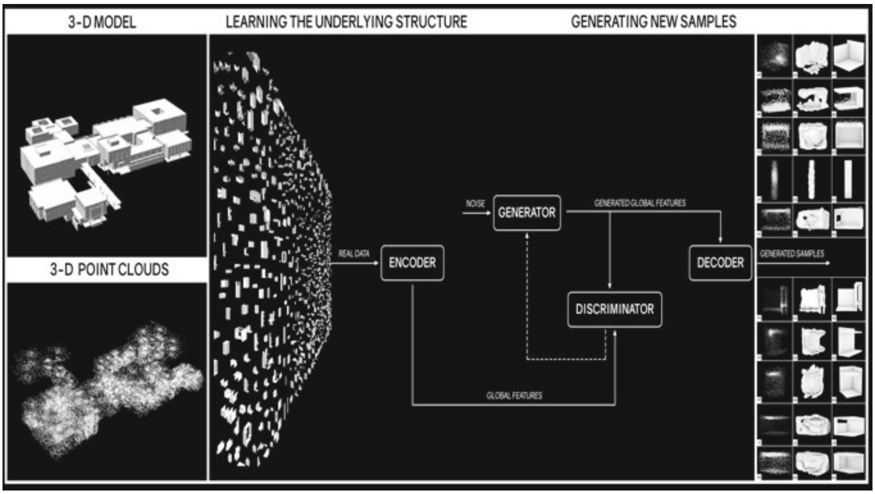

Fig. 6 Proposed methodology

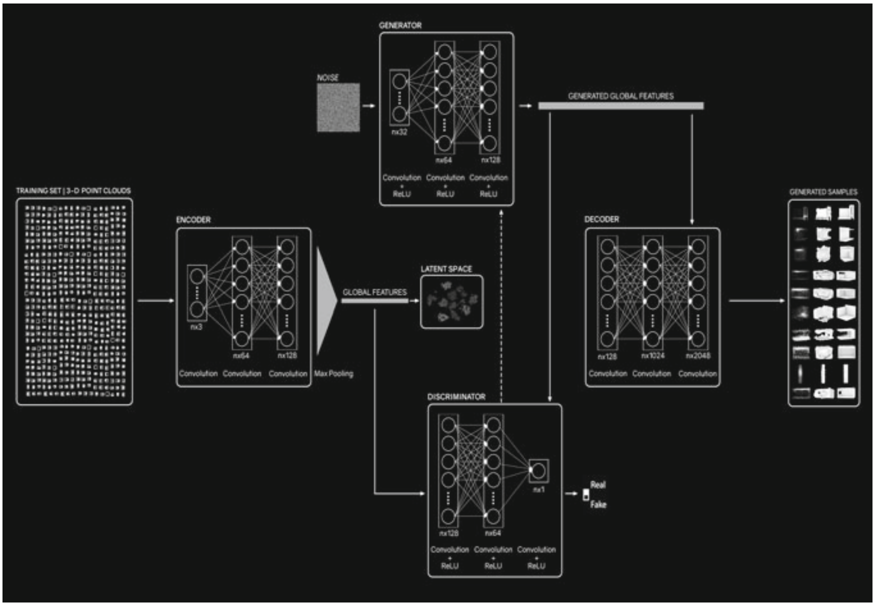

Fig. 7 System architecture

3-D mesh format for different experiments. The 3-D parts are converted to 3-D point clouds using uniform point sampling. Uniform point sampling is basically selecting a certain number of points to represent a surface. There must be at least 3 points to represent a triangle surface, and more points can be located using linear interpolation on the surface. Considering the mesh faces have different surface areas, to represent each surface uniformly, the resolution (point density) is set for each surface to its proportional area. All 3-D point cloud samples in the dataset are set to have 1024, 2048, 4096, or 8192 points for different experiments. After the conversion, all samples are positioned at the center of the coordinates and scaled into the unit cube. The dataset is randomly divided into train, validation, and test subsets with 80%, 10%, and 10% ratios, respectively.

Learning the Underlying Structure

Our first aim was to learn the underlying structure of the design system from the dataset. An encoder-decoder model [12] (see Fig. 8) is employed to encode the real data and form a latent space that represents the design context. This latent space consists of learned features and similarities of the dataset. Since the dataset is formed from a single building, we expect the model to learn the similarities from the parts of the building.

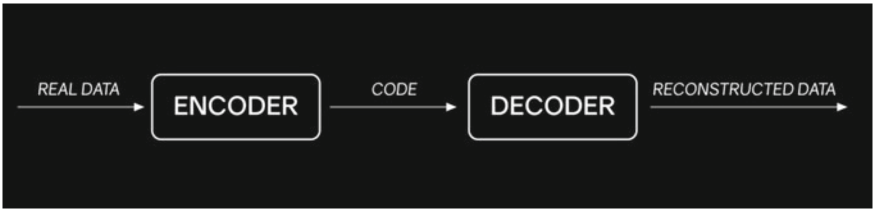

Fig. 8 The AutoEncoder model

The encoder model [13] is inspired by PointNet [14]. It is a 3-layer 1-D convolutional network with feature sizes (3, 64, 128). It extracts the features for each point having three dimensions for the x, y, and z-axis. Then a max-pooling is applied as explained in [14] to extract the global feature (code) that represents the point cloud model. The input and feature transform subnetworks are omitted since the input data is already aligned and scaled. All extracted global features form a latent space that represents the underlying style and similarities of the dataset.

The global features are then decoded using a 3-layer Fully Connected Network (128, 1024, 2048). The reconstruction loss is calculated with Chamfer Distance [9] between the real and reconstructed point clouds. The network is trained end-to-end using Adam [15] optimizer with the reconstruction loss and a learning rate of 5×10^{-4} for 1000 epochs. The reconstruction loss is around 10×10^{-4}, which indicates a good reconstruction performance with minimal error.

Generating New Samples

A GAN (see Fig. 9) is employed for generating new samples in the learned underlying structure of the design. The extracted global features (codes) are fed to the GAN to generate new global features. The generated global features are then decoded using the trained decoder to get 3-D point clouds that represent the real-world data.

Both the Generator and the Discriminator are 3-layer Fully Connected Networks with (32, 64, 128) and (128, 64, 1) sizes, respectively. All layers have ReLU activation functions followed by batch normalization layers except the output layers. The Generator input is sampled from a Normal distribution. A WGAN [16] objective function is used for training with better stability and diversity. Adam optimizer with learning rates of 5×10^{-4} and 1×10^{-4} for Generator and Discriminator, respectively.

Results

In the study, the dataset is prepared and pre-processed to work with the proposed model. The AutoEncoder model is trained to evaluate the dataset and the learning

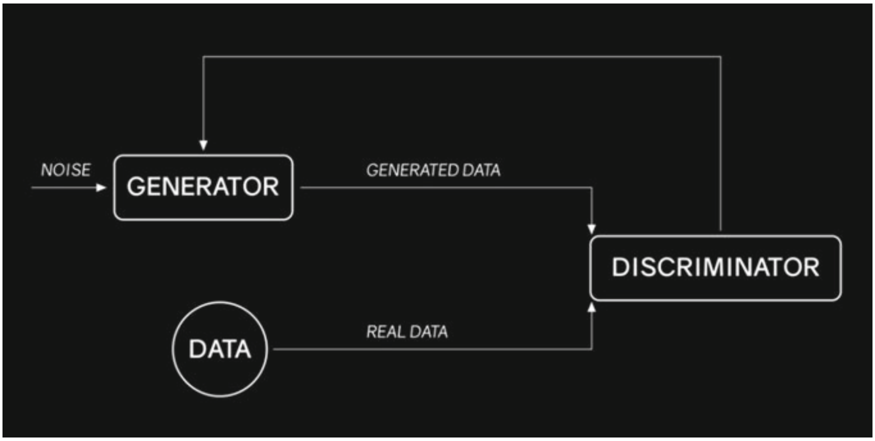

Fig. 9 The Generative Adversarial Network (GAN) model

ability of the model. The reconstruction loss between input and output is calculated using Chamfer Distance [9] which is a nearest neighbor distance metric for point sets. The reconstruction loss is 3.07×10^{-4} for training and 10.51×10^{-4} for testing, indicating a visually good reconstruction with a minimum loss between input and output.

The generated parts are evaluated using the same evaluation metrics of the LPMNet [13], which is used as a baseline for encoding–decoding the dataset and generating new parts. Our results are similar to the reconstruction loss of the LPMNet (8.07×10^{-4}), supporting our claim that our dataset serves well for the purpose of the encoding–decoding design system. The comparison with the baseline [13] shows that a better reconstruction can be achieved with a bigger and more diverse dataset by avoiding overfitting.

The results can be seen in Table 1. Coverage (Cov) measures the percentage of representation of generated parts in the input dataset. High coverage means that generated parts have high diversity to represent all different classes of data samples in the input dataset. Minimum Matching Distance (MMD) is the average of distances between the most similar samples in the input and generated sets. While low MMD means the samples are in the same scope and class, 0 means they are completely the same. Jensen-Shannon Divergence (JSD) (derived from Kullback–Leibler divergence [17]) is a metric to calculate distances between probability distributions. In this study, it is used to measure if the generated samples occupy a similar scale, rotation, and location as the input set. The results are again comparable to the LPMNet, indicating that our case is suitable to generate new samples reflecting the features of the design character. The quantitative results support visual results that the generated parts are meaningful enough for forming alternative representations of the design system.

The 3-D Deep Generative Model trained with partial built-in data can produce new formations with the help of Artificial Neural Networks. The generated samples can be seen in Fig. 10. The generated data is visualized in raw point cloud form

Table 1 The best WGAN results from the LPMNet [13] and our results

	Reconstruction Loss	Evaluation of the generated samples		
	Chamfer distance ($\times 10^{-4}$)	MMD	%Cov	JSD($\times 10^{-2}$)
Ours	10.51	3.92	67.83	3.01
LPMNet	8.07	4.76	60.93	4.17

first, as shown in the 1st columns of the tables in Fig. 10. Then the generated point clouds are automatically transformed to mesh form with the Poisson Surface Reconstruction [18] method to analyze the surfaces and the general connected structure of the data (see 2$^{\text{nd}}$ columns in Fig. 10). Later the mesh models in the 2$^{\text{nd}}$ columns are post-processed by manually flattening, as demonstrated in the 3$^{\text{rd}}$ columns in Fig. 10, to analyze and use a variety of spatial representations in different abstraction levels. Care has been taken to ensure that the samples of the results displayed in Fig. 10 are visually diverse. In order to observe that the post-processing is compatible with the original GAN-generated 3-D point cloud models, the raw point cloud outputs were preserved in the post-processed 3$^{\text{rd}}$ columns in Fig. 10 and the sample scene in Fig. 11. The spatial configurations of the generated samples can create various scenes, as demonstrated in Fig. 11. The results, which are considered as a design vocabulary, are used in a combinatorial formation as an alternative design suggestion with human influence in Fig. 11. Since the present study aims to investigate representing design cognition at the human–machine interface, the scene exemplified in Fig. 11 is generated with the designer's intervention of the GAN-generated results.

Conclusions

This research provides an investigation for a generative design understanding by decoding and learning from the physical environment. The research hence contributes to the representation of design cognition using real-world design data. In the experiments, a 3-D mesh model and sensory data collected from a built-in structure with a LiDAR Scanner are used. The datasets are produced by transforming the design data in accordance with the part-whole relationship and reference system, reflecting the design process. These datasets, which represent the 3-D nature of the design features and provide the information of coordinates, are then fed to an Artificial Neural Network to learn the underlying structure. A Deep Generative Model is used to generate new representations through the learned design character encoded in the physical structure. The generated samples can be analyzed in different forms, such as point clouds and 3-D meshes. We aimed to investigate the representation of design cognition at the human–machine interface. The results show that the generated samples are meaningful for creating a design vocabulary in order to produce combinatorial formations while preserving semantics for further generative tasks.

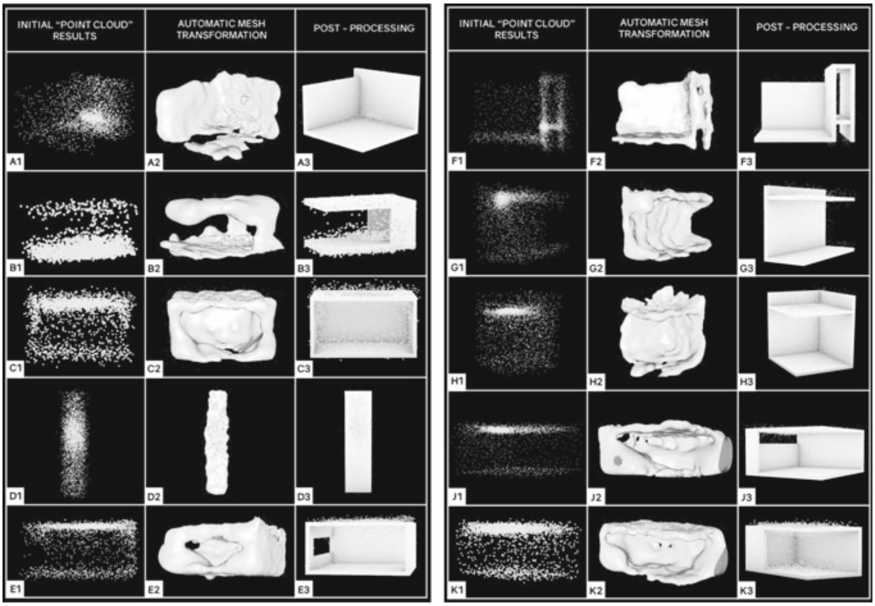

Fig. 10 3-D productions of the ML model in different abstraction levels

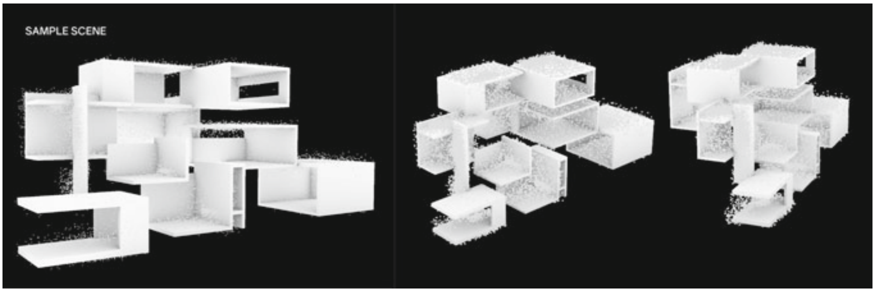

Fig. 11 A Sample scene with spatial configurations of the productions

We aim to extend this study by experimenting with various cases to provide a better analysis of the proposed model. To further this research, the proposed model is planned to produce more results in the current case and be adapted to different design contexts. In applying the model to various design data, it is possible to organize the experiments of data analysis according to the design features and adapt the model to other design systems by applying the described methodology. Also, the sample scene produced manually by the combination of generated samples would be further developed with an approach to search for a generative design system.

Acknowledgements This study was developed within the scope of the thesis [19] titled "Extending Design Cognition with Computer Vision and Generative Deep Learning," supervised by Prof. Dr. Zeynep Mennan at METU Department of Architecture. Original drawings of the building were provided by the Directorate of Construction and Technical Services at Middle East Technical University (METU). In the experiments, the LiDAR Scanner model was developed by Kemal Gülcen through the Photogrammetry laboratory of the Faculty of Architecture. We would like to thank the deanery of the Faculty of Architecture for allowing the use of data.

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Classifying Building and Ground Relationships Using Unsupervised Graph-Level Representation Learning

Abdulrahman Alymani, Andrea Mujica, Wassim Jabi, and Padraig Corcoran

When designing, architects must always consider the ground on which their buildings are supported. Our aim is to use data mining and artificial intelligence (AI) techniques to help architects identify emerging patterns and trends in building design and suggest relevant precedents. Our paper proposes a novel approach to unsupervised building design representation learning that embeds a building design graph in a vector space whereby similar graphs have comparable vectors or representations. These learned representations of building design graphs can, in turn, act as input to downstream tasks, such as building design clustering and classification. Two primary technologies are used in the paper. First, is a software library that enhances the representation of 3D models through non-manifold topology entitled Topologic. Second, an unsupervised graph-level representation learning method is entitled InfoGraph. Result experiments with unsupervised graph-level representation learning demonstrates high accuracy on the downstream task of graph classification using the learned representation.

Introduction

Studies have shown that graphs are an effective representational tool for a significant variety of data, including architecture, urban and planning designs [1, 2]. A graph is a network of nodes and edges [3]. With the use of graphs, explicit information can be obtained not only from the general graph network but also from smaller units inside the same graph. Additionally, graphs provide an intuitive way of assigning properties to nodes and edges. Recent developments have seen a rapid rise in the study of graphs because they can model rich information, which is critical in numerous architectural applications. For example, researchers have presented several graph

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theoretical approaches to the generation of architectural floor plans [4, 5]. Another application involves graph geometric measures and models for architectural planning to find the 'minimum-path graph', which constitutes a proposed analysis of all shortest-path traversals between any two locations in a network [2]. However, architectural works using machine learning usually consider 2D image-based representations of data. Recent graph research has focused on 3D topological supervised learning [6]. Despite this development, applying supervised learning approaches to graphs presents a challenge in that difficulties often occurs when collecting annotated label data. Furthermore, many data mining methods for tasks such as classification and clustering, demand that elements in the input data be fixed-length feature vectors. A graph in native form does not have such a representation and therefore such methods cannot be directly applied.

Unsupervised learning approaches are a promising method of overcoming the aforementioned limitations. Unsupervised learning focuses on unlabelled data and generates a representation, which can aid future downstream tasks, such as classification. For example, the unsupervised learning approach, like word2vec and Bert in the domain of natural language processing has demonstrated the potential of this approach.

The use of representation learning in the context of graphs corresponding to 3D meshes was examined by [7]. During the workflow, unsupervised deep learning of representation in a latent vector space classified the room types in design samples. Bouritsas and Bokhnyak utilised a research method to introduce a graph convolutional operator that explicitly models the inductive bias of the underlying fixed graph, implemented directly on the 3D mesh. The spiral operator enforces consistent local orderings of the graph's vertices, thus breaking the permutation invariance property existing in all prior work on Graph Neural Networks [8].

This paper aims to design a novel proof of concept workflow that applies unsupervised graph level representation learning to building/ground relationship data. The objective is to provide a vector for each graph to encode the relationship similarity between two 3D building/ground topological graphs. Our workflow is divided into two stages. The first stage uses the Topologic software library that enhances the representation of 3D models through non-manifold topology with embedded semantic information. The plug-in automatically and generatively creates a synthetic dataset of building and ground relationships with respective typological categories. A topological dual graph is then automatically generated by labelling the geometric models. The dual graph of a building consists of one node for each space or element that are then connected by edges if they share a surface. The ground is segmented into a grid of cells and therefore several 'ground nodes' are created to represent it. Similarly, columns are segmented as well and thus multiple 'column nodes' are created. In the second stage, this dataset acts as input to run the unsupervised graph level representation learning for generating fixed-length feature vector representations of graphs.

By implementing this framework, a similar precedent can be introduced into the design process, which will allow designers to estimate the performance consequences of their choices quickly. As examples of this application, the designer can use this

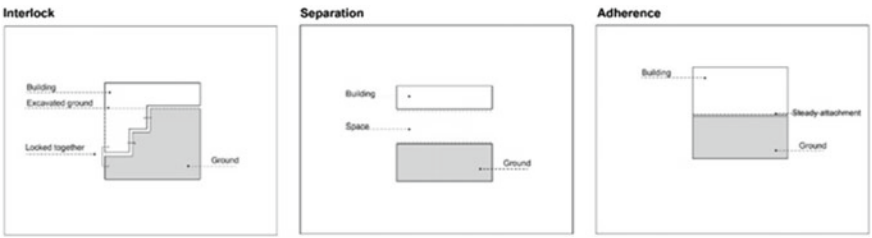

Fig. 1 The three main types of building and ground relationships are displayed

workflow to generate their new design, and then the machine learning models classifier can determine the type of design. This class information could then be used to retrieve other design precedents (from our 500-dataset archived) of the same type, which may inspire the designer.

Building and Ground Relationships

Building and ground relationships have long undergone discussion in the architectural field. For centuries, architects have used the ground as a reliable physical and conceptual support for their work. However, the notion of ground connections has improved with recent technological, philosophical, and geopolitical advances [9]. Modern architects respond to these conditions by inventing formal topologies. Several materials help provide a physical disengagement with the building form and the ground. For instance, the Convent of La Tourette by Le Corbusier facilitated a diverse range of approaches relative to the ground [10]. Other architects deconstructed the architectural objects by integrating the interior space into the surrounding landscape [11]. Contemporary architects have used similar methods to work with the ground; some have disregarded it, while others have focused on the division between landscape and building. However, T. Berlanda, a graphic lexicon, illustrates that buildings touching the ground are divided into three principal categories: Separation, Adherence and Interlock [12] (see Fig. 1).

Graph Representation Learning

Graph embedding represents a method of mapping a graph into a fixed-length vector that captures key features or properties of the graph. This approach means the graph embedding helps to translate a complex graph into a form that many popular machine learning, and data mining methods can use. Graph embedding machine learning models typically learn what is significant in an unsupervised generalised way. There are two major graph embedding types: Monopartite graphs, which have nodes with

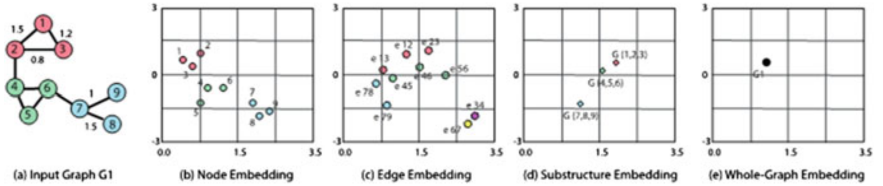

Fig. 2 Example of embedding a graph into 2D space with different granularities (author after [3])

a single label, such as Deep Walk, and Multipartite graphs, which have nodes with several labels, such as the Knowledge Graph. Moreover, there are three different aspects of the graph that are trying to represent as embedding: (1) vertex embedding, which describes the connectivity of each node; (2) path embedding for traversal across the graph; and (3) graph embedding, to encode the graph into a single vector (see Fig. 2) [3].

Unsupervised Graph Level Representation Learning (UGLRL)

In Graph Level Representation Learning, the graph is encoded into a single vector. Two graphs are said to be similar if they are represented by corresponding vectors that are embedded close together. A whole graph embedding provides a straightforward and efficient way of calculating graph similarities, which is essential to graph classification.

In 2020, Yun-Sun et al. introduced InfoGraph, a machine learning model that studies the representations of whole graphs in both unsupervised and semi-supervised scenarios [13]. The unsupervised InfoGraph accomplishes this task by providing both the number of nodes in and all graph matrix representations as The InfoGraph model focuses on graph neural networks (GNNs). Repeated aggregation of local neighbourhood node representations in embedding architectures produces node representations. By aggregating the features of neighbours, one can learn the representations of nodes, called patch representations. In a GNN, the READOUT function summarises all the obtained patch representations into a fixed-length graph representation.

Figure 3 illustrates the **UGLRL** model process: (a) with graph convolutions and jumping concatenation, an input graph is encoded into a feature map; (b) (global representation, patch representation) pairs are input to the discriminator, which determines whether they belong to the same graph; and (c) InfoGraph generates all possible positive and negative samples using a batch-wise fashion. For example, consider the two input graphs in the batch and seven nodes in total (above). The global representation of the graph (A) will apply seven input pairs to the discriminator as well as the graph (B). In this case, the discriminator will take 14 (global representation, patch representation) pairs as input.

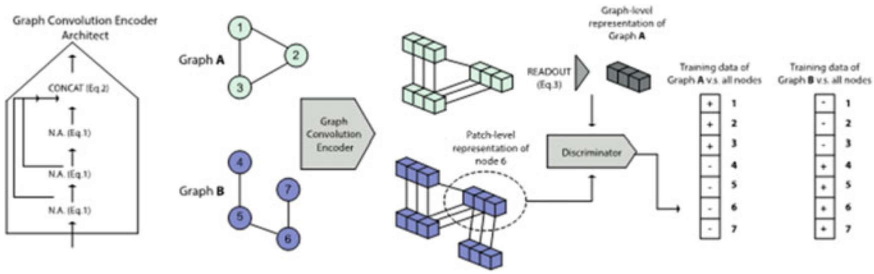

Fig. 3 Unsupervised graph-level representation learning model (author after [13])

Topology

The use of topology can help represent architectural designs, graphs and topological structures. The primary difference between geometry and topology is that the latter abstracts away the concepts of form and physical distance but retains the notion of connectivity. Consequently, one can explore complex designs at a much higher abstraction level than geometry allows. Different topologies can represent a multitude of designs [14].

Recently, Jabi discovered the potential of non-manifold topology in early design stages [15], by modelling architectural spaces using concepts from non-manifold topology [16]. This approach resulted in the Topologic toolkit [17]. Topologic is a software library that enhances the representation of space in 3D parametric and generative modelling environments. To date, the Topologic tool has shown its compatibility with Grasshopper [18], Dynamo [19] and Sverchok [20].

Topologic's classes include Vertex, Edge, Wire, Face, Shell, Cell, CellComplex, Cluster, Topology, Graph, Aperture, Content and Context.

This paper focuses on two essential features of Topologic for the proposed workflow: (1) the automatic derivation of 3D topological dual graphs using the Cell, CellComplex and Graph classes; and (2) the embedding of semantic information through custom dictionaries. In Topologic, a CellComplex is an enclosed 3D spatial unit (Cell) with a shared Face. The Graph class and associated methods are based on graph theory. A Graph comprises Vertices and Edges that connect Vertices to each other. A graph in Topologic is created with any 3D unit such as a CellComplex as input and outputs its dual graph as a network of labelled edges and vertices. The dual graph connects the centroids of adjacent cells with straight edges.

Dictionary data structures consist of key/value pairs. In computing, a key is any string identifying the data (e.g., 'ID', 'Type', 'Name'). Any type of data can be used as a key-value (e.g., floats, integers, strings). Topologic allows for the embedding of arbitrary dictionaries into any topology. Topologies are modified geometrically (e.g., by subdividing or creating a Cell Complex) so that dictionaries of operand topologies can be transferred to the resultant topologies. Using a topology, one can construct a dual graph by transferring dictionaries from constituent topologies to vertices. Using this capability, we can label the vertices of the dual graph.

Methodology

Recent work on graphs has focused on learning node representations or supervised learning tasks. These include graph analytic tasks, such as graph classification, regression, and clustering. However, such tasks typically require a fixed-length feature vector representing the entire graph. Graph-level representations can be derived implicitly through node-level representations. On the other hand, explicit graph extraction can be more straightforward and advantageous for graph-oriented tasks [13].

In this paper, the experimental workflow leverages two principal technologies. The first is Topologic, a library that enhances the representation of 3D models through non-manifold topology and embedded semantic information. The second is an unsupervised machine learning model that learns a representation of whole graphs as vectors for classification purposes. The experimental workflow involves two stages. In the first stage, an interactive system generates 3D prototypes of building and ground relationships with numerous topological variations. The architectural precedent's geometric models generated a semantically rich topological dual graph. In the second stage, the dual graphs were imported into the unsupervised graph-level representation learning model. The for graph classification. Using the results from the unsupervised embedding, the graphs were passed through a t-SNE (t-distributed Stochastic Neighbour Embedding) plot to visualise the locations and results of the classifications.

We applied the following four classifications methods to the vector representation learned by the InfoGraph method in an unsupervised manner. The performance of these classifications methods acts as a proxy for evaluating the usefulness of the representation in question.

1. Logreg, Logistic regression is used to describe data and its relationships with independent and dependent variables.
2. SVC, which stands for Support Vector Classification.
3. Linear SVC, which is similar to SVC, but it generates a linear classifier; and
4. Random forest, which is the result of the probability of an ensemble of decision trees.

Experiment Case Study

This experimental case study used Grasshopper and the Topologic plug-in to create 3D parametric models of buildings with different relationships with the ground and their respective dual topological graphs. Five architectural features generated the building/ground relationships: ground plate, building, columns, central core and plinth 'base'. The different features followed a set of rules. The ground plate was fixed in size. The plinth was then sized to be a certain percentage of the ground plate with equal offsets. We then placed the building geometries with the appropriate offsets and spacing. Buildings vary in height, but in one model, all building objects had the same height. A grid of cells also divided the building geometries internally. The models varied in the main building and ground relationship and were divided into three classes: (1) Separation; (2) Adherence; and (3) Interlock.

Completing three tasks created the dataset classes. The first task involves labelling the overall graph on the Grasshopper script. Firstly, separation follows five rules: ground, building, core, columns and plinth. Separation classes occur when the building is elevated from the ground with columns class (0) or when the building is elevated from the ground on the plinth and columns class (1). Secondly, Adherence follows four rules: ground, building, core and plinth. Interlocking follows three rules: ground, building and core. Adherence classes occur when the building is set directly on the ground class (2) or when the building is set on the plinth, which is set on the ground directly in class (3). Thirdly, interlock follows three rules: ground, building and core. Interlock classes occur when the building integrates and overlaps with the topology of the ground class (4). The second task involves the vertices. In our dataset, the vertices were classified into five categories: (0) Ground, (1) Plinth, (2) Columns, (3) Building, and (4) Core (see Fig. 4). The last step involves integrating the visual dataflow definition with a custom Python script to convert Topological 3D dual graphs into text files in the InfoGraph format.

The dataset produced consisted of 900 graphs, as follows (see Fig. 5):

- A total of 720 separation graphs comprising 90 building graphs separated from the flat ground with small, medium, and large columns; 90 building graphs separated from the flat ground with small, medium, and large columns and set into the plinth; 270 building graphs separated from the sloping ground with small, medium, and large columns; 270 building graphs separated from the flat ground with small, medium, and large columns and set into the plinth.
- A total of 96 adherence graphs comprising 12 building graphs set directly into the flat ground; 12 building graphs set on the plinth then into the flat ground; 36 building graphs set directly into the sloping ground; 36 building graphs set on the plinth then into the sloping ground.
- A total of 108 interlock graphs comprised 36 building graphs interlocked with the flat ground and 72 building graphs interlocked with the sloping ground.

Utilizing grasshopper, topologic and python script, we created our workflow that was used to develop the building and ground relationship iterations. The workflow contains five stages (see Fig. 6). The first stage was to create the building and ground geometry. The second stage was to slice the created geometry with curves into different cells. The third stage was to feed the geometry into the Topologic tool, so the geometry transferred from geometry to topology. The fourth stage was to implement a dual graph to the created topology. Finally, we created two python

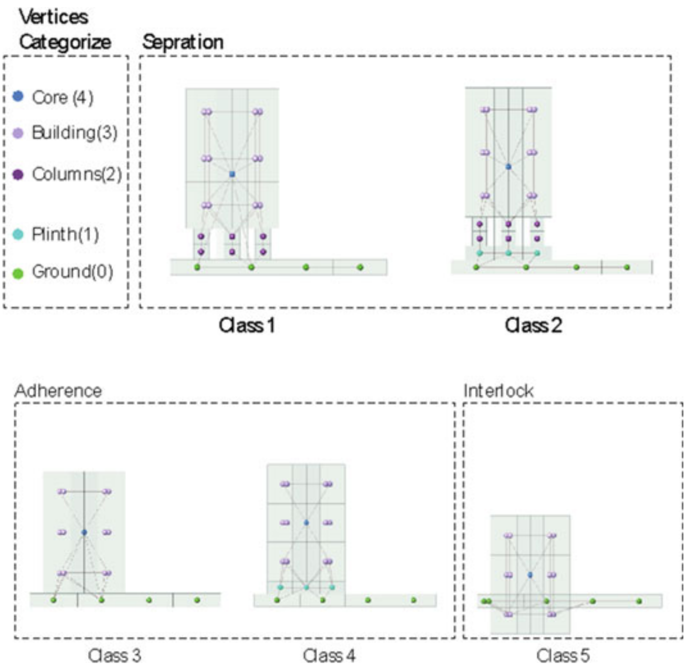

Fig. 4 Examples of the different classes of auto-generated building/ground configuration with associated dual graphs

scripts, one to repeat all the iterations and the other to transfer the dual graph to the required format.

The process of data creation resulted in numerous findings. The total number of vertices was 55,081. The average number of vertices per graph was 61. The minimum number of vertices per graph was 20. The maximum number of vertices per graph was 197. The total number of ground vertices in the data was 31,772, the total number of building vertices in the data was 18,626, the total number of plinth vertices in the data was 10,689, the total number of columns vertices in the data was 16,923 and the total number of core vertices in the data was 900.

We prepared the following three text files as input to InfoGraph which is the unsupervised graph representation learning model used.

1. DS_A.txt: Adjacency matrix for all graphs, in which each line corresponds to (row, columns) for (node_id, node_id).
2. DS_graph_indicator: The column vector of graph identifiers for all nodes of all graphs, the value in the i-th line is the graph_id of the node with node_id i.
3. DS_node_labels: The column vector of node labels, the value in the i-th line corresponds to the node with node_id I.

It is crucial to mention that the data that worked with InfoGraph comprised undirected graphs, so all the edges were bidirectional. Additionally, the nodes needed to

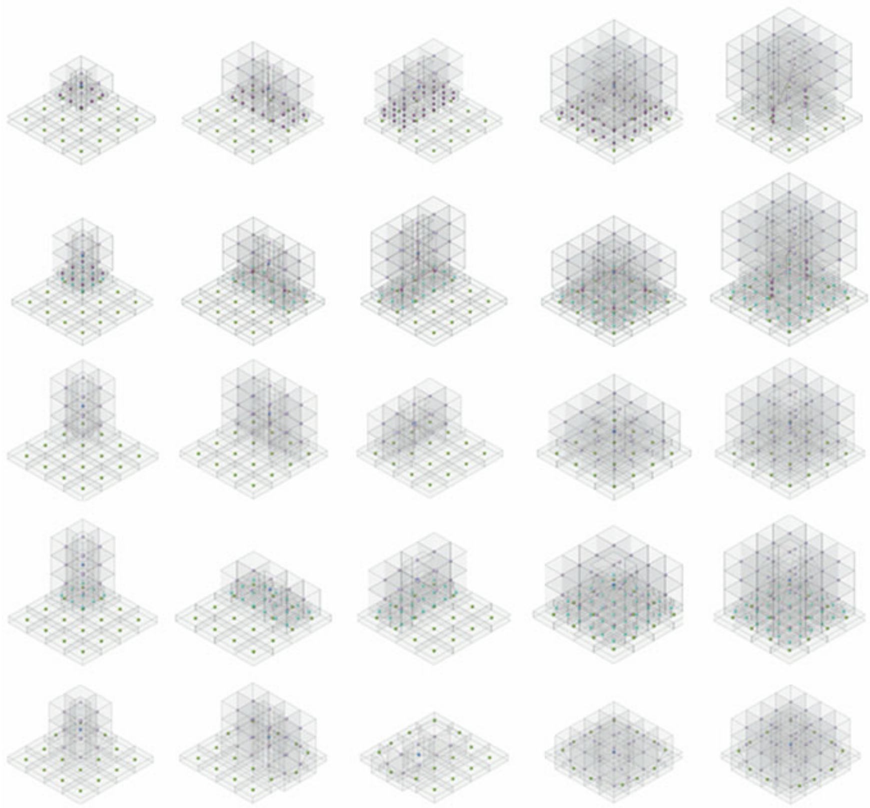

Fig. 5 Sample of automatically generated building/ground relationship typologies

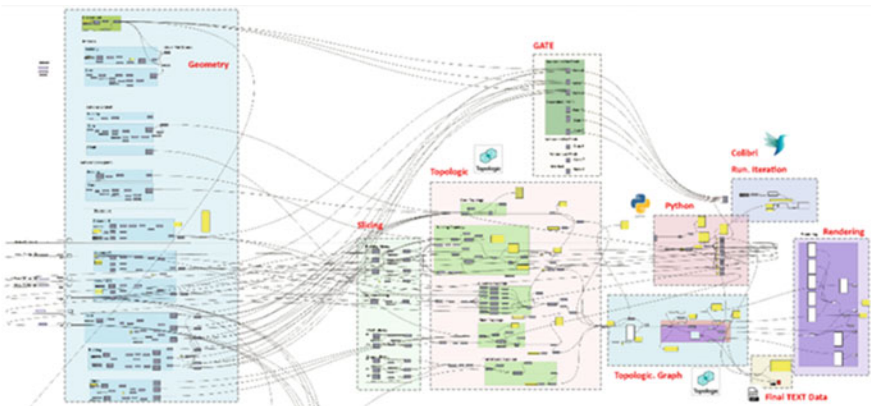

Fig. 6 An example Grasshopper script of 3D models generated using parametric and their associated topological dual graphs

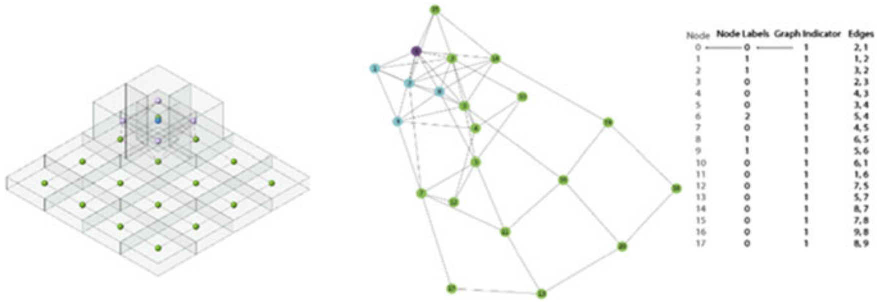

Fig. 7 Graph 1 from data. Visualised with matplotlib. The table shows how an adjacency matrix, node labels and graph indicators work within the text files

be in a continuous list, starting from 1 to 55,081 (the number of nodes in the dataset). Figure 7 below explains the different files' connections and what each text file line represents.

Figure 7 clarifies the representations of the topological graph within the 3D environment and within the machine learning software. While the nodes in the original dual graph (Left of Fig. 7) are placed at the centre of the model elements within 3D space, the topological graph (middle of Fig. 7) and its textual representation (Right of Fig. 7) is geometry-independent and thus the XYZ coordinates of the original dual graph nodes are not needed.

The code for InfoGraph was created to run using the TUDataset module from Pytorch Geometric. Therefore, the input data required conversion into the same format as all the TUDatasets. The original data containing all 900 graphs were created to work with the format from the DGCNN [22]. Using the dataset MUTAG as an example, a code generated an adjacency matrix for all 900 graphs (see Fig. 8).

For our experiment, we maintained the default Graph Isomorphism Network (GIN) model [13].

Experiment Results

Fer the experiment results below, and according to [13], we varied the following hyperparameters: learning rate, number of epochs and batch size. To visualise the graph, a t-SNE plot embedded the whole graph into a 2D space for graph visualisation, where each graph becomes a point. Providing human insights into the dataset facilitates further analysis of the data. The code was run in CPU mode in a Dell XPS Intel Core i7 with 16 GB RAM.

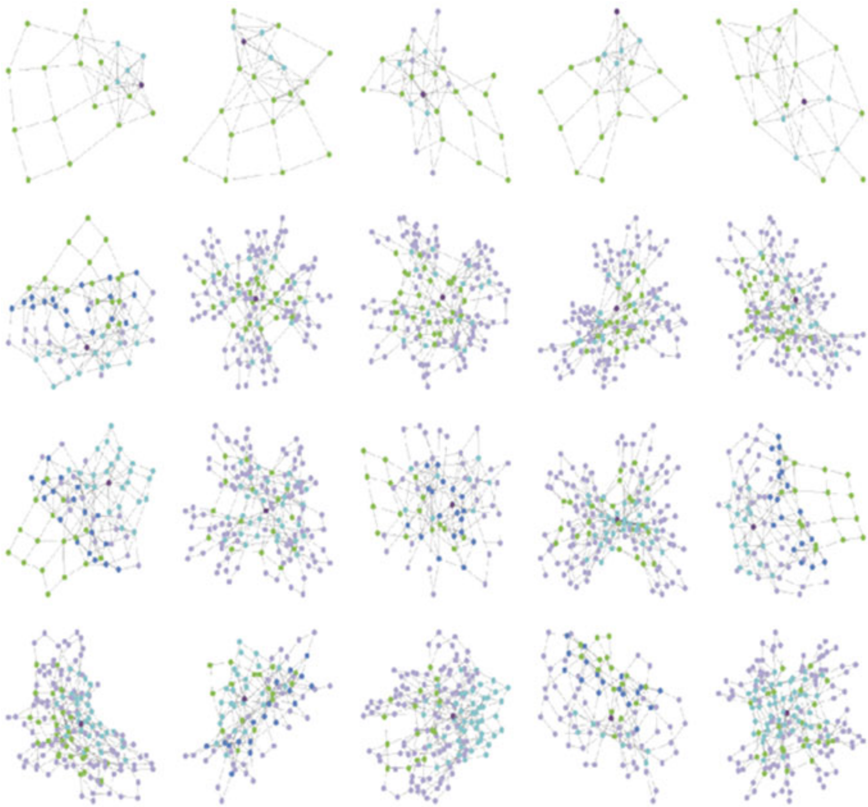

Fig. 8 First 25 graphs of the data were created and visualized using network X and matplotlib

Learning Rate

In a convolutional neural network, the learning rate represents the rate at which the model parameters are updated each time an optimisation step occurs. Varying the learning rate can affect the model performance. We experimented with four different learning rates (1e-5, 1e-4, 1e-3 and 1e-2) and documented the results (see Table 1). Initially, the test had a fixed batch size of 128 and epochs set at 20. All four runs achieved high representation learning accuracy when used in the downstream classification task. The highest prediction accuracy result (98.4%) was achieved through a learning rate of 1e-4 (see Fig. 9). To choose the learning rate for the next experiments, the t-SNE plot for the last epoch of each run underwent examination. All the t-SNE plots have a clear distributed representation of every group of graphs (see Fig. 10). Therefore, the best accuracy (98.4%) with the learning rate of 1e-4 was selected to test other hyperparameters in subsequent experiments.

Table 1 Accuracy results using various learning rates

Learning rate	Mutual information loss (MI)	Accuracies			
		Logreg	Svc	Linear svc	Random forest
1e-5	20,148.611	0.981	0.986	0.980	0.986
1e-4*	3774.354	0.984	0.985	0.987	0.978
1e-3	488.991	0.972	0.985	0.983	0.977
1e-2	142.172	0.963	0.987	0.988	0.975

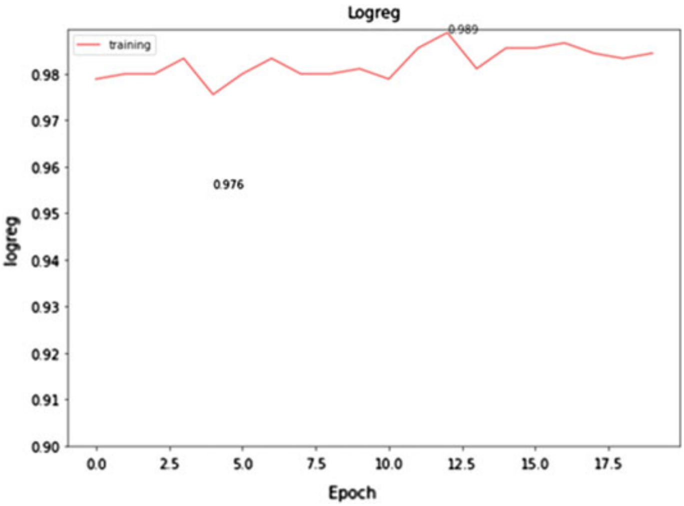

Fig. 9 Best Learning rate (1e-4) and the number of epochs (20) performance

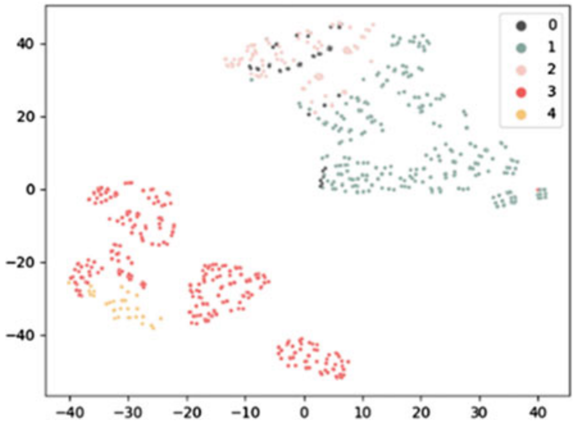

Fig. 10 Best t-SNE plot for learning rates (1e-4) and the number of epochs (20)

Table 2 Accuracy results using various numbers of epochs

Number of epochs	Mutual information loss (MI)	Accuracies			
		Logreg	Svc	Linear svc	Random forest
10	5668.682	0.984	0.987	0.99	0.984
20*	3774.354	0.984	0.985	0.987	0.978
50	909.848	0.984	0.988	0.983	0.980

Number of Epochs

Epochs refer to the number of complete training dataset iterations. The number of epochs is an important hyperparameter to optimize because too low or too high a value can result in under and overfitting respectively. We experimented with several epochs while maintaining a testing rate of 1e-4 (see Table 2). The representation learning model accuracy results were stabilised with 10, 20 and 50 epochs. Exceeding the 50 epochs resulted in lower accuracy. Therefore, we used the t-SNE plot to examine the distributed representation of every graph. According to the t-SNE plot (see Fig. 10), we chose the run with 20 epochs to continue testing other hyperparameters in subsequent experiments.

Batch Size

The gradient descent batch size controls the number of training samples to iterate through before updating the model's internal parameters. We maintained a 1e-4 learning rate and 20 epochs for this last hyperparameter experiment. We experimented with three different batch sizes of 32, 64 and 128, respectively (see Fig. 11). All the experiments achieved high accuracy; therefore, the t-SNE plot underwent examination to see the best-distributed representation of each graph (see Fig. 12). Moreover, we documented the total processing/run time to see how the batch size affects the run time. The total time was neglectable for two reasons. Firstly, the data is limited and secondly, unsupervised representation learning takes less time than its supervised equivalent (Table 3).

Conclusion

This paper aimed to determine the possibility of classifying architectural building/ground relationship forms through a novel workflow that uses unsupervised graph representation learning on 3D graphs rather than on 2D images. We leveraged a sophisticated topology-based 3D modelling environment to develop dual graphs

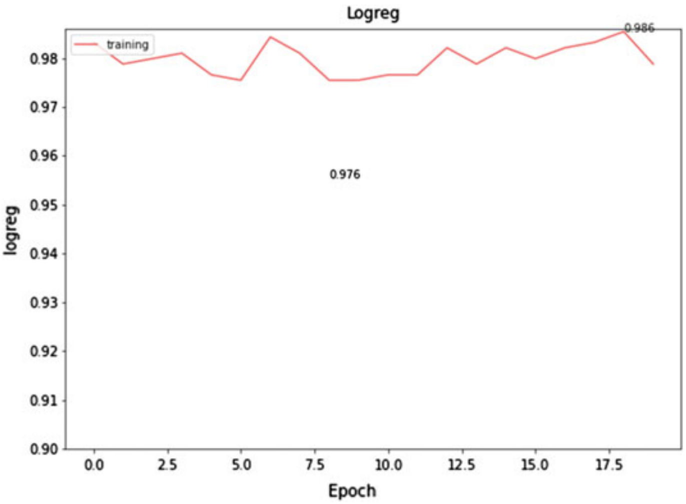

Fig. 11 Best batch size performance (32 batches)

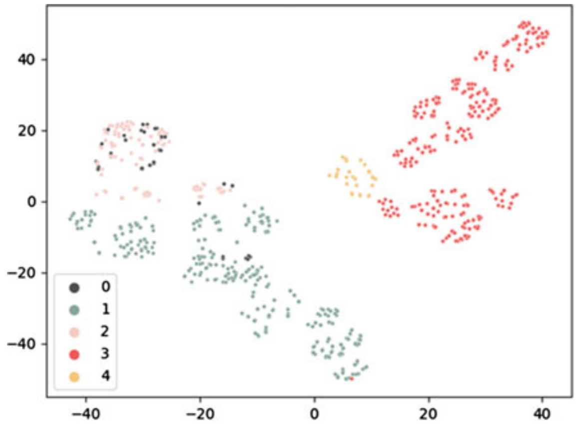

Fig. 12 Best t-SNE plot for 32 batches

Table 3 Accuracy results using various batch sizes

Batch sizes	Accuracies				Total processing time
	Logreg	Svc	Linear svc	Random forest	
32*	0.978	0.987	0.984	0.980	1:29:58
64	0.981	0.982	0.986	0.984	1:53:52
128	0.984	0.985	0.987	0.978	01:25:53

from 3D models and label them automatically. We then fed those graphs to an unsupervised graph representation learning system. To discover the best accuracy rates, we experimented with different hyperparameters, such as learning rates, the number of epochs and the number of batches.

At the conclusion of our experiments, we found that all the experiments achieved high representation learning with more than 98% accuracy for all four different accuracy measures, namely Logreg, Svc, Linear svc and Random Forest. Our approach illustrates strong promise for recognising architectural forms using more semantically relevant and structured data. A novel workflow will undergo comparison to other approaches and will be tested with other datasets and labelling schemes in future work.

The findings have identified several new research areas. We will first try to classify nodes instead of just the overall graph. Secondly, we plan to classify the same dataset with a semi-supervised graph level representation learning approach and compare the results with this paper. Finally, this paper is part of ongoing PhD research devoted to developing a system that may recognise the topological building/ground relationships designers may build in near real-time and suggest precedents from a visual database.

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Data-Based Generation of Residential Floorplans Using Neural Networks

Louise Deprez, Ruben Verstraeten, and Pieter Pauwels

Most generative design applications used in architectural design are developed with rule-based approaches, based on rules collected from expert knowledge and experience. In other domains, machine learning and, more in particular, neural networks have proven their usefulness and added value in replacing these hard-coded rules or improving applications when combining these two strategies. Since the space allocation problem still remains an open research question and common generative design techniques showed their limitations trying to solve this problem, new techniques need to be explored. In this paper, the application of neural networks to solve the space allocation problem for residential floor plans is tested. This research aims to expose the advantages as well as the difficulties of using neural networks by reviewing existing neural network architectures from different domains and by applying and testing them in this new context using a dataset of residential floor plans.

Background

During the last decades, generative design (GD), a technique used for the automatic generation of design proposals, is more and more used when designing architectural projects. These types of design proposals can vary from for example the building envelope of the Beijing national stadium using genetic algorithms [9] to the volume generation of the prairie houses of Frank Lloyd Wright using shape grammars [26],

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both automatically generated by using a GD algorithm. More recently, with the improvement of computing power and the emergence of more data, artificial intelligence (AI) is on the rise in many industries, even so in engineering and art. Architectural design has a long record in exploring the possibilities of AI within its domain. An old, but still open research question concerns the space allocation problem [28]. This research objective covers the generation of floor plans when an architectural program and a fixed building boundary, two requirements that are hard to unite, are given. An automation of this process will help the architect to quickly discover the potential of a parcel when used for a specific building program.

From around 1970 up until now, the automation of the space allocation problem started without the input constraint of a building boundary, to a rectangular constraint, later on going to orthogonal boundaries and finally also irregular boundaries. The possibility to use boundary constraints as an input for the generative program is important in for example renovation projects or when considering the context, such as neighboring buildings. The input constraints concerning the architectural program became also more complicated during this time span. First, almost no constraints were given, but later, room definition, room dimensions and adjacencies were also considered. However, when the complexity of the building boundary arose, room requirements were kept simple and vice-versa [28]. This resulted in tools dealing with complex interior layouts where the building boundary is the direct result of the spatial organization or tools where a fixed boundary is filled with rooms that could fit into this building, mostly leading to room adjacencies that do not correspond with the input requirements. A lot of research has been done on this design problem using common GD techniques and few good solutions were found merging the complexity of the building boundary and the room requirements [28]. Therefore, the aim of this research is to test the applicability of a popular AI technique, namely neural networks (NNs), for solving the space allocation problem in its full complexity.

First, the paper will document some disadvantages of common GD applications used for space allocation, so these can serve as points of attention when evaluating the different types of NNs. Secondly, related work will be discussed. Thereafter, pixel-based strategies are reviewed, after which the same is done for graph-based approaches. The most promising types of pixel- and graph-based NNs will be tested using a database of residential floor plans. Finally, the main advantages and difficulties of using NNs for solving the space allocation problem will be discussed.

Disadvantages of Common GD Applications

In most GD applications, when used for the automation of space allocation, input is processed directly into a final result. This full automation results in a first common problem, namely the lack of control of the architect over the design process. To resolve this, the design process can be broken down into several consecutive steps. This allows the architect to interfere between each step or to only automate certain steps in the process. The idea is based on a *grey boxing* method instead of *black boxing*, which allows the user to intervene along the way instead of inputting information upfront and getting a finished design at the end of the process [6]. Within this paper, the process will be broken down into two steps. First, a building boundary is generated on a blank page. This step becomes unnecessary when the architect wants to use the boundary conditions of a project as an input. Secondly, the interior spaces are filled into this boundary. Each step in this *grey boxing* method will be supported by a separate NN to execute a specific task. It is possible that different types of NNs will be needed for these different steps (Fig. 1).

Most algorithms used in the field of architectural design are based on one or more of the following five GD techniques: shape grammars, L-systems, cellular automata, genetic algorithms and swarm intelligence [30]. All of them are rule-based techniques, which reveals a second common problem in the application of GD techniques concerning the time-consuming task of the development of new rules by experts, in this case architects. Because the space allocation problem situates itself in the initial stage of the design process, during the exploration phase when decision-making still needs to start, the development of new rules can be even harder and an automation of this process would help the architect in this phase. Furthermore, since each algorithm is developed to perform a specific task in a specific project, rules supporting the algorithm can seldom be used in another context. This means that for each project, new rules need to be defined and since the rules are to some extent hard-coded, a lot of reprogramming or even starting from scratch is needed. To avoid the need of developing new rules for each new GD algorithm, one could use generic grammars [4], potentially allowing greater flexibility than shape grammars, or one could use NNs to replace rule-development with deep learning. In this research the latter is chosen. A NN is a data-trained method which can, as the word says, learn rules from real-world data and extract statistical information that can be used in the generation of new artificial data points, i.e. designs. The advantage of NNs compared to rule-based systems is that, besides the detection of intentional rules, NNs could also detect rules that are not consciously used by the architect [2]. Since data is used to learn a specific task, the execution of a task is dependent on the data. Other data may lead to the execution of another task. This means that one sample of code can theoretically train on different datasets, learning different tasks without the need of rewriting the whole algorithm [17], saving valuable time for the architect. For

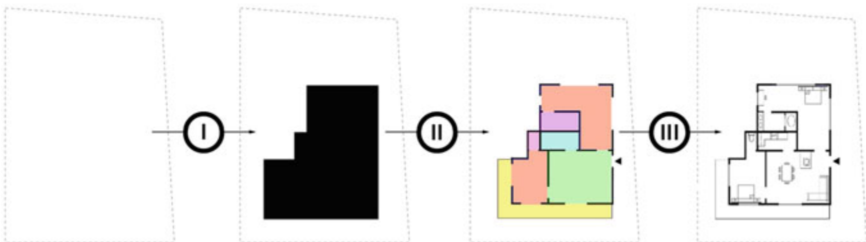


Fig. 1 Chaillou [6] used the *grey boxing* method to generate floor plans

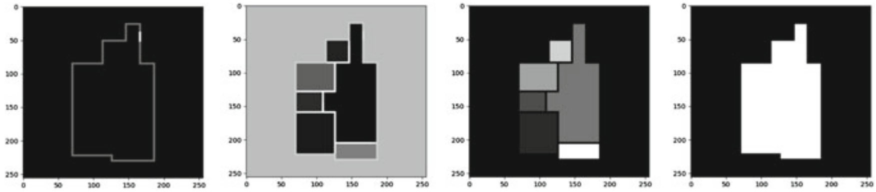


Fig. 2 The four channels of one data point in the RPlan dataset [33]

example, the code used in this research for generating residential floor plans could be used for the generation of another typology of floor plans without the need of hard-coding new rules. The model only has to be trained and tuned again within another dataset with the right typology of floor plans.

The Dataset

When implementing a data-trained method like NNs a suitable dataset is needed, in this case a dataset of residential floor plans. The quality of the final application will also be influenced by the quality of the training data. Moreover, the format of the data is important to control the type of information the network will learn. As an example, just showing the model building footprints will yield a model able to create typical footprints. There do not exist many, easily accessible, large datasets, that are formatted into a machine readable way and are at the same time based on real-world architectural designs. One available dataset is the *RPlan* dataset. It is a dataset of more than 80,000 residential floorplans manually collected by Wu et al. [33] from real-world residential buildings in the real estate market in Asia. Each data point represents a 255×255 px image existing of four channels: the building boundary, the interior room types (e.g. living room, bedroom), their room identities (e.g. id 1 and id 2 to distinguish two rooms of type bedroom) and the interior-exterior mask (Fig. 2). The channels are compatible with the *grey boxing* method mentioned before. This dataset will be used in the experiments when testing different types of NNs, by which statistical rules to generate new designs can be extracted from the dataset.

Related Work

Space allocation and building massing are old and popular research topics resolved many times, most of the time leading to an algorithm searching a restricted design space. In 2003, Hansmeyer [15] developed a flexible system that generates modular building forms adaptable to the environment using L-systems. In L-systems, design components are symbolized as strings and string rewriting mechanisms are applied according to a set of production rules, resulting in a string that can be translated back to a graphical representation. Kou et al. [19] used swarm intelligence in 2013 to find optimal evacuation routes for the Wuhan Sports Center. In 2016, Govaert [13] designed a building massing tool with hard-coded rules concerning sunlight, view and access based on cellular automata. Koning and Eizenberg designed a detailed shape grammar that makes it possible to generate all prairie houses designed by Frank Lloyd Wright and many more within his style [26]. These four examples show the possibilities of regular GD techniques, but despite the promising results, many rule-based systems still need to be hard-coded separately for each specific design problem.

Strobbe [31] showed the possibilities of machine learning (ML) by automatically classifying floor plans belonging to the style of the Malagueira houses designed by the architect Alvaro Siza Viera or to any other style by using a one-class support vector machine (one-class SVM) trained on adjacency graphs of floor plans. When using rule-based systems, these rules would need to be hard-coded for each style separately instead of being extracted automatically. Related to this, As, Pal and Basu [2] used GANs, a special type of NNs, to learn the main clusters of rooms in floor plans. Again, adjacency graphs are used to train the NN.

These deep learning algorithms need large datasets based on real-world data. Sharma et al. [27] did not only develop DANIEL, a deep learning application that captures semantic features of floorplans to use in floor plan retrieval, but they also created their own publicly available benchmark dataset, called ROBIN. Liu et al. [20] specifically recognized the need for converting rasterized floorplan images into vector-graphics representations to use in for example data analysis.

More recent research specifically tries to solve the space allocation problem. In 2020, Chaillou et al. [7] used Bayesian modeling, a statistical method, to generate adjacency graphs. However, they did not actually generate floor plans. In 2010, Merrell et al. [23] generated a floor plan given a list of rooms and their types, sizes and adjacencies using a Bayesian network. However, the external appearance of the building was a result of this layout. Nauata et al. [24] did the same thing only using a GAN, again the building footprint was not used as an input parameter, but was a result of the internal layout. Chaillou [6] on the other hand, generated the interior layout when given a fixed building footprint using GANs. Liu et al. [21] generated the functional zoning and architectural layout of a campus when given a campus boundary and the surrounding roads, using *Pix2Pix*, a method based on GANs. Both algorithms of Chaillou and Liu cannot take a desired number of rooms nor their type and size as input restrictions. It seems that the restriction of a fixed building boundary cannot be united with the restriction of a specific number of rooms and their properties. It therefore stays an open research topic.

Methods

ML is a broad field of research within AI. ML algorithms build a model, trained on training data, in order to make predictions or decisions without being explicitly programmed to do so. NNs are the backbone of deep learning algorithms that are a subfield of ML. A NN is a layered system of neurons passing messages from one layer to the next and the "deep" in deep learning refers to the depth of layers in a NN. By learning the probability distribution of a set of training data, a data-trained generative model is able to generate new valid data points that fit the probability distribution of the model [22]. This generative power is exactly what is needed in the scope of this research. Because NNs are powerful in the classification of images or the generation of new images, pixel-based NNs are considered before looking into graph-based methods.

Pixel-Based Methods

Image Classification Using a Neural Network (NN)

NNs have become extremely powerful in analyzing and even generating pictures. The most basic NN is a classifier or a prediction network. To explain the working of a simple NN, one can think of a network that gets a picture of a digit as an input and gives the digit represented on the picture as an output. The network is able to classify the picture because it was trained on a training dataset where each data point contains a picture and the class/digit, i.e. ground truth, it belongs to. The dataset mentioned here, with the pictures of digits, is called the *MNIST* dataset and can be seen as the *"Hello world!"* of NNs. At first, the untrained network predicts a random class when given an input image, the output is evaluated on the basis of a loss function which compares the predicted digit to the ground truth. This type of learning is called supervised learning.

To visualize this abstract concept of NNs, you could think of it as a set of layers, each with some neurons holding a value between zero (black) and one (white) (Fig. 3). The neurons of different layers are fully connected, i.e. each neuron of one layer is connected to each neuron of the next layer, and these connections each have a learnable weight or strength. The input layer receives the 28×28 px image of the digit, thus 784 pixels represented as neurons, communicates it to the first hidden layer and so on, until the last hidden layer communicates it to the output layer, holding ten neurons representing the ten digits, which tells us the prediction of the digit. The prediction can be recognized as the neuron/digit in the output layer with the highest value, i.e. the strongest signal.

The above NN could also be used to predict an architectural style when given an image of a floor plan, which was the research objective of Strobbe in 2016 [31]. Although this could be a possible solution, Strobbe used another ML technique,

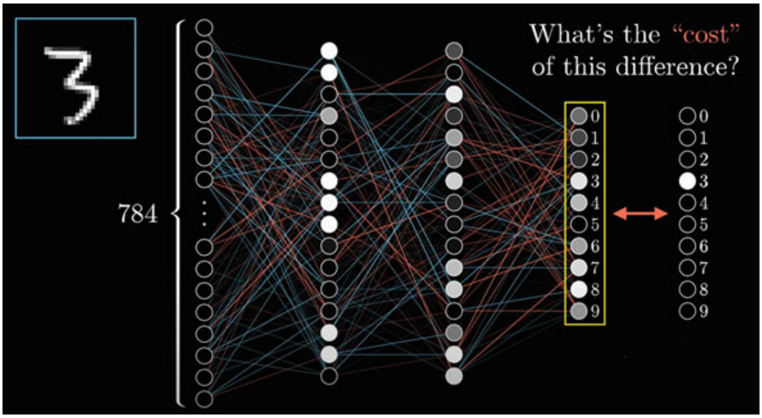


Fig. 3 A NN trying to predict the correct class of the image at the beginning of training, thus resulting in a bad prediction [1]

namely a one-class SVM. Since our interest is not simply the classification of images, but rather the generation of new images that would fit into the original dataset, a more complicated NN architecture is needed. Therefore, no experiments are done using this simple classification network.

Image Generation Using a Generative Adversarial Neural Network (GAN)

One very common network for generating pictures, that has furthermore proven its quality, is the GAN. Where a data point first had two pieces of information, namely the image and the ground truth, a data point now only has one piece of information, namely the image. To follow along, one could think of a database full of images of building boundaries, such as the fourth channel of the *RPlan* dataset (Fig. 2), and our goal is to generate a new, synthetic image of a building boundary. The previous network learned to generate the ground truth given the input image by comparing them and calculating the cost. But now, when generating a synthetic image, there is no right or wrong, there is no clear output that can be compared to a true value to calculate the cost. And without a clear loss function to calculate the cost, the network cannot receive feedback to improve its performances.

So, another feedback system needs to make sure the learning process can happen. For this, two NNs are linked to each other: a generator and a discriminator. The generator learns to generate a synthetic image that fits the probability distribution of the original dataset, while the discriminator learns to separate the false, synthetic images from the true images present in the original dataset. The feedback from the discriminator helps the generator to generate better samples, while the discriminator gets more skilled in separating the real images from the synthetic samples. Increasing the error rate of the discriminator, i.e. fooling the discriminator, is the learning driver of the generator, comparable to what the loss function of a standard NN is. The generator and the discriminator are both separate NNs.

The discriminator is a convolutional neural network (CNN), a simple classifier with a ground truth, which gets a 28×28 px image as input and learns to classify the images into a "Real" or a "Fake" category. The generator is a deconvolutional neural network (DNN) which gets 784 input neurons filled with random noise and outputs a new synthetic image of a face as 784 output neurons, which correspond to a new 28×28 px image. The loss of the generator is solely the predicted label of the discriminator, i.e. the prediction of a "Real" image is telling the generator it is doing a good job in tricking the discriminator.

A CNN is not a fully connected network like a basic NN, but uses a tensor/filter to reduce the number of learnable parameters/weights. To clarify this, each connection between two neurons has a learnable strength. By dropping some of these (less significant) connections, the computational cost drops significantly, especially for images that tend to have a large number of input neurons. Interesting is that these filters can pick up on certain patterns, like horizontal lines or corners, that are in most cases very important to recognize what is shown on a picture. The generator is a DNN, which is similar to a CNN but runs in reverse.

Based on the promising results, this paper will test this method twice using the *RPlan* dataset [33], once to generate the building footprint, corresponding to the first step of our *grey boxing* method, and a second time to generate the interior layout. Only one channel of the data points is used to keep the input layer a reasonable size and to support the *grey boxing* method.

The fourth channel (Fig. 2), representing the inside mask, will be used as training data for the GAN in the first experiment when generating the building footprint. This means that the input neurons only take one of two values: one (white) for interior and zero (black) for exterior. Important to notice is that this dataset is highly normalized, by which the input data is highly controlled, to learn one small task, namely the masking of the interior. The GAN takes random noise as an input, so requirements concerning area cannot be inputted upfront, but need to be checked afterwards. This does not cause any problem since generating multiple images is a matter of milliseconds and an area check can be quickly done to filter out irrelevant results.

For the second experiment, the second channel of the *RPlan* data points (Fig. 2) representing the interior layout is used. The learning process of the NN will become more complicated because the pixels can take more values than strictly one and zero, since each type of room or wall is represented by a different pixel value, e.g. a value of two for the kitchen and three for the bathroom. Again, the GAN takes random noise as an input, so no building boundary will be inputted upfront. The GAN is expected to generate the building boundary along with the interior layout.

Interior Layout Generation Using Pix2Pix

One major problem with the setup of the second experiment is the absence of a fixed building boundary as input for the network, a random interior layout was generated in a random building boundary. In some projects, the building boundary is a fixed requirement that cannot be changed to satisfy the interior layout. To constrain the GAN to a fixed building boundary, an image of it should serve as input. However, the architecture of a GAN should change since its input can only be random noise. Fortunately, Isola et al. [17] developed *Pix2Pix* which can be described as an image-to-image translation with a conditional GAN (cGAN).

Instead of using random noise as an input, *Pix2Pix* uses an input image and learns to map an output image to it. This means that this time, both the second and the fourth channel (Fig. 2) are used as respectively the ground truth and the input. One could think that solely using a basic NN could work since there is a ground truth, however, it would only learn deterministic outputs, meaning each building boundary only has one correct solution. In practice, one building boundary should result in different possible interior layouts. Because of this, *Pix2Pix* uses a GAN which makes it possible to implement noise and a less deterministic loss function and, by this, create variation. The noise is not added as an additional input, like in a basic GAN, but will be added as dropout, i.e. by randomly dropping some of the neurons in the network [17].

Pix2Pix is previously used in several contexts for the mapping of labeled pictures or edges to images (Fig. 4). Within the third experiment, this paper will generate an interior layout starting from a building boundary, which corresponds to the second step in our *grey boxing* method.

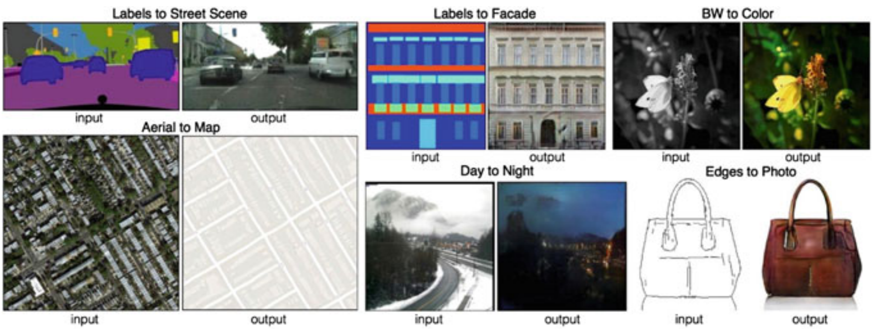


Fig 4 Several applications of Pix2Pix [17]

Graph-Based Methods

When approaching the research question with a pixel-based method, the input requirements are too limited. Inputting additional requirements such as room type, room number, areas and orientation are not possible when using one of the above NNs. Graphs can contain these requirements as node, edge and graph attributes, by which it is possible to add semantics to the graph, and they can be used as an input/output of other types of NNs [2]. This is why graph-based methods are considered.

An architectural plan can be represented by two different types of graphs or variations to them. In the first one, called semantic building footprint graphs (SBF) [12], rooms are represented by nodes and their adjacencies by edges. The second type is the one where the corners of the rooms are represented by the nodes and the lines between them by edges. In the context of this paper, the first type is used, because it is important for the NN to learn the adjacencies rather than the geometry of the rooms. As said earlier, what the NN is able to learn and generate is dependent on the data shown to it. Besides adding semantics to the data, using graphs has another advantage. Since each room is represented by one single node, the number of variables is strongly reduced. In the case of a NN, this means a smaller network with less neurons and consequently less weights and biases to learn, resulting in less computation time.

GANs are very powerful in the generation of real valued data, such as images, but they fail in generalizing to discrete objects, like graphs. The adaptation of GANs to support this new input format remained an open research question until 2018 because large repositories of graphs coming from the same distribution are not easily available. Since 2018, a few new approaches arose [5].

When representing an image as a graph, its nodes/pixels are fixed in space and they are always connected with their closest neighbors (Fig. 5) by which a filter can operate on it to find patterns in the picture. Because nodes in a graph are not necessarily ordered, do not have a fixed number of adjacent nodes and the graph does not have a fixed size, a filter cannot operate on this structure, therefore other methods for grasping the structure of the graph are needed. There are two possible ways to handle the variable size and structure of graphs. Common NNs, GANs included, need the input data to be fixed in size and structure, e.g. a fixed $n*m$ px picture, by which the first approach is to represent the graph as a fixed matrix, e.g. adjacency matrices or random walks. A second approach is to use graph neural networks (GNN), which can handle data with a varying number of nodes and edges. Depending on the type of GNN, predictions on graphs can be made (like node attribute prediction, classification of graphs or link prediction) or even new graphs can be generated.

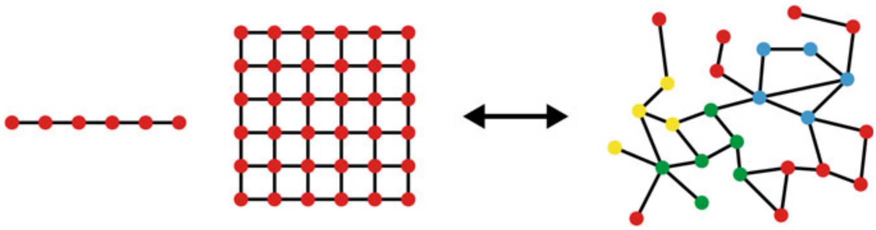


Fig. 5 A graph is a data type without a fixed size or structure. An image can be represented by a fixed size matrix

Adjacency Matrix Generation Using a GAN

The following method is based on molecule generation with GANs, where atoms are represented by nodes and their bonds by edges [10]. This method shows the difficulties concerning the representation of a graph as an adjacency matrix, however, when we choose to continue using GANs, such a representation is needed. Most researches focus on molecular graphs, since these datasets are easily accessible, something which is missing in the domain of architecture. A graph, whether it is representing a molecule or a floor plan, is defined by its nodes and edges and these two can in turn have several properties. A fixed size adjacency matrix ($A \in \{0, 1\}^{n \times n \times (b+1)}$) and a node feature matrix ($X \in \{0, 1\}^{n \times d}$) are able to hold this information [22] where the graph has a fixed number of nodes n, edge types b ($b+1$ to include non-edges) and node types d. When a node or edge has a certain type, the value 1 is inserted, otherwise 0. This is called one-hot encoding, which has proven to perform well as training data representation in prediction networks [12]. The GAN can, after learning, generate these type of matrices representing new floor plans.

When using adjacency matrices, some challenges occur. First, a graph with n nodes has to output at least n^2 values, mostly zeros. Secondly, this same graph can be represented by $n!$ different matrices depending on the node ordering [34]. Tavakoli et al. [32] learned the topology of social graphs by making 10,000 permutations of node orderings over only 4 social graphs. Imagine the computational power needed to represent a few more graphs. On top of that, the adjacency matrix is still a very restricted method where every graph has a fixed number of nodes. When more rooms are present in a new reference project, the whole model needs retraining on a new dataset with architectural plans containing an equal number of rooms. This means that the design space is strongly restricted beforehand. Because of its limitations, no further experiments are done using GANs to generate adjacency matrices.

Random Walk Generation Using a GAN

Another possible solution is the transformation of the problem of generating graphs, to the generation of fixed-length random walks. Two major advantages are the possibility of inputting graphs with varying dimensions and avoiding the problems concerning node ordering. This method, called *NetGAN* [5], is developed for the generation of large graphs like social networks, where one graph, represented by a lot of random walks, serves as input data. The generator learns to generate walks, as a sequence of nodes, that are plausible in the real graph. After generating a set of walks, they are assembled in a count matrix and used to produce the adjacency matrix of the new graph. The resulting graph has a comparable size and connectivity as the input graph [5].

Since *NetGAN* is developed for large graphs and these are not the subject of this research, one can think of an extension of this algorithm to produce small graphs based on a set of random walks over a set of small input graphs. However, one major disadvantage remains, this model is developed for homogeneous graphs, i.e. networks without any edge and node types, so no further experiments are done using this exact method.

Variational Auto-Encoders (VAE)

All above mentioned methods are based on GANs, but in reality other generative structures exist. For the generation of graphs, three structures can be distinguished: GANs, VAEs and autoregressive models.

VAEs are comparable to GANs, because their key building blocks are the same: a DNN/decoder and a CNN/encoder. First, the encoder compresses a given input data point to a lower dimensional space after which the decoder reconstructs the low D representation back to a high D representation. Finally, each reconstruction can be compared to its original input data point and the loss is calculated. This means that a new artificial sample can be generated when decoding a random point in this low D space.

The graphs are in most cases still represented as adjacency matrices [14, 22], thus a lot of challenges occurring with GANs still remain in VAEs. Since VAEs still show too much limitations, again, no further experiments are done using this method.

Autoregressive Models

GANs and VAEs are types of NNs that were originally developed for pixel-based approaches. Autoregressive models, on the other hand, are developed for more

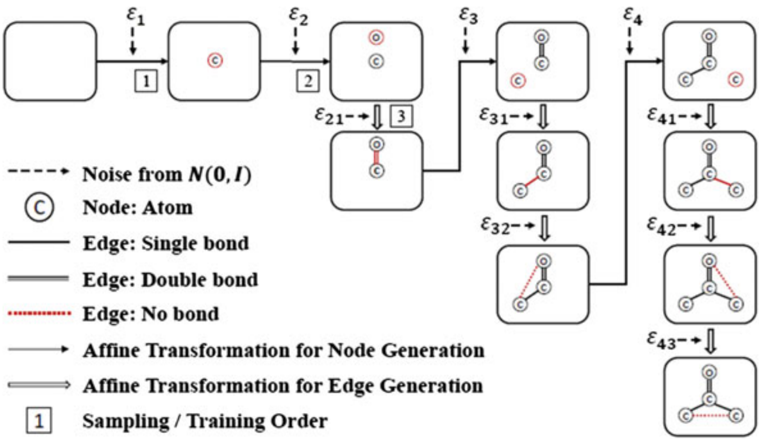


Fig. 6 Autoregressive model for molecule generation [29]

complicated data structures, such as graphs. *GraphAF* [29], for example, is especially developed to generate molecules represented by a graph structure.

In autoregressive models the adjacency matrix is generated by sequentially generating the adjacency vector of each node considering the previous state of the graph. Starting from an empty graph, each step a new node is added after which its edges are computed (Fig. 6). Additional architectural rules can be added, which can be used to check whether the addition of a certain node or edge is regulated. These rules could for example include the need of certain rooms or the avoidance of less desired adjacencies.

It is the only method that can generate graphs of varying size, with node and edge types (wall, door) and attributes (area, center coordinates) present. *GraphAF* is originally developed to generate molecules, but can be adjusted to generate interior layout graphs. Thus, in the fourth experiment an autoregressive model will be trained to generate adjacency matrices of interior plan layouts. In this paper, the *RPlan* dataset is automatically converted from an image dataset to a graph dataset, by first vectorizing the images and then creating their matrices.

From Graph to Plan

When the layout graph is generated together with its desired attributes, like room area or adjacency type, the graph needs to be mapped into a fixed building boundary. By breaking down this process into two consecutive steps, the architect has a lot more flexibility in deciding at which point to step into the process. The whole graph can for example be generated by the autoregressive model or the architect could create the graph all by himself/herself. To map the graph inside a building boundary, two researches pop out, giving an initial grasp of what a NN performing this task might look like.

The first research creates an interior layout in a fixed building boundary, however without using an input graph, but still using a pixel-based approach. This still remains relevant since a sequential process comparable to the autoregressive model is used. Wu et al. [33], who put together the *RPlan* dataset, trained a NN to first locate the center of the living room inside a given building boundary, then sequentially determine the next room type and location based on the current state of the plan and finally generate the interior walls. They trained an encoder-decoder network by randomly removing rooms from the dataset and trying to predict the center of these missing rooms [33] which could also be done with the autoregressive model by adding the center as an attribute to the graph (Fig. 7).

A second research, called *Graph2Plan*, tries to give the designer the option to add a graph additional to the boundary restriction. The NN serves as a search algorithm and searches for similar building boundaries and graphs in the dataset. Then, the layout graph from the similar boundary gets copied into the input boundary and finally the interior rooms are plotted. However, except from a well-trained search algorithm, the NN is not used to its full potential [16] (Fig. 8).

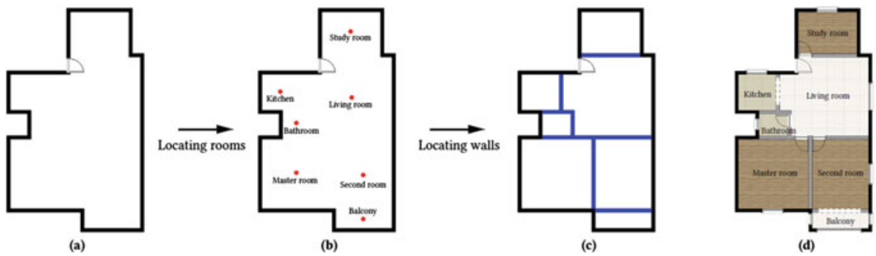


Fig. 7 Model architecture used by Wu et al. [33]

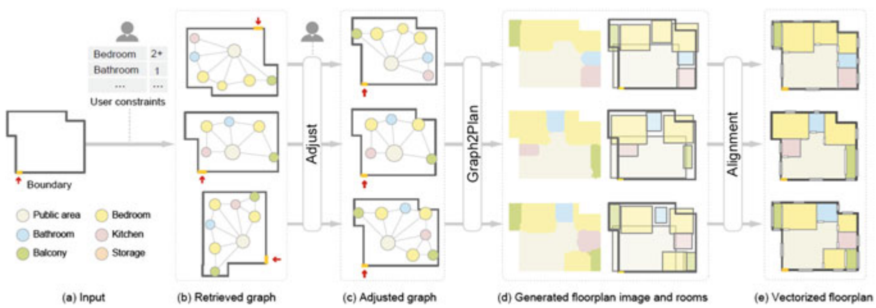


Fig. 8 Model architecture used by Hu et al. [16]

Results

In these experiments, the learning capacity of a basic GAN is evaluated based on its number of data points, the sizes of the pictures and the number of epochs while learning. The results will show the influence of these three parameters.

Within the first experiment a GAN was trained on the fourth channel of the *RPlan* dataset. The generator uses convolutional layers to upsample the input and turn random noise into an image. *LeakyReLU* is used for the activation of each layer, except for the output layer that uses *tanh* as activation function. The discriminator uses *LeakyReLU* as activation for each layer and dropout to lower the computational cost. When using 1,000 data points for 100 epochs, the learning takes a long time and results in blurry pictures (Fig. 9a). When compressing each picture to a 56×56 px image, by which the number of trainable parameters is reduced significantly, the results become much better. The generated pictures are still blurry, but shapes are recognizable (Fig. 9b). When learning for a longer time, the results do not improve significantly, but when using the whole 80,000+ dataset, clear shapes can be recognized (Fig. 9c). However, note that a 80,000+ dataset is not common and may not be available in a lot of projects.

Within the second experiment, the tests done in the first experiment are repeated, but instead of the fourth channel, the second channel of the *RPlan* dataset is used, representing the interior layout. Even when using the best model of the previous experiment, i.e. when using more than 80,000 data points, compressing the images and letting the network learn for a long time, the generated images are still too blurry to identify specific shapes, similar to the situation in Fig. 9a. Even when learning for a longer time or changing the architecture of the network, the results are not expected to be excellent within a reasonable computation time using a reasonable amount of data.

Within the third experiment, the interior layout is generated using *Pix2Pix*. Here, the fourth channel of the *RPlan* dataset is used as an input and the second channel

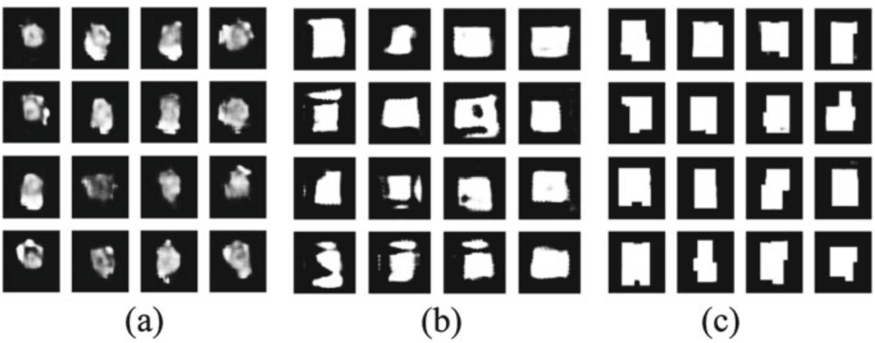
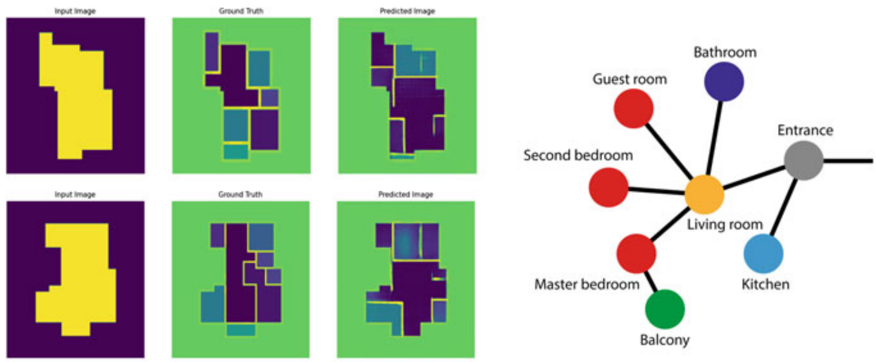


Fig. 9 **a** Training 1000 data points for 100 epochs. **b** Training 1000 compressed data points for 250 epochs. **c** Training 80k+ compressed data points for 100 epochs

as the ground truth. The encoder consists of convolutional layers activated with *LeakyReLU* and the decoder consists of transposed convolutional layers activated with *ReLU* and with dropout applied to them. Again, several problems occur when the algorithm is tested. While the model, trained with *Pix2Pix*, seems to result in acceptable results, one can see that the interior layout of the two data points as shown in Fig. 10a are almost identical. The model always places the interior walls at the same location regardless of the building boundary. Moreover, only minor stochasticity is observed in the output of the network when given the same input boundary, despite the dropout. This disadvantage was already observed by Isola et al. [17]. Still, if the network would give the desired results, only the input boundary is given as a demand, the desired interior rooms are not considered as an input.

When approaching the research question with a pixel-based method, an enormous amount of data and computation time is needed to avoid blurry pictures and even so, the input requirements are too limited.

Within the fourth and last experiment a graph-based method is used, namely an autoregressive model is trained using the adjacency matrices extracted from the *RPlan* dataset. Because of how the model is build, it is only trained during 3 epochs with a batch size of 15. The generated adjacency matrices have a novelty value of 1, which means no copies are made from the original dataset, and have a unique rate of 1, which means no identical data points exist in the set of newly generated graphs.



(a) (b)

Fig. 10 **a** In the third experiment Pix2Pix learned to map the interior layout of a residential unit to a building boundary. From left to right: the input image, the ground truth and the predicted image. **b** In the fourth experiment the autoregressive model learned to generate graphs

Conclusion

In this paper, the application of NNs to resolve the space allocation problem for residential floor plans was tested. This research aims to expose the advantages as well as the difficulties of using NNs by reviewing existing NN architectures from other domains and by applying and testing them in this new context using *RPlan*, a dataset of real-world residential floor plans.

First, pixel-based approaches were explored and tested. The experiments demonstrated that (c)GANs can generate acceptable pictures of floor plans when the model is trained for a rather long time on a large dataset. However, large, publicly available datasets of real-world floor plans are still rare. At the beginning of the paper, it was mentioned that the constraint of an irregular building boundary and the room constraints are hard to unite. *Pix2Pix* can handle highly irregular building boundaries, as long as the training data also contains irregular building boundaries, but using room restrictions as an input to the model is not possible. Since images do not contain semantic information, pixel-based approaches are not promising considering room restrictions. Graphs, on the other hand, can hold this information and therefore graph-based approaches were explored as a following step.

Many graph-based approaches, like GANs and VAEs, are based on pixel-based approaches, resulting in new disadvantages concerning the representation of the graph. Autoregressive models are developed to handle complex data types, like graphs, and are able to generate new graphs of varying size with node and edge attributes. Since geometry is ignored in these graphs, except for maybe an area attribute or a center attribute, graph-to-plan methods need to be developed. Two researches give a grasp of what this might look like, but more research still has to be done on this topic.

To summarize, NNs can only perform well when trained on large, suitable datasets, which are rarely available. On top of this, the NNs tested within this research use predefined functions and are built in a way that needs highly structured data as an input. The experiments show that the tested NNs can be used to perform small tasks, but a larger program architecture would be needed to sequentially use networks to perform these small tasks. For now, the space allocation problem is still not completely solved, when taking into account both a fixed building boundary and room allocations, but this research shows the potential of using NNs for solving this problem. Also, this research, together with previous research, shows that, for now, NNs are more limited than rule-based methods. In other domains, the combination of NNs and rule-based systems have led to strong program architectures. Recently, together with the development of new graph databases, new researches concerning graph NNs keep popping up in other domains. Thus, the full potential of NNs are still to be discovered.

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Voxel Substitutional Sampling: Generative Machine Learning for Architectural Design

Immanuel Koh

The paper aims at addressing a common limitation in dataset availability when designers attempt to use deep learning or machine learning models for generative design in three-dimensions. It proposes an alternative non-parametric and 'small data' machine learning approach that is capable of utilising single (or few) inputs for model training and design generation. The paper extends the Markov random field (MRF) statistical model by first illustrating its naïve architectural design appropriation before contrasting it with the proposed algorithmic improvements. Using increasingly complex and real architecture voxel models as input examples for the experiments, the strengths and weaknesses of the proposed method 'substitutional sampling' is discussed alongside the results. The paper thus seeks to provide a means to investigate and better understand the ways in which machine learning models such as MRF could be strategically adopted and effectively harnessed for the generation and exploration of three-dimensional forms in the architecture domain.

Introduction

This paper demonstrates a generative machine learning approach called *substitutional sampling* through a proposed 3D voxel interpretation of the Markov random field (MRF). MRF is a model with Markov property in multi-dimensions [1] and has been used in 2D nonparametric texture synthesis [2] for the past 20 years, including other pioneering works such as multiscale MRF [3] and combination of filtering theory with MRF [4]. In fact, MRF has continued to be used well into the late 2000s [5] in the texture synthesis domain until the advent of parametric deep neural networks. The use of MRF within architecture domain in 3-dimensions, however, has always

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remained relatively unknown nor ever been considered as a potential generative machine learning model for design purposes. MRF is a powerful statistical concept that exploits dependencies of a set of random variables. In texture synthesis domain, each random variable is the colour of a 2D pixel (in our case, the colour of a 3D voxel). Each pixel has a neighbourhood of other pixels and the Markov locality property assumes that the value of this pixel is only conditioned by this set of neighbouring pixels. In other words, it is independent of all other pixels outside this neighbourhood. More concretely, a naïve 3D voxel-based MRF algorithm would work as follows in pseudo code:

1. Extract from the exemplar input voxel model all the conditional probabilities of a voxel given its 3D neighbourhood. These probabilities constitute a transition matrix.
2. Sample a random voxel from any initial input voxel model for single voxel-to-voxel substitution.
3. Retrieve its neighbourhood and its corresponding probability distribution from the transition matrix.
4. Given a matching neighbourhood, substitute the current focal voxel with a new value according to the transition matrix.
5. Repeat step 2 recursively.

Naïve Method

We shall begin by reviewing the naïve algorithm in greater details, alongside illustrations, that first motivated our design of the *substitutional sampling* algorithm, which in turn, find its place in the proposed general theory of *architectural sampling* [6].

Neighbourhood Pattern

The first goal is to build the transition matrix from an exemplar input model. The transition matrix is the probability distribution of a voxel (note: a voxel is defined by its colour, just like a pixel) given a neighbourhood. However, before building a transition matrix, one needs to decide or design the neighbourhood selection pattern—an extremely important parameter that would lead to very different results as we will see later in the paper. Although there are standard 2D model types, such as Radial, von Neumann and Moore neighbourhood patterns, we will now simply consider 3 possible patterns shown in Fig. 1. For simplicity, these are represented in 2D, however, the implemented algorithms are in 3D. The voxels in grey represents the neighbourhood of the focal voxel (in green). The second pattern checks every surrounding voxel while the other two only check a subset of it. With regards to the quantity of information, the second pattern ('box' pattern) should yield better results, though also computationally more expensive.

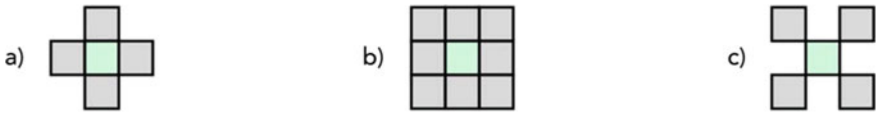

Fig. 1 Different possible types of neighbourhood pattern

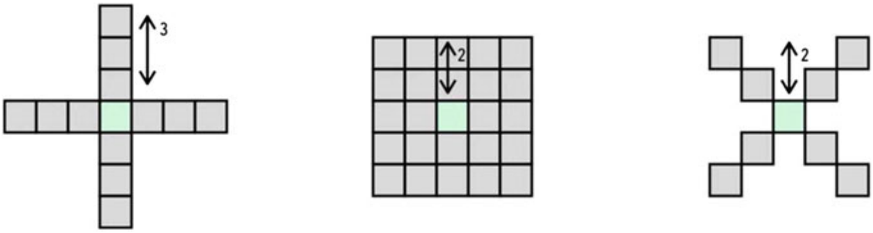

Fig. 2 Different possible types of neighbourhood distance

Neighbourhood Radius

After selecting a pattern, its spatial extent or radius need to be considered. This parameter defines the neighbourhood's distance limit. In Fig. 2, although the second pattern has a denser neighbourhood (with 24 neighbouring cells), its extent is less than the first pattern which has a radius of 3 instead of 2. Similarly, larger radii could lead to more coherent outputs but also reduce time efficiency.

Transition Matrix

Now that the neighbourhood pattern is set, the next step is to build the transition matrix accordingly. This is done by iterating over the whole input model and mapping the neighbourhoods with a list of colours with which the centre focal voxel can be assigned to. Each colour of the list is associated with a frequency: it is the probability that the centre focal voxel can be assigned with this colour given the neighbourhood. These mappings are the entries of the transition matrix. Once the transition matrix has been extracted from the input model, we will have captured its markovian logic.

In Fig. 3, we visualize the process of building the transition matrix and the pseudocode is as follows:

1. Encode each voxel as a list [X, Y, Z, R, G, B], where X, Y, Z represent the integer values of the respective 3D coordinates and R, G, B represents the individual colours (red, blue and green) between the value 0 and 255.
2. For each voxel of the input:
    1. Select the neighbourhood according to the specified pattern and radius

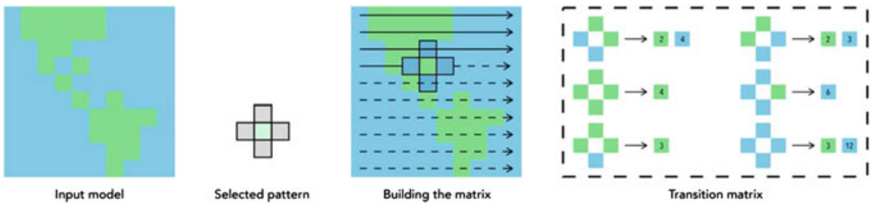

Fig. 3 Learning process via building the transition matrix from an input model

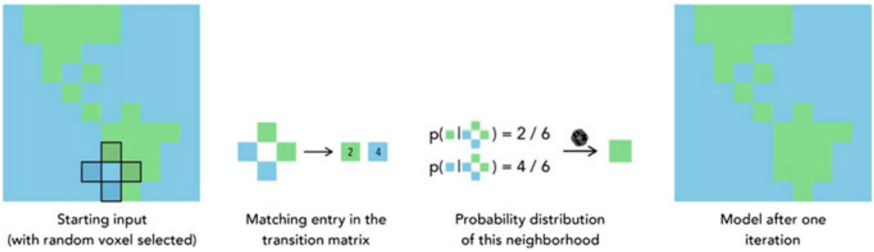

Fig. 4 Generative Process via applying the transition matrix on the same input model. This initial input model could be any input model sharing the same set of colours as the learnt input model

2. Map the neighbourhood to the centre focal colour
3. Keep track of the number of occurrences of this colour.

After building the complete transition matrix, an initial input massing is required to begin the generative process. This initial input massing can be any model that shares the same set of colours, such as the same model that was used for building the transition matrix, random noise or another input model created by the designer. In Fig. 4, we visualize the process of applying the transition matrix to generate new outputs and the pseudocode is as follows:

1. Load the initial input massing to be modified via the *substitutional sampling* process.
2. For N iterations
   1. Randomly select a voxel from the loaded input model
   2. Compute the neighbourhood of the selected voxel
   3. Check and retrieve the corresponding neighbourhood entry in the transition matrix.
   4. If neighbourhood entry exists in the transition matrix:
      - Randomly select a colour according to its number of occurrences.
      - Substitute the current voxel colour value with the new one.

Toy Example

We shall now test this first naïve implementation of the algorithm on two 3D voxel models of the same design, but the first in 3 colours and the second in single colour, and observe the generated results. In Fig. 5, we built the transition matrix with the Greek-cross neighbourhood pattern (a) as shown in Fig. 1, with a radius of 2. The generated output was the result of 100 000 iterations. Clearly, the output is far from what was expected. The output model seems to disintegrate and gradually disappear, rather than generating a new model with formal and spatial features captured from the original input model.

In Fig. 6, we observe that even loading the second model (single coloured) with the same neighbourhood parameters, the output barely managed to recreate some of the input model's details. In conclusion, this naïve 3D extension of MRF is not scalable. For instance, the neighbourhood radius has to be large in order to create a transition matrix that could learn larger chunks of the model (and not just small local details). This scalability issue is due to the cubic increase in complexity when in 3 dimensions. Furthermore, with the increase in number of colours of the input voxel model, the matrix's complexity also increases.

Proposed Method

As we have seen, the naïve implementation of the MRF algorithm in 3D does not provide satisfying results, some extensions are needed in order to cope with the mentioned issues. Among these extensions, the major ones are the *best matching neighbourhood scoring*, *neighbourhood pattern with block selection*, *grid selection with grid* replacement, *noise initialisation* and the *remix mode*. The other minor extensions are *applying function*, scaling *inputs* and *masking voxels*. We will discuss them in detail in the following sections.

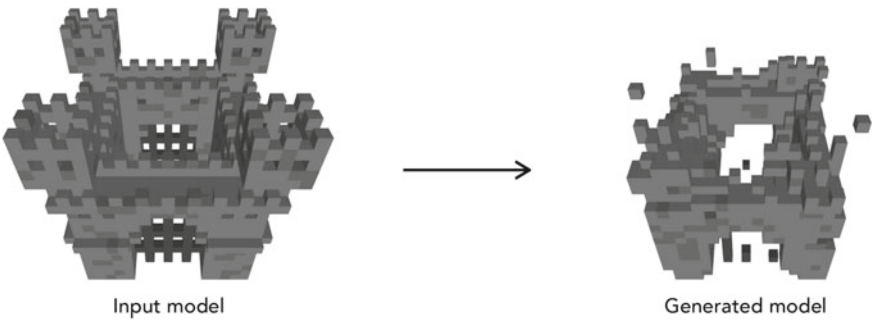

Fig. 5 A toy example with voxels in 3 colours

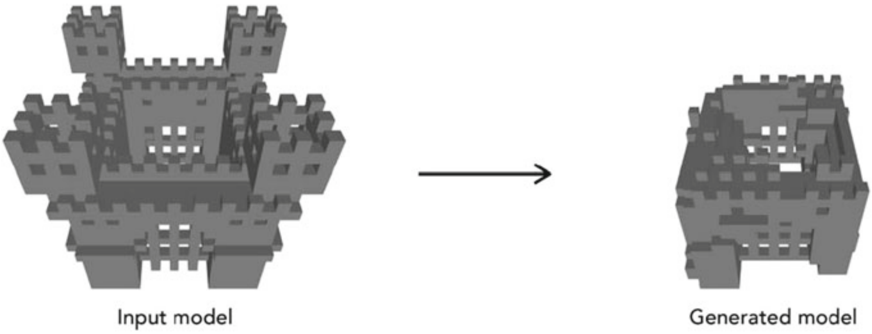

Fig. 6 A toy example with voxels in 1 colour

Best Matching Neighbourhood

Since our algorithm is in 3D, the size of the neighbourhood pattern is $O(radius^3)$: the number of distinct neighbourhoods explodes with the increase in radius. Therefore, there is a high likelihood that the input model would not contain every possible neighbourhood. Consequently, the algorithm often encounters missing entries in the transition matrix while generating the new model. The goal of this extension is to find a way to approximate these missing entries.

The basic idea is that if there is no exact match, this extension finds the best matching neighbourhood in the transition matrix. The best match is the entry with the highest score. An entry's score is computed with the following formula:

where $\boldsymbol{MV}$ is the set of voxels that are identical in both neighborhoods (i.e.: same position and same colour), $\boldsymbol{d}()$ is the distance to the center and $\boldsymbol{max\,D}$ is the pattern's maximum distance to the centre.

We shall demonstrate how the scoring is computed to select a best matching neighbourhood, given that no exact match is to be found in the transition matrix. Suppose there are only four different neighbourhood entries in the transition matrix (Fig. 7), according to the above formulate given, the score of the respective neighbourhood is computed as shown in Fig. 8. The updated pseudocode for applying the transition matrix with the best matching neighbourhood is as follows:

1. Load the initial input massing to be modified via the *substitutional sampling* process.
2. For N iterations
    1. Randomly select a voxel from the loaded input model
    2. Compute the neighbourhood of the selected voxel
    3. Check and retrieve the corresponding neighbourhood entry in the transition matrix.
    4. If neighbourhood entry exists in the transition matrix:
        - Randomly select a colour according to its number of occurrences.

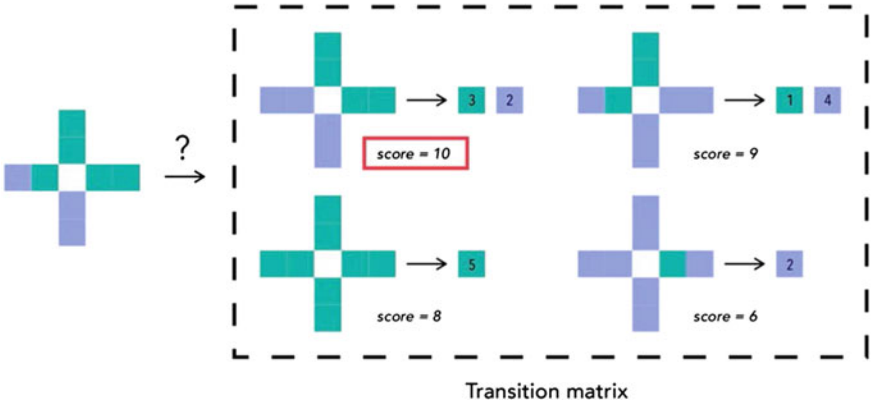

Fig. 7 (LEFT) Given a neighbourhood that does not exist in the transition matrix, (RIGHT) find the best matching neighbourhood using a score metric

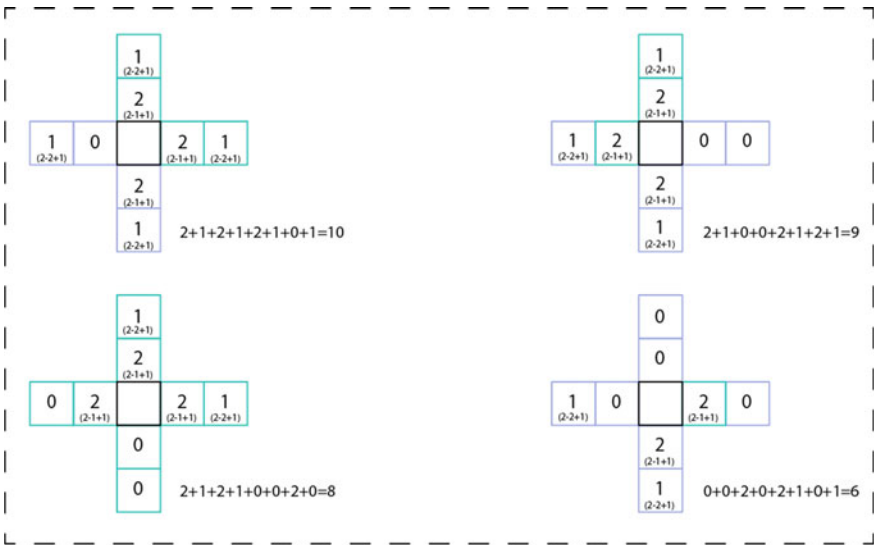

Fig. 8 Enlarged diagram showing how the scores for the 4 neighbourhoods in Fig. 7 are computed

- Substitute the current voxel colour value with the new one.

5. Otherwise, if neighbourhood entry does not exist in the transition matrix:
    - Compute the score for each entry and keep the best scoring one.
    - Randomly select a colour from this best scoring neighbourhood according to its number of occurrences.
    - Substitute the current voxel colour value with the new one.

Neighbourhood Pattern with Block Selection

The purpose of this extension is to increase the receptive field of the scanning window to capture more global configurations of voxels. In this way, the transition matrix will be able to quickly generate output models that have more coherent details. Instead of updating one voxel at a time, the algorithm now updates a chunk of voxels per iteration. In order to support this block selection functionality, the neighbourhood pattern provides a new parameter: the *selection radius*, which dictates the size of the selection chunk. Constructing the neighbourhood (grey) and selection (green) patterns is now done as shown in Fig. 9. The transition matrix then works exactly the same way, except that the neighbourhoods are not associated with a list of single voxels anymore but with a list of voxel blocks. For example, a transition matrix could be in the form shown in Fig. 10. Thus, the updated pseudo code for building the transition matrix with block selection is as follows:

- For each voxel of the input:
  1. Get the chunk of voxels that is centred around the current voxel according to the selection radius.
  2. Select the neighbourhood according to the specified neighbourhood pattern and neighbourhood radius.
  3. Map the neighbourhood to the chunk of voxels

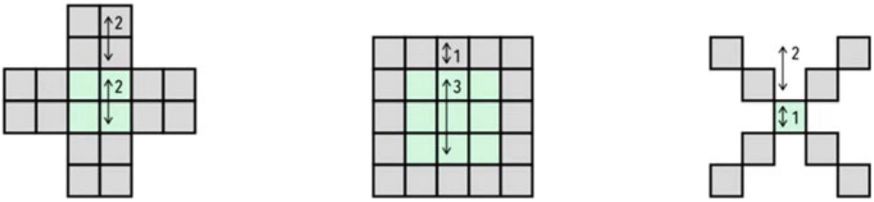

Fig. 9 Setting the neighbourhood radius (in grey) and selection radius (in green)

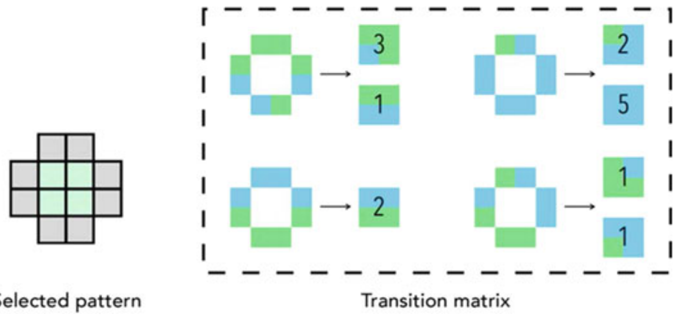

Fig. 10 Transition matrix that maps a neighbourhood to a chunk of voxels (instead of single voxel)

4. Keep track of the number of occurrences of this chunk of voxels.

The updated pseudo code for applying the transition matrix with block selection is not very different and is as follows:

- For N iterations

1. Randomly select a chunk of voxels from the loaded input model
2. Compute the neighbourhood of the selected chunk of voxels
3. Check and retrieve the corresponding neighbourhood entry in the transition matrix.
4. If neighbourhood entry exists in the transition matrix:
   - Randomly select a chunk of voxels according to its number of occurrences.
   - Substitute the current chunk of voxel colour values with the new one.
5. Otherwise, if neighbourhood entry does not exist in the transition matrix:
   - Compute the score for each entry and keep the best scoring one.
   - Randomly select a chunk of voxel colour values from this best scoring neighbourhood according to its number of occurrences.
   - Substitute the current chunk of voxel colour values with the new one.

This extension is actually very effective, and the results are now corresponding to what was expected. Let us test the improved algorithm on the previous problematic toy example (castle). The transition matrix of this example is built with the neighbourhood pattern (a) in Fig. 1, with a neighbourhood radius of 1 and a selection radius of 5. The generated output is the result of 1500 iterations as shown in Fig. 11. The input and the generated model clearly share similar features, while the algorithm is now able to deal with voxel models with multiple colours. Here, the initial input massing (a massing consisting of five towers within an enlarged walled compound) is made by a designer to guide the algorithm.

The space required by the transition matrix becomes huge when the selection radius is large, because each possible chunk of voxels is stored. However, there is

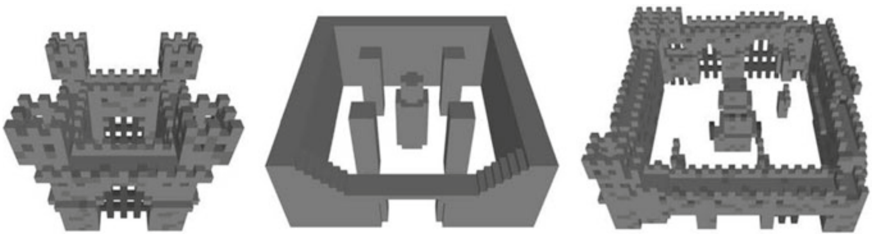

Fig. 11 With block selection turned on, the output model (RIGHT) now retains similar features of the original input model (LEFT). The sampling algorithm is also able to better deal with voxel models with multiple colours. In this example, the initial input model (MIDDLE) is made by the designer to dictate certain massing configuration and guide the generative process in a more targeted manner

a way to optimize the program and to avoid this side effect. Instead of copying the chunks of voxels into the transition matrix's entries, only the chunk's xyz coordinates are stored. If the chunk is needed it is computed but not kept in memory. Therefore, the size of the transition matrix is,

$$O(neighborhoodRadius^3 \cdot inputSize)$$

instead of

$$O((neighborhoodRadius^3 + selectionRadius^3) \cdot inputSize)$$

With this optimization, the program is able to build transition matrices with big selection radiuses without the issue of running out of memory.

Grid Selection and Grid Replacement

Block selection considerably increases the space occupied by the transition matrix since it stores a list of chunks and each chunk contains $selectionRadius^3$ voxels. With grid selection, the transition matrix is a lot smaller but is still a good approximation, therefore it is a good trade-off between accuracy and performance. Instead of registering every possible chunk of voxels in the transition matrix, each voxel is visited exactly once. This extension is called *grid selection* because one can imagine a virtual grid over the input so that each cell (=chunk of voxels) of this grid is registered into the transition matrix (Fig. 12). This is actually a subset of the complete transition matrix. In fact, this approach is similar to our previous work on voxel synthesis [7, 8], except that now the building of this transition matrix is inverted. In other words, rather than mapping a unique focal pattern to an aggregated list of allowable neighbours; *substitutional sampling* maps a unique neighbourhood pattern to a list of allowable focal patterns.

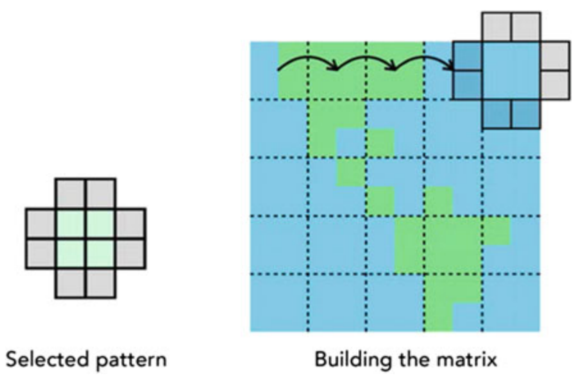

Fig. 12 Learning process via building the transition matrix from an input model by moving in block/chunk of voxels

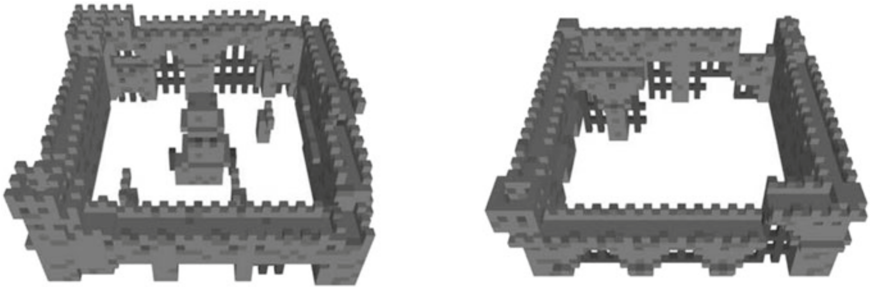

Fig. 13 Two generated output models: (LEFT) Using the complete transition matrix; (RIGHT) Using only a subset of the complete transition matrix as a result of turning on the grid selection and grid replacement features

In generating the new model, a random chunk of voxels is selected and updated at each iteration. If the algorithm is using a transition matrix built with grid selection, the replaced chunks would be misaligned with one another, since it is selected randomly across the whole model. However, if the grid policy is reused for the generation step (i.e.: randomly select a cell of the virtual grid), every chunk of voxels should be well aligned and the result would look less glitchy. Let us compare the model generated with a complete transition matrix and the model generated with grid selection and grid replacement, and see if there are any noticeable differences as shown in Fig. 13. Here, the two models seem very similar, and it is not obvious that one of them was generated with a subset of the transition matrix (i.e. grid selection). Therefore, grid selection does provide satisfying results with better performance. It can be crucial for very large models or transition matrices with a large selection radii. However, it is usually more interesting to use the complete transition matrix if the runtime is reasonable.

The same toy example (castle) is now tested with different parameter settings, namely with or without grid selection and varying sizes (3,5,7) of selection radii as shown in Fig. 14. It is clear that the selection radius has to correspond to the size of the model's features. In our case, a radius of 5 will approximate well with the size of the castle's tower.

Noise-Initialised Input Model

Due to the nature of the proposed *substitutional sampling* algorithm, the generative process can only begin given an initial input massing for voxels replacement. Instead of using the same learnt input model, having a different but meaningful initial input massing can play a huge role in the generated output. In this situation, especially in testing the current transition matrix and finding the right parameters, the Perlin noise is a good and convenient way to quickly obtain an initial input massing. This extension helps to quickly compute a massing based on Perlin noise and the voxel

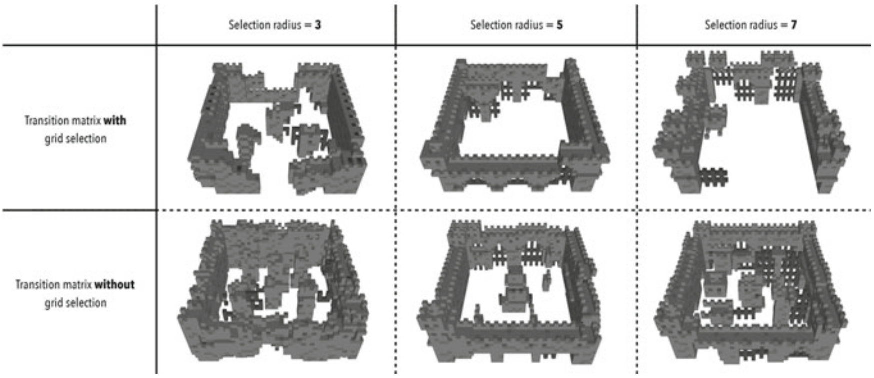

Fig. 14 Tests with different parameter settings—with or without grid selection and varying sizes (3, 5, 7) of selection radii

colour frequencies of the learnt input. Having a starting input that is different than the input that was used to build the transition matrix is crucial in order to get a final result that is very different. Starting inputs provided by the user are ideal but those take time to design, whereas Perlin noise is generated almost instantly. Another benefit of this extension is that one could apply the noise at a larger scale and produce results of any size. Using a noise-initialised massing is especially effective for generating large buildings.

Remix Mode

The remix mode is derived from the idea that a transition matrix can be built from several models instead of just one. Merging matrices is an effective way to combine the logic of different models together. The only constraint is that they must share a similar set of colours so that they can blend together. A new feature is thus introduced to combine a given transition matrix with the logic of another model. The algorithm is essentially the same, since it has the same functionality except that it does not create a new transition matrix but completes the given one.

Applying Global Function

After discussing all 5 of the core extensions, we will now briefly describe the other 3 minor extensions for the proposed *substitutional sampling* algorithm. If the starting input is the same as the input that was used to build the transition matrix, the generation can be very slow because the model is likely to be relatively steady or even ending up in a stalemate (i.e., each iteration replaces the chunk's colours with the

Fig. 15 (LEFT) Generated output model with the original probability distribution. (RIGHT) Generated output model with an inverse function applied to the original probability distribution

same colours). Changing the probability distribution could be a way to break this steadiness and enforce the generation. The intention is thus to have the added capability to simply apply a function on the transition matrix's frequencies. The function might be the typical mathematical ones, such as linear, constant, inverse, inverse square, exponential, power square and square root. They might also be the more custom ones to reduce or remove or increase voxels which are void. For example, as shown in In Fig. 15, one could apply the inverse function on the transition matrix in order to resolve the steadiness issue. The transition matrix of this example was built with the neighbourhood pattern (**a**) as shown in Fig. 1, with a neighbourhood radius of 3 and a selection radius of 1. The generated outputs are the result of 1,000,000 iterations. The generated model with inverse distribution turned out closer to the initial input massing and might not have indeed resolve the issue of steadiness. Applying functions on the probability distribution is in fact not a good idea because it is very hard to predict how the end result will be influenced by it and therefore is not a useful tool for the user. Moreover, steadiness is not really a problem anymore since the starting input is usually a different model (provided by the user, Perlin noise… etc.)

Scaling Inputs

This minor feature is to provide a way to increase the number of voxels of a given low resolution input model during the learning and that of the initial input massing during the substitution.

Masking Voxels

The ability to intuitively mask portions of the input model to alter or reduce the complete transition matrix is a means to introduce biasness during the learning process. Similarly, the masking can be made on the initial input massing, such that only desired portions of the models are being probabilistically substituted. In the design domain, this allows one to target at a specific section in a building alteration project or a specific territory in an urban or landscape intervention project.

Results

Thus far, for ease of illustrating the algorithm and its proposed extensions, we have been using the toy voxel model of a castle. In the following sections, we will integrate these design considerations into a single software application porotype and use voxel model inputs of actual buildings. Two formally contrasting staircase designs by Ricardo Bofill have been sampled from his 1973 *La Muralla Roja* housing complex for our study. One of the motivations for selecting this particular project is to examine how might its aggregational logic be sampled rather than planned, given the high degree of varied repetition in its formal and spatial configurations. For instance, several staircases found in the complex look similar, yet not exact copies of one another. Thus, the use of a probabilistic approach, in our case with *substitutional sampling*, to automatically learn and generate similar (but not exact copy) of *La Muralla Roja* seems to be a promising endeavour. Both staircases selected are encoded as coloured voxel input models for our experiment. Architecturally, one is characteristically outward-looking with an opaque core in the centre, while the other inward-looking with an opened courtyard in the centre. These highly distinguishable formal features will serve as our qualitative guide in evaluating the effects of our *substitutional sampling* algorithm in relations to the training inputs and inferred outputs. In our experiment, we will observe how the different parameter settings might give rise to different outputs, given each of these input models, individually and in combination.

Prototype

To facilitate quick iterations with different input models and parameter settings, a software application was implemented as shown in Fig. 16. It consists of a very basic interface that allows designers to quickly set the various key feature parameters and visualize a quick 3D rendering of the generated outputs (i.e., flat shading and without shadow-casting or other more fine-tuned lighting setup). Other utility functions are also included to provide further interaction with the 3D models. All the parameters are located on the top panel, namely toggling grid selection, choosing neighbourhood type, setting selection radius, setting neighbourhood radius and the number of iterations desired. The rightmost sliders are used to determine the bounding box size of an initial input massing generated with the provided Perlin noise functionality. This allows the generation of outputs with any proportions, from densely packed city skyscrapers to low-density suburban sprawl. The bottom panel consists of keys for loading models, building and applying the transition matrix and exporting the output for further CAD/CAM analysis. The middle panel is where the main 3D visualization and interaction occur. On the left is the input model (or models if it is in the remix mode) which the current transition matrix is built from; in the middle is the initial input massing (in this case generated with the Perlin noise functionality); on the right is the generated output when the current transition matrix is applied to the initial input massing.

While setting up and carrying out the design experiments, many different input models were being used to better understand the effects of the parameters and the logic of our proposed algorithms. The decision to eventually enable the grid selection parameter for all the experiments with Ricardo Bofill's *La Muralla Roja* was based on the quick exploratory tests in Fig. 17. The results showed that there is no perceptible difference between enabling and disabling the grid selection parameter, yet the computing performance in space and time is far better with the enabled mode. Prior to deciding which architectural input model to use, one needs to decide its formal type—volumetric, planar or frame-like, and its semantic type—buildings, furniture, objects or abstract diagram. Likewise, the choice of input models is also dependent on the resolution achievable once they are encoded as voxels. As a result, all of the

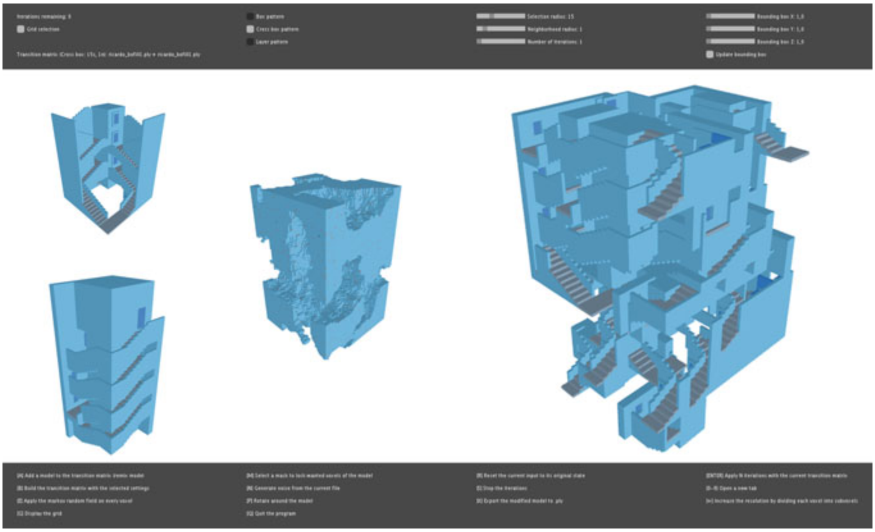

Fig. 16 Prototype Interface: (LEFT) The input models used here are the two stair cases taken from Ricardo Bofill's 1973 apartment complex in Spain called *La Muralla Roja* which the current transition matrix is built from in the remix mode; (MIDDLE) The initial input model used here is generated with the Perlin noise functionality; (RIGHT) The generated output after applying the current transition matrix on the initial input model. In this example, the neighbourhood radius is 1, selection radius is 15, grid selection is enabled, and the result is generated after of 1500 iterations

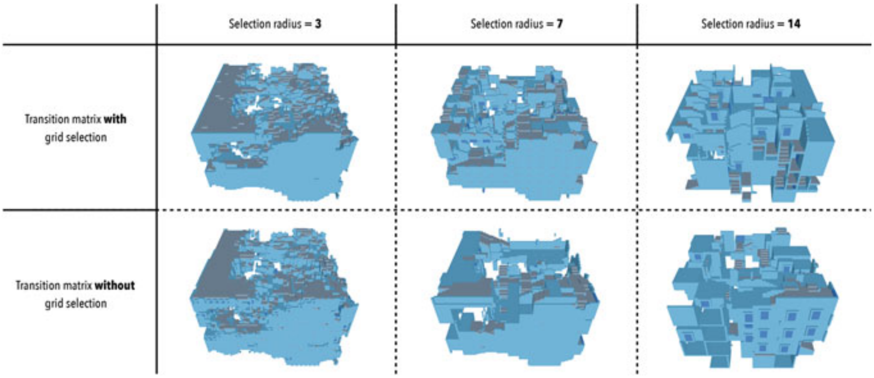

Fig. 17 Tests with different parameter settings—with or without grid selection and varying sizes (3, 5, 7) of selection radii

input models tested were generally orthogonal buildings with more than 1 colour, of which Ricardo Bofill's *La Muralla Roja* seemed most ideal.

Failures

In this paper, we will also illustrate the examples that did not work well with our proposed *substitutional sampling* algorithm when using the default uniform neighbourhood and selection radii. At the furniture scale, where the global form of the input model is relatively more constrained in relation to its function, our algorithm fails to learn the functional global configuration For example, with Gerrit Rietveld's baby chair in Fig. 18, the generated model clearly does not resemble a chair that could be sat on, although it did manage to capture the red frames of the chair, but unable to generate the brown planar seat and back rest at all. This same issue with planar input models is especially obvious when tested with Theo van Doesburg's *Construction de l'espace, Temps III* as shown in Fig. 19.

Setting a neighbourhood radius of 0 (i.e., uniform randomness) actually yields better results than sampling from a learnt transition matrix (Fig. 20). It is clear that our proposed algorithm (with the default symmetric radii) is not applicable to every type of input models.

Conclusion

The paper has demonstrated the ways in which non-parametric, statistical, probabilistic machine learning model such as MRF could in fact be effectively appropriated for three-dimensional generative design purposes. Through *substitutional sampling*,

Fig. 18 (LEFT) Reconstructed model of Gerrit Rietveld's Baby Chair encoded as voxels. (MIDDLE) Initial input massing via perlin noise generation. (RIGHT) Generated output that failed to capture the planar features of the original input model and its function as a chair

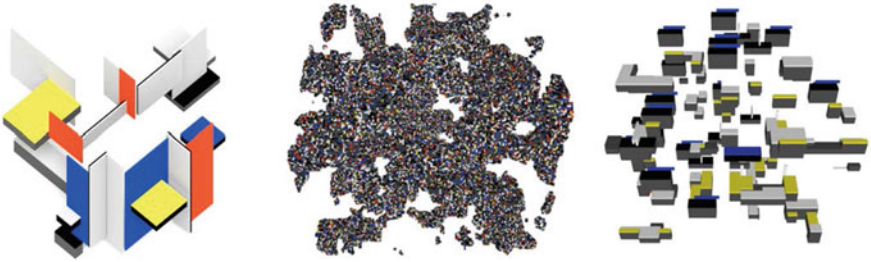

Fig. 19 (LEFT) Reconstructed model of Theo van Doesburg's Construction de l'espace, Temps III encoded as voxels. (MIDDLE) Initial input massing via perlin noise generation. (RIGHT) Generated output managed to capture the volumetric elements (in yellow and white) but failed to capture the thin planar elements (in blue and red)

Fig. 20 Generated output based on a neighbourhood radius of 0 (i.e., uniform randomness) is showing better results than having a learnt transition matrix with our proposed *substitutional sampling* algorithm

only one or few voxel-based architectural models are needed as inputs to generate a variety of similar (yet different) outputs via the proposed design exploration software tool integrated with specific algorithmic extensions. Future works will address the range of failed input models highlighted in the study, so as to expand the diversity and scale of three-dimensional architectural design inputs for an MRF-based generative approach.

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Creative Design and Co-design

The 'Atlas' of Design Conceptual Space: A Design Thinking Framework with Cognitive and Computational Footings

Jielin Chen and Rudi Stouffs

Background and Motivation

Unveiling the mystery of design thinking patterns has long been a holy grail in the field of design research. An intrinsic understanding of the nature of anthropocentric design and creativity is an essential necessity. There are some consistent arguments that can be drawn from hitherto literature studying design and creativity. One is that they all involve some sort of search process inside a conceptual space, which can be interpreted from various perspectives and reveals itself in different forms. Another is that they all require some repositories of prior knowledge, acquired through experience or learning. Last but not least, connection or association between the knowledge instances are inevitably involved. The past century has witnessed the development of computational design and computational creativity, both rooted in the theoretical development of design and creativity. It has been widely acknowledged that with a richer and more nuanced understanding of the cognition of designers, there are opportunities to augment human creative design performance by giving algorithmic form to psychological findings about the workings of creativity in the human brain [1].

By mapping pertinent studies with a focus on design cognition, we draw a theoretical outline as the foundation for the major motivations adopted in this paper, aiming at clarifying research assumptions, connecting relevant issues, and identifying significant research needs.

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The Role of Experience in Creative Design

There is a consistency in the literature concerning the importance of experience for design activities. The propensity to find resemblances with prior design experience and the ability to make analogies have been found to be the very essence of design thinking [2]. Designers tend to accumulate a great deal of knowledge of existing solutions and their potential affordances through practice rather than through instruction [3]. Previous studies have shown that the major difference between novice and expert designers is that expert designers have accumulated numerous pairs of design problems and solutions, and are thus able to access information in larger cognitive chunks [4]. A key competency of expert designers is the ability to mentally stand back from the specifics of prior examples residing on different scales and levels, and form abstract conceptualizations in a highly flexible manner [5], which usually requires finding patterns and forging connections between seemingly unrelated elements [2]. Numerous studies have confirmed the existence of creative leaps or the "AHA!" moments in design ideation. Pioneering philosopher Henri Poincaré [6] once explained the phenomenon by arguing that beyond conscious thoughts, the key of the ideation process lies in the unconscious state, as connections can occur between widely disparate and seemingly unconnected elements within the unconscious mind.

From the perspective of neurocognition, identifying underlying abstract patterns enables a designer to make connections with precedents stored in episodic memories, while the evoked episodic memory may relate to something from an entirely different context. Episodic memory is typically thought of as a neurocognitive system that supports the ability to recollect past experiences and mentally re-experience specific episodes [7]. There is consensus in neurocognition that memories are not static recollections, but ever-changing interpretations of past events, as simulating possible future experiences depends on the ability to retrieve episodic memory and recombine them into novel scenarios, which also well explains why imagining possibilities in the future feels as vivid as remembering the past, while our imagination can be limited by what we have experienced in the past [7, 8].

The various statements in the literature regarding the role of prior design information all indicate a pronounced fact that the human brain possesses a system with the capability to flexibly extract and recombine elements of prior experiences. Yet the intrinsic structure and mechanism of this system remains ambiguous from the perspective of design thinking theory.

Conceptual Space Exploration as a Model for Designing Process

The premise that design space exploration is an apposite model for design actions has been broadly taken as an approximation of the design process, which is generally depicted as the activity of mapping a latent 'design conceptual space' (also referred to as 'conceptual space' or 'design space'), and searching for preferable design alternatives within the space [9]. To avoid any confusion with the indication of physical space [10] and to emphasise on the metaphorical aspect, we adopt 'design conceptual space' in this paper. Design conceptual space is an age-old concept in systematic studies of design, dated back to the 'design methods movement' in the 1960s [11]. The term designates a space where all design possibilities reside [10, 12, 13]. Perkins [14] initially used the metaphor of 'Klondike space' for the description of its complexity by identifying four typical issues (Fig. 1): (a) Rarity: proper solutions are scattered; (b) Isolation: locations of high creative value are incoherent; (c) Oases: existing solutions offer an oasis, causing the phenomenon of design fixation; (d) Plateaus: many parts of the space are similar, providing no clues to accessing areas with greater creative potential.

From the computational design perspective, Woodbury [15] defines a design space as all the machinery required to computationally search for solutions, with a search space and a search strategy, whereas a search space is a way of describing configurations to be considered as possible solutions, and a search strategy is a policy for making decisions during search. This paradigm has been extensively investigated with the help of heuristic optimization based on predefined objectives as search policies [16]. The nature of this paradigm can be perceived as a pathfinding task inside the conceptual space with observable access at local level guided by predefined navigation mechanisms, which has intrinsic limitations concerning the exploration scope. Coyne et al. [17] argue that the term 'exploration' indicates a process of design that can be externalised, yet there are aspects of design that cannot be made explicit in the same way, by which we may call the products of intuition intimately related with prior experience. As aforementioned, more experienced designers are usually more capable to recognise and associate new design situations with the old. This capacity to associate instances of concepts, data, and other levels of design abstraction, has a criticality in design that demands attention, yet is difficult to externalise.

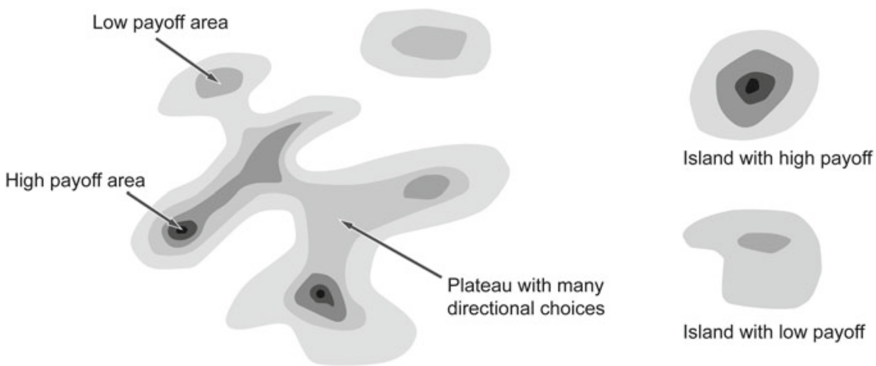

Fig. 1 Illustration of the 'Klondike spaces', adopted from McCormack [18]

The Uncertain Relationship Between Prior Design Information and Design Outputs

It is evident that the prior design information possessed by a designer has great impact on the yielded design outcome of a design process, yet existing statements portraying their relationship are not consistent, even contradicting with each other:

Prior experience can have both positive and negative influences on design creativity: On one hand, 'functional fixedness', the phenomenon of thinking about objects only with respect to their most characteristic function, is often observed among designers, and prior experience with particular problem-solving strategies may reduce the likelihood of using potentially more efficacious alternatives, which can limit our flexibility in thinking and inhibit the production of creative solutions [8]. On the other hand, knowledge acquired in a specific discipline provides conceptual tools that are needed to develop creative solutions, and by leveraging analogous structures from prior designs, designers can identify previously unexplored parts of the conceptual space [9].

Prior design experience can both cause and mitigate the issue of design fixation: With more accumulated design experience, designers tend to 'think faster' and propose solutions in a more effortless and intuitive manner [19]. However, 'thinking faster' is often concomitant with the 'design fixation' phenomenon, namely the premature commitment to a design idea, which can restrict the design exploration scope [20, 21]. Contradictingly, prior design experience can both cause and mitigate the issue of design fixation [20, 22]. On one hand, past experience can lead to conservativeness in design thinking, as experienced designers can 'think faster' and be more committed to their initial ideas [8, 22]. On the other hand, prior exposure to the variety of design alternatives can have benign effects on the widening of design exploration scope [22].

To unravel these contradictory phenomena, recent studies offer plausible explanations based on the dual-process theory [23], a theoretical model of cognitive psychology claiming that human cognition is governed by two systems: System 1 that is intuitive and effortless, and System 2 that is analytical and requires more cognitive efforts. Gonçalves and Cash [20] find that System 1 tends to have unequally dominant impacts on the overall design process by substantially influencing what can be taken into System 2. Such 'overconfidence' of System 1 can be more obvious among experienced designers, as they are more skillful with shortcuts based on deep acquaintance with well-established routines [20, 21, 24]. Attempts to break the chain of System 1 and to trigger novel associations become crucial [21]. Yet convincing answers to this demand are still lacking. Apparently, the relationship between prior design information and design outputs is neither purely positive nor negative; A theoretical framework with sufficient explanatory and predictive power is missing to structurally elucidate the explicit mechanism leading to the ostensibly convoluted relationship (Fig. 2).

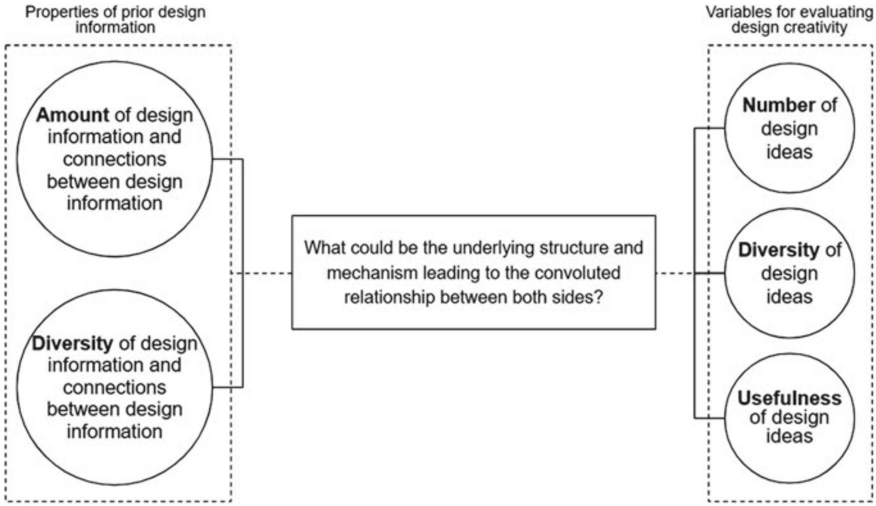

Fig. 2 Clear explanations are still scant concerning the underlying structure of the human brain as an ‘information processor’

Aims and Significance

The objective of this paper is to gain a more comprehensive understanding of the design conceptual space. We re-examine the theoretical foundation of design conceptual space and promote a conceptual space-oriented theoretical framework for elucidating the mechanism of design thinking based on novel discoveries from the field of neurocognition. The framework can also serve as pragmatic guidance for developing new design creativity boosting systems. This paper’s contributions are fourfold: (1) conceptualising and formalising the term—“the ‘Atlas’ of design conceptual space”–based on jointly cognitive- and computational-footings, (2) suggesting the ‘interpretation’ of the design conceptual space, (3) envisaging and demonstrating a set of computational strategies for interpreting the design conceptual space, and (4) re-examining some puzzling phenomena of design activities in the context of conceptual space-oriented thinking.

Methodology

What is consistent with all the aforementioned arguments is that we create by connecting and reconnecting things that exist already in our mind in particular ways, which shed light on the underlying structure of the human brain as information processors guiding the acts of creative design. A recently proposed neurocognition framework, in which numerous neurocognitive facts accumulated overtime can be meaningfully interpreted, gives rise to a novel way to re-examine the conceptualization of design conceptual space. By drawing inspiration from the seminal breakthroughs of the neurocognition field, we propose the notion, "the 'Atlas' of design conceptual space", and associated 'interpretation' strategies with jointly cognitive- and computational-footings.

'Reference Frames' and 'Thinking by Moving'

It is widely believed among neuroscientists that human brains learn models of the world by organising knowledge about the world in particular ways, and our ability to think is intimately attached to these models. To unravel the mechanism of human thinking and learning abilities, how the brain learns such models need to be figured out in the first place. Hawkins and his team's [25] recent discoveries offer explanations to this quest with inference that the brain stores all knowledge about the world using constructs called 'reference frames'. According to Hawkins [25, 26], reference frames are invisible grids attached to every object the brain learns, either physical or conceptual, allowing the brain to learn the object's structure and fictitiously manipulate it; the word 'object' is used in the broadest possible sense and it is possible that the reference frames have more than three dimensions. Once the reference frames are established, the brain can then build models of the world by associating sensory inputs with locations in the reference frames. Organising abstract concepts this way makes them 'actionable', and one can make plans and mentally 'move' the concepts as if they are real objects based on their locations in the reference frames. Any learned concepts are deposited at specific locations relative to established reference frames as features [25, p. 76]. It is likely that when the brain learns a model of an object, it doesn't have a preconceived notion of what kind of reference frames they should use in the first place, and part of the learning process is to discover a proper reference frame for the object, namely, the brain is an agnostic learning machine [25, p. 90]. Moreover, reference frames can be nested inside other reference frames, and the brain works by creating a myriad of simultaneously active reference frames [25, p. 88, 27].

According to Hawkins [25, p. 76], the thinking process can be treated as a form of 'movement' traversing established reference frames and invoke locations in succession. Without a good reference frame, one can get lost in the thinking 'space', in the same way as one can get lost in an unfamiliar city without a map. He gives a cogent example of a mathematician proving a conjecture: what is happening under the hood is that various equations are embedded in one or a series of reference frames, and the adopted mathematical operations are the movements taken to get to different locations in the reference frame(s), but having the reference frame(s) and the skills to move inside it requires a lot of training. Metaphorically, the proposition of 'thinking by moving' coincides with Schön [28]'s 'reflection-in-action' theory, which treats design as 'seeing-moving-seeing' cycles. Albeit the resemblance, their emphases are somehow different; while 'reflection-in-action' emphasises the dynamics of ‘actions’, the essential premise of ‘thinking by moving’ is a good reference frame in the first place, as better reference frames enable one to identify analogies more efficiently and creatively. It is worth noting that good reference frames are not necessarily exclusive, as two individuals can configure the same facts in differently structured reference frames and both reference frames can be appropriate, which also corresponds to the idea of ‘situatedness’ that the same design problem or artefact can be conceived in entirely different ways by different designers or at different times [13, 29].

The ‘Atlas’ of Design Conceptual Space: The ‘Reference Frame’ for Design Thinking

In this paper, we take the stand that the construct of ‘reference frames’ from the neurocognition field, which is claimed to be essential for learning/thinking, can be taken as the synonym of ‘design conceptual space’ in the context of analysing design thinking mechanisms. The connotative power of the alignment between reference frame and design conceptual space can be huge. Design space exploration is preceded by a preliminary phase in which designer educates oneself by means of gathering information and forming stances towards potential design problems [24]; this preliminary phase starts long before the exploration, which actually indicates the construction of the design conceptual space, i.e., the reference frames for design thinking.

We take the metaphorical echo of the term ‘Atlas’, a notion conventionally depicted as a collection of maps with extended multimedia embedding locations information [30], and suggest the concept of “the ‘Atlas’ of design conceptual space”. This concept inherits two key properties of the neurocognitive concept ‘reference frames’: the first is that the number of design conceptual spaces can be many with relations either in parallel or in series; the second is that the design conceptual spaces are multidimensional. We can further pose questions like, “What makes a ‘good’ design conceptual space for design exploration?” “What are the corresponding actionable operations that can be taken to trigger movements in a design conceptual space?” Before we can proceed to further address these questions, we need to clarify some remaining issues regarding the conception and formulation of design conceptual space in literature.

The Multifaceted Portraits of Design Conceptual Space

The noisy research landscape reflecting different opinions towards the nature of design conceptual space in literature is not the result of actual disagreements, but of differences in emphases. To this end, we examine the multifaceted portraits of design conceptual space while raising attention to some significant pitfalls, with the aim of providing an overview and prospect of conceptualising the design conceptual space.

Implicit space versus explicit space: Conventionally, design space is represented using highly formalised constructs, including two- or three-dimensional Cartesian space whose axes represent design parameters and associated values, and tree graph/network structures where each node is a design representation derived from its parents [9, 10, 31]. Woodbury and Burrow [9, 31] initially proposed the parting of design space into implicit and explicit ones as network structures, whereas the implicit one is the graph of all possible design alternatives, and the explicit one is the subgraph of the former that designers have visited. Although the definitions of implicit and explicit design spaces proposed by Woodbury and Burrow are rooted in the paradigm of knowledge-engineering systems [32], we can extend the notions in a more general sense. We define the implicit design conceptual space as an agglomeration of all possible features of design artefacts organised in a particularly structured manner where all possible design alternatives can emerge. Obviously, explicit conceptual space is a part of the implicit one, where the term 'part' can take the meaning of either a subset of all possible features or a subset of all possible conceptual spaces. It might be intractable to acquire a whole picture of the implicit one, but it is theoretically possible to unravel the inner structure of the explicit one. The representational schema of explicit conceptual space should be able to offer designers overviews of all accumulated knowledge at a particular point in time. Maher et al. [33] initially proposed the model for the co-evolution of problem- and solution-space regarding the interdependence between design problems and solutions, indicating that designers seek to generate matching problem–solution pairs while the problem- and solution-spaces evolve in parallel [34]. Yet, it remains a question whether we can make a good enough distinction between the problem and solution spaces, and the separation of the two spaces can be confusing at times [24, 35]. There is no meaningful distinction between analysis of the problem and synthesis of the solution in the design process, as they are seen as emerging together rather than one logically following the other [34, 36, p. 118]. A key question is whether the separation of design space into problem and solution spaces can yield useful structures at a constructive or representational level. The answer is generally negative, at least in devising data structures and algorithms for the representation of design conceptual space [31]. Thus, some researchers have suggested a merge of the problem and solution space [31, 34], and they can both be treated as explicit design space with specific intentionality.

The pitfall of objectives: The 'path' or the 'map'? Conventional design exploration strategies typically leverage heuristic optimization based on predefined objectives or rules as search policies. Surprisingly, it has been found in some recent computational experiments that objectives can have deleterious influences towards discovery of creative solutions [37, 38]. Woolley and Stanley [38] initiated an art breeding experiment based on genetic algorithms, allowing participants to breed pictures they find most interesting. They set images discovered by participants as targets and constructed an algorithm to mimic the participants' exploration actions, trying to reproduce the target image by choosing evolved pictures most similar to the target at each generation. The algorithm never succeeded with the explicit objective of reproducing the target image. Meanwhile, other experiments have found that searching without explicit objectives may yield better results than searching with one. Lehman and Stanley [39] simulated agents moving in a maze with two different search algorithms: novelty search (trying new and novel behaviours only) and objective-based search (reaching the other side as an explicit goal); the formal agents can reach the other side of the maze 39 times out of 40, while the latter agents can get there only 3 times out of 40. Hence, objectives can provide meaning or direction, but they may also become straitjackets to the freedom for exploration [37]. Meanwhile, in the creative design field, creativity is rarely thought of as finding a single optimisation, which also renders conventional search strategies unsuitable [5, 18]. Although when art and design collide, such as in architecture, objectives do play important roles, as buildings need to be functional, energy efficient, environmentally friendly, and so forth, what is worth noting is that these are more like constraints on creativity rather than conventional objectives for engineering problems. Woodbury and Burrow [9, 31] used to argue for the primacy of accessibility over possibility in making new discoveries in design exploration, and developed a resolution mechanism by means of which one can reuse past experiences explicitly represented as previously traversed paths, such that designers can adapt them in new contexts by using successful past 'moves'. They allege that the exploration paths are the only tractable component of the conceptual space [31]. However, the notion of moves in design can be equivocal and difficult to define [24], and the structure of the design space and the paths are inseparable. A path that suits one space with a certain underlying structure may not fit another one with an entirely different structure, and cannot be straightforwardly grafted. Thus, recording the 'path' of design exploration may not be an efficient, even justified approach. As we are well-aware, the landscape of the design conceptual space can be noisy and full of deceptions; having explicit objectives for exploration can be even counterproductive. With the underlying assumption of perceiving design as pathfinding tasks at a local level with predefined navigation policies, the conventional design exploration paradigm has intrinsic limitations hindering its scope of dealing with complex design problems. What matters most is not the paths of exploration, but a good 'map'; the map here refers to the design conceptual space(s), or the reference frames for design thinking. In this context, a particular avenue worth pursuing is how to get a better understanding of the design conceptual space per se. In line with the statement that design exploration is a compelling model for designing, we argue that a more efficient way to surmount human cognitive limits might not be merely amplifying designers' exploration actions, but to get a deeper understanding of the design conceptual space and its underlying foundation from a more essential level.

Design Thinking by Interacting with the Design Conceptual Space

The view that we learn the model of the world by interacting with it has long been established among neuroscientists, which is essential for learning and thinking [25].

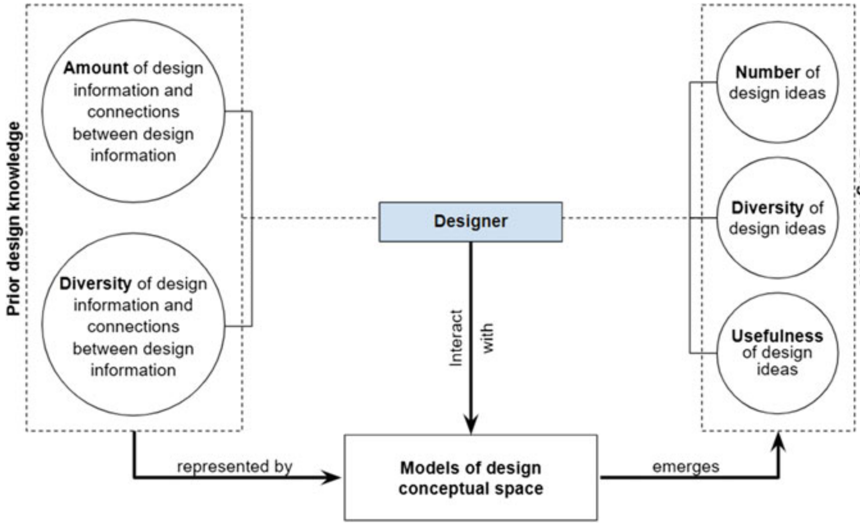

Fig. 3 Design solutions emerge as the outcome of interacting with the models of design conceptual space

This epistemology is also reflected in the formulation of 'situated interpretation' proposed by Kelly and Gero [13]. In line with this epistemology, we argue that design solutions emerge as the outcome of interacting with the design conceptual space (Fig. 3). We further conjecture that all design activities are made possible because of the existence of designers' mental models of conceptual spaces that designers constantly perceive, formulate and expand. Interaction with the external world overtime is the key to learning the models, represented as evolving memories with intrinsic connections with each other. But a concept will remain a concept if it cannot be consolidated into programmable algorithms and earn extra gains. Thus, we further promote two types of models of explicit conceptual space, serving as the anchor of interactive interpretation system for design conceptual space: one is the human-learned model which is presumably sparse in design information, another is the machine-learned one as pseudo simulation of human-learned ones with distilled design information. Ideally, by simulating an explicit design conceptual space with concentrated design information, a human designer can have extra gains by interacting with the simulated conceptual space models.

The 'Interpretation' of Design Conceptual Space

The studies of design conceptual space, especially in the field of computational design research, mainly focus on looking for more superior space exploration strategies [9]; the intrinsic structure and mechanism of design conceptual space remains vague. Woodbury and Burrow [9] ascribe the dearth of investigation concerning this aspect to the inadequate knowledge of representation techniques. In the context of computational creativity, Kelly and Gero [13] define interpretation as constructing representations of design artefacts by leveraging experiences. We adopt this definition and extend the subject being interpreted to the constructs of the design conceptual space as a whole; truly powerful interpretation may not be done merely by human or by machine, but by their interactions. Coyne and Subrahmanian [40] initially advocate systematic examination of design space with permutation of all possibilities, which can be treated as design space interpretation in a brute force manner. Yet exhaustive enumeration can soon become computationally infeasible in high-dimensional space, especially when encountering design problems with high complexity. What we need is not brute force interpretation, but skillful anatomy of the conceptual space. A key question we need to address in the first place is how the representations of prior design information should be like in the models of machine-learned design conceptual space. Ideal design representations are supposed to afford necessary inferences across model domains and support changes of design states to assist designers shifting between ideas during exploration [9, 31]. To incorporate such representations into the conceptual space, we need more sophisticated representation learning schemes other than conventional knowledge engineering approaches. Fortunately, the issue of inadequate knowledge of representation techniques which seemed once intractable is now worth taking another look. The development of data-driven representation learning techniques in the field of machine learning [41] has shown signs of the ability to do interpretation of design conceptual space by approximating convoluted probabilistic distribution of hyperspace with latent features extracted from large-scale data resources in a generalised manner [42].

The two camps of computational representation language: To fully understand the advancement of the data-driven representation learning techniques, we need to first understand the drawbacks of its predecessor, knowledge-based systems based on knowledge engineering. The two major camps in artificial intelligence, machine learning versus knowledge engineering, speak different languages: machine learning speaks probability, and knowledge engineering speaks logic [32]. Knowledge-based systems typically treat the design space as discrete and finite, and have no inherent structure or agenda for evolving and learning, which leads to its deficiency for generalisation and limitations of rigidity and brittleness [40]. By contrast, the learning-based systems (neural network models as paradigms) convert external symbols into internal vectors of neural activity. The main advantage of using vectors of neural activity to represent concepts and capture relationships between concepts is to neatly skirt around the issue of formulating explicit representations of design features to facilitate design reasoning task, as learning-based models can establish their own linkages between descriptors of features and work out which ones are significant based on given data samples [17]. That is to say, the models can develop their own design schemas established on the basis of matching patterns and independently determine their categories, whereas the schema is neither hard-wired nor prescribed, which accords with the idea that there is no preconceived reference frames when the human brain learns the model of the world and the construction process of any latent reference frames is agnostic [25].

Fig. 4 Controlled manipulation of semantic attributes of images synthesized using deep generative models based on disentangled representation learning, adopted from Chen and Stouffs [42]

Symmetries and disentanglement: Active research on disentangled representation learning has further provided tools for more in-depth and controllable interpretation of latent design conceptual space [43]. The subject of representation disentanglement in the field of machine learning is to disentangle the underlying structure of the targeted conceptual space into disjoint parts of its representation, and ensuring that changing one latent feature does not affect the distribution of other features [44]. A key concept for the mechanism of representation disentanglement is the notion of symmetry. A symmetry of a group of entities is a transformation that leaves certain properties of the entity invariant, where the word 'entity' is used in its broadest possible sense, and 'group' can be any abstract space structure [44]. A vector representation can be disentangled if it can be decomposed into a number of subspaces, while each one of which can be transformed independently by a unique symmetry transformation [44]. Empirically, Chen and Stouffs [42] have examined the possibilities of leveraging disentangled representation learning to extract symmetries of design features and making use of the extracted feature symmetries to conduct exploration of design alternatives by demonstrating experimental manipulation of architectural image generation in a disentangled manner (Fig. 4).

We need to be cautious concerning the questions raised by Akin [11]: given that design conceptual space exploration is a compelling model for designing, are the properties presented in the 'Atlas' of design conceptual space isomorphic to the maps of physical spaces; if they are different, how different? And how can we deal with such differences? As for now, we are almost certain that they have quite discrepant properties, albeit the metaphorical meaning of the concept is akin. Regarding the properties of the 'Atlas' of design conceptual space, we have the following conjectures.

Properties of Design Conceptual Space

Design conceptual space is multi-/hyper-dimensional: This property is almost self-evident. The set of latent features or schemas of a design entity can be large, if not altogether infinite. If each isolatable feature can be treated as a symmetry group of an explicit design conceptual space that can be controlled or manipulated, and the number of such features can be myriad, then we can say that the explicit design conceptual space is multidimensional. In other words, design problems do not have a firm prescriptive dimension. Meanwhile, it is also probable that some of the features can be correlated or even conflicting with each other, namely they are not orthogonal with each other. Then, approaches for disentangling these features will come into the picture [42].

Design conceptual space is recursive: Design problems are naturally hierarchical in both scale and process [31]. Just like reference frames can be nested in reference frames in the context of cognitive thinking process [25], we can also have conceptual space nested in conceptual space, which makes the design conceptual space recursive. Theoretically, this property can endow extra flexibility to the design conceptual space by light-weighting the representation. Specifically, the possible representation of this property has been discussed in length in the ‘Sortal’ descriptions or sortal layering of features proposed by Stouffs and Krishnamurti [45], which is based on partial relationships specifying orders of representation.

Design conceptual space is heterogeneous: There is no singular way of characterising design knowledge, as designing is essentially nonmonotonic [46], which gives rise to the heterogeneous property of latent design conceptual spaces. The heterogeneity nature of the design enterprise discloses the fact that the (explicit) design conceptual spaces can be inclusive, but they cannot be generic. Yet arguably, the heterogeneity might only be applied to certain aspects of the design conceptual space, including sets of features and topological relationships among features, while other aspects will be similar or identical among design conceptual spaces, including the intrinsic general topological structure and other properties of the conceptual space.

Design conceptual space is dynamic/interactive: It is well-established that the design space should be dynamic [10]; it is not merely a depository into which the designer or others routinely deposit representations encountered along their design activity. In other words, the design space ought to be updated constantly. Veale and Cardoso [1] state that creativity arises from more than merely systematic search of the conceptual space for possibilities, instead, it arises from knowingly exploiting or subverting/interpreting the conceptual space. Intrinsically, as human brains learn the model of the world by interacting with it, designers come up with design solutions by interacting with the design conceptual space. Human designers learn the model of the design conceptual space by constantly interacting with the external world. As human designers are endowed with limited cognitive structure that constrain their representational scope of a design conceptual space [9], the information embedded in the learned design conceptual space in a human designer’s mind is conjecturally sparse. If machines can learn a distilled version of the models of the design conceptual space with dedicated design data, and let human designers interact with this densified version of design conceptual space, it can offer new threads of approaches to assist human designers to overcome the cognitive limitations and boost their performance of creative design in presumably unprecedented manners.

Discussions and Future Work

Our theoretical framework offers explanations to some conundrums of design thinking that cannot be readily explained by current theories. Firstly, let us take a second look at the initial puzzle raised in this paper regarding the convoluted relationship between the prior design information possessed by the designers and the emerged design outputs during the design process. On one hand, we can be almost certain that the human-learned models of design conceptual space of the novices and experienced designers are different. For novice designers, the learned models of design conceptual space are most likely immature and cabined if compared with the models learned by experienced designers (Fig. 5). This may contribute to the phenomenon of novice designers' tendency for a depth-first approach to design problem solving [47] given the restricted amount and diversity of prior design information represented in their learned models of conceptual space. Instead, with the wider scope and diversity of prior design information embedded in the conceptual space models learned by experienced designers, they possess the prerequisites to adopt search strategies that are regarded as being predominantly breadth-first [4]. On the other hand, just like there could be good or bad reference frames for thinking through a mathematical problem [25], there could be good or bad models of design conceptual space for design thinking and exploration. The conceptual space models learned by experienced designers can also be dissimilar from each other and possess idiosyncrasies leading to different design exploration behaviours. Importantly, the phenomenon of design fixation among some experienced designers can be caused by homogeneously structured models of design conceptual space they are sticking to, even if the models have a large scope of embedded information. On the other hand, experienced designers in possession of conceptual space models that are more assorted and heterogeneous can circumvent the issue of design fixation and truly reap the benefits of the wide and diverse scope of prior design information embedded in their learned models.

Secondly, our proposed theoretical framework can also bolster the experimental findings rooted in the dual-process theory regarding System 1 and System 2 thinking

		Information density of the models of design conceptual space	
	Interaction → **↑**	Human-learned model (sparse)	Machine-learned model (distilled)
Level of experience of designers	Novice	*Immature/Cabined*	*More breadth in search*
	Experienced	*Sophisticated/Extensive*	*Avoiding design fixation*

Fig. 5 The human-learned models of the novices and experienced designers can be different, and machine-learned models can be potential modus operandi to assist designers with different levels of experience with varied mechanisms

patterns [19–21]. As mentioned before, the System 1 thinking, which is intuitive and effortless with dominant contribution to the ‘thinking faster’ pattern, tends to over-confidently influence what can be taken into the System 2 thinking process requiring more analytical efforts, and becomes the culprit of design fixation [20]. We can make well-informed conjectures and assign well-developed models of design conceptual space, namely ‘reference frames’ for design thinking, to the System 1 thinking process, which can function in an almost reflex-like manner, while System 2 thinking is actually the process of expanding the conceptual space models which will need deliberate efforts. As has been pointed out by Cash et al. [21], it is essential to break the chain of initial association dominated by System 1 and to trigger novel associations. In the context of conceptual space-oriented thinking, we promote to leverage machine-learned models of design conceptual space as potential modus operandi to respond to the demands; the potential benefit to novice and experienced designers when interacting with the external conceptual space models can be different when superimposed with the designers’ own models of design conceptual space (Fig. 5).

Thirdly, we can also offer to rethink the ‘ill-defined’ or ‘ill-structured’ nature of design [48] in the context of conceptual space-oriented thinking. It is widely acknowledged that design problems are intrinsically open-ended, situation specific and controversial, and in design there are no optimal solutions, only trade-offs [49]. While it is assumed that an amount of knowledge is being held tacitly within the minds of the human designers and implicitly within design products, explicitly stated procedural knowledge is rare. Despite widespread consensus on several important issues, there is no consensus on how to carry out design. Schön [28] used to summarise the characteristics of design situations as uncertainty, instability, uniqueness, and value conflict. Notably, different designers who tackle the same design problem are likely to come up with different solutions [29], while the same design problem approached by the same designer at two different times can be conceived in different ways [13]. Intrinsically, on one hand, the fact that there are only trade-offs and no optimal solutions in design has something to do with the hyperdimensional and heterogeneous properties of the design conceptual space, as some of the features can be conflicting with each other. On the other hand, compared with “well-defined” problems such as mathematical or engineering problems, the ‘movements’ that can be taken inside the ‘reference frame’ of design thinking can be difficult to clearly define, as the ‘movements’ of designing can be constantly evolving and often highly peculiar, namely, the ways of design are highly contextual and can be idiosyncratic to the designers who adopt them [31]. Specifically, the sets of operational actions that can be taken inside the models of design conceptual space learned by different designers can be either similar or unique, and there might be no unified list of operations or ‘movements’.

As asserted by Woodbury and Burrow [31], the absence of evidence should not be taken as evidence of absence. Given the state of work concerning conceptual space-oriented thinking today, we still have little evidence for boosting creative design performance of designers through interaction with machine-learned models of design conceptual space. Nevertheless, we also have little ground against these boosting potentials. Having no existing mature, or even experimental, systems that can provide platforms for designers to interact with proper machine-learned models of design conceptual space, we can for now only make tentative inferences about their benefits.

Conclusions

In this paper, we propose the theoretical framework of "the 'Atlas' of design conceptual space" based on the neurocognitive concept of 'reference frames', with an emphasis on the interactive interpretation mechanism of its constructs, interweaving human design actions and computational interpretations as an organic whole. The 'Atlas' of design conceptual space has four inherent properties: the design conceptual space ought to be multi-/hyper-dimensional, recursive, heterogeneous, and dynamic/interactive. Akin [11] once keenly posed the following question: "What would be the example that benchmarks the ultimate success of formalised exploration spaces; one that would enable generations of future scientists and designers to pluck dozens of both tractable and intractable problems, as if they were an organised series of well-defined ordered search acts in structured 'space'?" Our theoretical framework contributes to this quest, serving as a blueprint for tackling some existing conundrums of the mechanism of design thinking. We have elucidated the idea that an informative interpretation of the design conceptual space has the potential to enhance the cognitive capacity of designers with respect to both design performance and creativity. Meanwhile, the framework also serves as pragmatic guidance encouraging future developments of more effective creative design assisting systems, as the framework has the potential to allow expression of new algorithms and further development of computer-aided design systems to the benefit of designers.

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Computer Games for Design Creativity Research: Opportunities and Challenges

Esdras Paravizo and Nathan Crilly

Abstract This paper discusses opportunities and challenges related to the use of computer games for design creativity research. Two bodies of work were analysed: (1) scientific papers published in design and creativity journals and (2) commercial computer games available on the Steam game platform. The qualitative analysis of the papers reviewed (n = 21) revealed the main games used and game features exploited, as well as the research challenges (e.g., managing game abstraction and real-world fidelity) and opportunities (e.g., novel data collection methods). Data analysis from the selected games (n = 68) enabled the identification of the most relevant game genres, features and technological aspects, which supported the discussion of novel avenues for research. The paper contributes to raising awareness of possible uses of games for design creativity research and provides recommendations for game use in future research endeavours.

Introduction

In July 2021, alongside the Tokyo Olympic Games, another "olympic" event took place: the Poly Bridge Olympics. This was a competition played out on the computer game *Poly Bridge 2*, a physics-simulated bridge-building game. The Poly Bridge Olympics was a competition among content creators familiar with the game. They played on four custom-made levels with different challenges to overcome and constraints to work with. Limits were placed on players' budgets, choice of materials and game time. Their results were evaluated based on various metrics, including distance spanned, structural strength and time to complete the level. Players recorded themselves throughout their gameplay and released the videos (both edited and unedited) online. In most instances players narrated their own videos, providing insights into their thought processes and decision-making.[1]

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[1] A compilation of players' videos with their participation in the Poly Bridge Olympics can be seen in this YouTube playlist (last accessed 5/jan/2022).

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From a design research viewpoint, because the players effectively explained their objectives, strategies, design decisions, and how time constraints influenced their process, the videos resemble think-aloud protocols [1]—either concurrent or retrospective. Compared to many of the design protocols used in research, one notable feature of these gameplay videos is that they were generated spontaneously, without researcher influence. The gameplay is apparently sufficiently engaging to be its own reward. The Poly Bridge Olympic videos are just an example of the various opportunities for both design researchers and educators to use computer games to study and enhance design creativity.

Poly Bridge 2 is just one of many computer games that engage players in activities of designing, building, and testing. These games are a subset of a gaming industry that reaches almost half of the worlds' population and in 2021 generated over $175 billion in revenue [2]. Many of these games are expertly developed to be engaging, involving, and rewarding while also promoting players' creative confidence, abilities, and outcomes. Given this context, there are many questions to ask about how to best select and implement these games for design creativity research.

In this paper we aim to advance the understanding of how computer games can be employed in the context of design creativity research. We do this in two ways. First, we review the design and creativity literature to establish what the current practices, challenges and opportunities are when employing games. Then we report on a search of commercial-of-the-shelf (COTS) computer games to establish their relevant features and characteristics in relation to the aspects identified in the literature. Finally, we explore the intersection of the literature and games to map out the implications for design creativity research.

The contribution of this study is two-fold. First, the identification of the most relevant features of computer games can be a useful resource for those who plan to employ existing games or develop new ones for design creativity research. Second, previously overlooked aspects of the game ecosystem (including user communities) are highlighted as a potentially fruitful empirical domain for future exploration.

Background

A long-running discussion of methodological opportunities is underway in the design creativity field. In a 2013 editorial for the *International Journal of Design Creativity and Innovation*, members of the board already highlighted the tendency of empirical creativity studies to employ experiments which fall short of representing real-world complexity and the need for novel research methods [3]. In 2022 another editorial for the same journal, discussing the evolution of the field in the past 10 years, reiterates the overall need for novel methods and approaches to address ecological validity issues and enhance the field's multidisciplinary nature and impact [4].

It is against this backdrop that this study takes form. To understand the opportunities for computer games in design creativity research, it is important to understand what 'games' are and why they might be valuable. In this section we provide a brief overview of the concept of 'game' adopted in this paper, as well as a synthesis of relevant research looking at game use in the field. Because our focus is on how games can be used in research rather than on the research itself, we do not detail the key concepts in creativity and design cognition, which are already reviewed elsewhere [5, 6].

Games and Serious Games

To gain insight on what games are, it is useful to look first at the concept of play. The phenomenon of play (and games as enablers of play) as a human, cultural manifestation has long been discussed [7]. For Huizinga, play is in essence a free, voluntary activity, non-serious in nature that thoroughly engages the player and is deliberately removed from daily life [7]. Furthermore, the temporal and spatial boundaries, the rules and order of play and its social aspect, can also be seen as central characteristics of games.

The distinction between play and game is explored by Caillois, in his attempt to classify games in general [8]. He contrasts the concept of *paidia* (indicating the "spontaneous manifestations of the play instinct") and *ludus* (encompassing the rules, order, and discipline aspects of games). These are located at each end of a continuum on which different game types) can be positioned (such as those based on competition or chance, for example) [8].

The multitude of different game types renders the definition of what is a game an elusive and challenging issue. For instance, Salen and Zimmerman define a game as "a system in which players engage in an artificial conflict, defined by rules, that results in a quantifiable outcome" [9], whereas Schell posits that "a game is a problem-solving activity, approached with a playful attitude" [10]. Schell's framing of games as problem-solving activities encompasses some of the core qualities of games presented by Huizinga [7] and Salen and Zimmerman [9], namely the rules that organize a system that presents an artificial conflict (removed from reality). On the other hand, to account for the voluntary willingness to take part in games, Schell proposes the "playful attitude". It is particularly interesting to note the relationship that can be traced between Schell's game definition to one of the fundamental structures of engineering design, the problem-solving process [11].

A significant distinction can be made between games as discussed above, and games designed for purposes other than pure entertainment, the so-called serious games [12]. Serious games can be employed for educational and training objectives, incorporating simulation features and, usually, reflecting real-life aspects [12]. In an attempt to develop a model for the systematic classification of such games, Djaouti et al. [13] proposed the 'Gameplay/Purpose/Scope' (G/P/S) model, which takes into account both game-related and serious-related aspects. In this model, 'gameplay' classification builds from Caillois' *ludus/paidia* conceptualization which identifies games as either game-based (in which there are clear goals, win states, etc.) or play-based (in which no goals are present). Further, the 'purpose' of serious games is divided in three categories: broadcasting a message (educative, informative, persuasive, subjective), training (mental or physical) and data exchange (e.g., games for scientific data collection). In the G/P/S model, the 'scope' (S) refers to two domains: market (e.g. military, healthcare, education, corporate, scientific research, etc.) and public (general public, professionals and students) [13]. This classification provides a starting point to analyse games for serious applications that can be further enriched with other taxonomies.

Design and Games

The discussion of games in the design field is not necessarily new. The idea of employing "design games"—games created for investigating design activities—has been explored since at least the 1980s. Habraken and Gross discussed the use of such games to explore design concepts held by the players. They argue that the manipulable and bounded nature of games enables researchers to focus on specific aspects of the design process, as for instance, the communication and sharing of concepts among players [14].

Researchers have also explored how design games' use is linked to the different roles of the people involved in the design processes [15]. The design game can be seen as a 'tool' for the designer (e.g. to promote discussion, collectively identify and solve problems, etc.); it can be seen as a 'mindset' for the players (promoting the experience of engaging in a playful, orderly activity); it can be seen as a 'structure' for the game designers (with the tangible materials, game pieces, roles and rules) [15]. Furthermore, in a review of physical tools for supporting collaborative ideation [16], researchers identified a range of existing card games and board games, among other analogue tools. For design games in particular, the solutions reported in the literature usually rely on custom made games/applications (co-)developed by researchers, designers and users.

Theoretical discussions in the design field have also turned to games to gain insight into design activity. Contrasting how computer games are played to how designers undertake their work, Coyne [17] discusses how repetition is both a feature of game mechanics and design activities alike. Furthermore, Coyne argues that, both in games and design, repetition cycles are modified by a multitude of factors that introduce variation, thus allowing for a reinterpretation of concepts and the development of novel solutions [17]. From this perspective, we can develop new understanding (i) of models and their role in design processes, (ii) of designers' cognitive processes to use unreliable information and to cope with complexity and (iii) of the cooperation and communication processes undertaken by design teams [17].

With the popularization of computer games and the tools to develop them, researchers have investigated how particular games could be employed for design. Both COTS and custom designed games have been investigated as potential tools for design research. For instance, the use of COTS computer games has been explored in the investigation of design creativity, including both conventional games and VR games [18, 19]. Researchers and designers have also created their own games to investigate their potential effect on design activities [20], architectural design and representation [21] and on co-design processes [22]. Computer games were also employed in design education initiatives, for example, as a learning tool for complex system design [23] and design history [24].

Across the different fields and specialities, we can find reports of the ways in which game use has implications for design theory, design research tools and methods, design education and design practice. Nonetheless, we are still missing a systematic mapping of game features and characteristics that could support game use in the design creativity field. Furthermore, the small number of studies employing COTS games for design research suggests that such games are being overlooked by researchers. These observations motivate this present study, which investigates COTS games' untapped potential for the field.

Creativity and Games

Research examining creativity and games may take different perspectives. One strand focusses on game design activities, for instance, investigating how game developers enable creative behaviour through gameplay (e.g., freedom of play, environment, tools, avatar customization, creation features) [25]. On the other hand, players' understanding of creativity in games has also been explored [26]. From interviews with players, researchers identified that gameplay promoted novel thinking patterns. The ability to create game content (e.g., sandbox-style game, level editors, and 'modding') was perceived by players as a personal creative expression.

In parallel, researchers explored the game space to gain insight on how different types of games support creativity. In a study of divergent thinking abilities, researchers found that players who engaged in table-top role-playing games outperformed players who played electronic role-playing games, and also outperformed non-players. [27]. Researchers also analysed the effect of different types of board games ("creative" and "non-creative") on players' creative potential, observing an improvement regardless of the type of game played [28]. Similarly, high-school students' who played a custom-made scientific board game didn't just improve their conceptual understanding of the subject matter, but also their creative problem-solving skills [29].

Turning to computer games, several studies discuss the benefits and challenges of employing them for creativity research and education. Employing the COTS game *Minecraft*, researchers verified that both the game and how it is played matter: players who played *Minecraft* freely subsequently scored higher on creativity tests than those who were instructed to "be creative" during gameplay, and also higher than those who played a driving game and those who watched a TV show [30]. Another study investigated the effect of game-induced physical activity on cognitive states and creative outcomes, finding that different states of arousal and mood influence creative capability (this research used the *Dance Dance Revolution* game, in which participants have to "dance" by following fast-paced on-screen instructions to step on game controllers) [31].

The subject of creativity assessment using computer games was investigated in a review study pointing to a series of challenges faced by researchers: scaling up (increasing the number of participants), internal validity (controlling the participants' external environment during gameplay), online availability (supporting scale-up and results sharing), game difficulty (in terms of the mechanics and other variables that might hinder participant experience), game features to support ecological and construct-validity, convergent validity (among game-based assessment and traditional assessments) and a focus on divergent thinking, among other aspects [32]. The researchers suggest possible pathways to address these challenges by employing games to further deepen our understanding of creativity itself and how to assess it.

One point highlighted by Rafner and Sherson [32] relates to the possibility of turning to commercially available games to take advantage of larger user bases. However, the authors point to three "daunting" challenges to fully realize this potential: (i) inability of capturing or logging gameplay data, (ii) identification of games with suitable "subtasks" or liaison with game developers for inserting such features in the game, and (iii) providing structured conditions to improve the reliability of out-of-lab testing [32].

We suggest that systematically identifying the relevant game features reported in the literature should precede the search and identification of games that have those features. This mapping study is what we report now.

Method

This exploratory study explores two bodies of work: (1) published literature discussing **specific instances of computer game use** for design creativity research and education and (2) **commercially available computer games**. The review method for the literature corpus followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) [33]. Certain intrinsic features of the game corpus prevented exactly the same review method being used for that corpus, but we still employed a PRISMA-inspired approach. In this paper we focus on digital games (played in computers), whether or not originally intended for entertainment or for serious application.

Literature Search Overview

The guiding question for the literature search was: *how are computer games being employed in the creativity and design fields?* To address this question the data sources selected focused on a limited set of relevant journals from each field. These journals were selected based on learned societies' endorsed journals, and by identifying

	Literature		Games	
Identification	Records in creativity (*n*=130) and design (*n*=139) journals. Total (*n*=269)		Games with "Sandbox & Physics" and "Building" tags (*n*=853)	Additional games identified (*n*=50)
			Games matching the "Top Rated" tag (*n*=170)	
Screening	Records evaluated by title and abstract screening (*n*=269)	Excluded, per criteria: E1 (*n*=50), E2 (*n*=118), E3 (*n*=37), E4 (*n*=38), E5 (*n*=5)	Games evaluated for eligibility by reading their description (*n*=220)	Excluded, per criteria: E_g1 (*n*=8), E_g2 (*n*=14), E_g3 (*n*=7), E_g4 (*n*=11), E_g5 (*n*=1)
			Eligible games (*n*=179)	Games inaccessible (*n*=110)
Included	Papers included for qualitative analysis (***n*=21**)		Games included for qualitative analysis (***n*=69**)	

Fig. 1 Overview of the literature search (left) and game' selection (right) processes

relevant journals listed in the Journal Citation Report. The Scopus database was employed for performing the literature search in the selected journals.

The term "gam*" was searched for in the papers' title, abstract and keywords to enable the identification of a large number of possibly eligible research papers. The papers' titles and abstracts were screened to assess their relevance for the present research. Studies were filtered out if they matched any of the following exclusion criteria (E): do not report on digital games (E1), game use is not the focus of the paper (E2), the field of application is outside Science, Technology, Engineering and Mathematics (STEM), design or creativity (E3), the paper focusses on game theory (E4) or reported review studies (E5), see Fig. 1.

After the screening, a total of 21 relevant studies remained (7 from creativity-focused journals and 14 from design-focused ones), composing the corpus of papers that were read in full. These papers were analysed following a general inductive approach for qualitative data analysis [34]. This analysis focussed on identifying and synthesizing the challenges and opportunities of employing games in design creativity research, as well as the core features of the games employed. Additionally, the games reported were classified according to the G/P/S model. The full list of journals and papers analysed is available in the supplementary material.

Game Search Overview

The game search aimed to identify games that could potentially be used for the field of design creativity As such, a PRISMA-inspired, systematic search of potentially relevant games was performed. The selected database for game search was the game distribution platform Steam because it is the largest desktop-focused game store [35]. Due to the lack of advanced search features in the Steam platform it was not possible to employ a search string to retrieve matching games. Nonetheless, the platform provides a comprehensive classification system, in which developers can assign gameplay or technology-related “tags”to their games.[2] These tags are grouped in broader categories such as “genres” (e.g., action, adventure and casual, simulation), “themes” (e.g., anime, open world), “player support” (e.g., cooperative, multi-player) and “special sections” (e.g., free to play, demos). The platform also enables users to further restrict and sort searches by selecting standard filters such as “new & trending”, “top sellers”, and “top rated”, etc.

Given these particularities, the game search focused on games categorised in the “Simulation” genre, further refining it with the “Sandbox and Physics” and “Building” tags. These tags were selected in line with previous literature reports the use of physics building games for design creativity research (e.g. [18, 19]) and because of the inherent features of this type of games that are relevant to design, build and test activities (e.g. physics-enabled simulation, creation tools, etc.). Another filter step was applied to select only the “Top Rated” games that matched all the above-mentioned criteria to ensure that the selected games presented good usability overall.

In parallel, to further expand the sample of games analysed, potentially relevant games were added, where they could be identified through organic and snowball-like referrals (from the platform’s recommendations of similar games). These games included well-known games not available on Steam (e.g., *Minecraft*) and games not necessarily matching the tags employed in the systematic search (e.g., puzzle games or games that are not “top rated”). The inclusion of puzzle games in particular is justified due to their potential for creativity research as previously highlighted. The corpus of games was consolidated, and the data collected included the games’ description on the Steam platform.

A screening process to select potential games was conducted by reading the game descriptions, which usually describe their main features and mechanics. Games were removed from the sample if they fitted one of the exclusion criteria of games (E_g): Role Playing Game (RPG) focus (E_g1), game contained sensitive content, e.g., explicit violence (E_g2), older games in franchises (E_g3), survival/adventure focused games (in which design/building/testing features are secondary) (E_g4), and VR-only games that require specialist hardware (E_g5).

The final pool of possibly relevant games was consolidated and access to the games was requested (either by contacting developers or downloading those that are free to play). The final sample consisted of 69 games (68 games on Steam) that were analysed to verify the prevalence of the relevant features found in the literature review and to uncover emergent ones. Information regarding game genre, game features, number and type of reviews and number of active players were gathered. Figure 1 provides an overview of the game search and refinement process. The full list of analysed games is presented in the supplementary material.

[2] Table of available tags: https://partner.steamgames.com/doc/store/tags#12.

Results

This section presents the results from the literature review and game search, highlighting the reported challenges and opportunities for employing games in design research, the characteristics of the games already employed, and an overview of the features of available COTS games.

Computer Game Use Reported in the Literature

The literature search process delineated in Fig. 1 yielded 21 papers for review. In these papers, a total of 28 instances of game use were identified (some studies reported employing more than one game). Out of the 28 game use instances, *custom games* developed by researchers accounted for 57% (16 games) and *COTS* represented 43% (12 games). Among the COTS games employed, *Minecraft* and *Half-Life 2* were employed in two studies, whereas other games were employed only once: *Garry's Mod*, *Fantastic Contraption VR, Pontifex, Active World, NASCAR, The Humans, Grand Theft Auto V* and *Dance Dance Revolution.*

Overall, the number of papers reporting the use of games for design creativity research indicates a certain level of awareness of the value that they may add. However, the many custom games created by researchers for their particular studies suggests a possible lack of knowledge of existing COTS games and the features that could render them useful for research or educational endeavours (or a resistance to using them). The diversity of COTS games already reported in the literature suggest that it is possible to find relevant games among the myriad of available ones.

Regarding the reported challenges of employing games, a total of 82 instances were identified and grouped into five broad categories (which emerged inductively from our analysis of the reviewed papers: *outcome reliability* (30%), *game design* (27%), *generalisation* (21%), *research design* (18%) and *communication* (4%).

The outcome reliability category is fundamental to ensure the validity of the results. The specific challenges reported can be seen as researchers' need to better control the variables and experimental process. This interpretation might partly explain the use of many custom games: by developing their own games, researchers might expect that they will have better control of the data, game processes and game content.

On the other hand, the game design category points towards some of the issues that may arise from poorly designed games—such as usability problems, steep learning curves, high development costs or lack of fun. The game design process is neither easy nor cheap: it requires technical and artistic capabilities alongside subject-matter expertise. Researchers might find it challenging to mobilize all the resources required to develop a custom game from scratch. However, adapting an existing COTS game could prove to be a more straightforward process, allowing researchers to start from a meticulously crafted game that exhibits high levels of usability and high quality visual and audio effects.

The analysis of the opportunities for game use identified, a total of 87 instances which were grouped in six broader categories (which emerged inductively from our analysis of the reviewed papers): *game aspects that influence creative outcomes* (30%), *outcomes*, as the actual results from games use (22%), *motivation* (18%), *education* (13%), *potential uses* (10%) and *research implications* (7%).

Many of the opportunities identified are related to intrinsic aspects of games which could be used in design research applications. These include developing a sense of presence, increased motivation, carefully planned onboarding processes and iterative play guided by real-time feedback. Similarly, the literature showed that games can promote improvements for creativity and design outcomes. These opportunities further support the relevance of investigating games as tools for research.

Additionally, 56 relevant game features for research applications were identified in the literature occurring a total of 166 times. Since only 23 features accounted for over 75% of the feature occurrences, we focused on them for this analysis. These features were grouped into 3 distinct categories: *game components*—the most basic features games can have (49%), *game mechanics*—the overall systems that organise gameplay processes (35%) and *technology* (16%). The supplementary material presents the 23 most-commonly reported features.

Regarding the specific game components, "metrics" (related to players' performance), "budget" and "roles" (assigning specific roles to players) are strongly related to design-oriented games and are also elements of design practice. The mechanics of designing, creating, and simulating are closely tied together and are supported by the physics-simulation capabilities of games. The mechanics of collaboration among players can be seen manifested in the "roles" component (players have roles and need to collaborate), and in the technological capabilities of communication (e.g., in-game chat).

Besides the game components analysis, the classification of the games in terms of the G/P/S model (reviewed earlier) is also discussed. In terms of the *gameplay* (G), games with clear goals (i.e., game-based) were employed in over 80% of the studies. This preponderance might relate to the goal-oriented nature of design creativity activities, although undirected, play-based activities showed promising results for enhancing creative outcomes [30]. The *purpose* (P) of the games was mainly related to transmitting a message (i.e., message broadcasting), which includes educational objectives and accounted for 57% of the papers. Games used for research purposes (i.e., data exchange) and for skills training were used in 33% and 29% of the studies, respectively (there were five instances of games classified as having more than one purpose). Particularly in terms of the data exchange purpose, two examples of custom games aimed to tap into the potential of large numbers of players for gathering insights to improve design outcomes or processes: the *BioP-C* game for supporting the creation of a database of biological analogies in design [20] and the *EcoRacer* game for vehicle powertrain design [37].

The last dimension of the G/P/S model, the *scope*, takes into account the public targeted by the games: custom games created by researchers mostly targeted student populations (over 61% of game use), with comparatively few instances of such games focusing on professionals (23%). This public distribution is consistent with traditional research on design creativity which mostly relies on the participation of students or novice professionals. However, games could also be used to attract and motivate professionals to take part in research activities [19].

A summary of the analysis of computer game use in the reviewed papers is presented in the supplementary material.

Results from the Search of Potential Games

The game search process delineated in Fig. 1 yielded a sample of 69 games of interest. For streamlining the analysis, we focused on 68 games that are available on the Steam platform. Game information was retrieved using both automatic processes (using Python scripts for downloading game data through Steam's APIs) and manual processes (accessing game pages on Steam and Steamcharts—a third-party service that tracks the number of active players for each game).

Regarding game genres (as retrieved from the Steam platform), simulation was the most common (89% of the games) followed by indie (80%), strategy (42%), casual (36%) and early access (35%) genres. Unsurprisingly, the high number games in the simulation genre shows the close relationship between this form of gameplay and the activities normally investigated in design creativity research. The substantial proportion of indie games (i.e., games developed by smaller game studios/independent developers) is particularly interesting: it indicates that larger studios tend to focus on high budget games that fit other genres that are more popular (e.g., first-player shooters or massively multi-player online games). The strong presence of indie game developers, on the one hand can make it easier for researchers to directly contact the game designers and access smaller game communities. On the other hand, it can be an issue for intensive, long term game use—potentially facing lack of support, shorter game lifecycles and fewer updates. Games in the casual genre—which are usually simpler, less competitive, quicker, and easier to play (fast onboarding)—can be particularly suitable for design creativity experiments and other activities which are of short duration.

In terms of game features, originally 31 feature types were identified from the Steam platform. For this analysis we focused on four core features (in parentheses the percentage of games which presented each feature): *support for varied interaction modes* (44%), which includes joystick, AR/VR, consoles, among others; *user-generated content* (40%), i.e. sharing levels, models, multimedia content through the Steam platform; *multi-player support* (34%), including online, LAN, collaborative, competitive, among others; and *level editor* (25%), which enables players to create their own challenges, levels and content using the game. In total, 50 games presented at least one of these features and 13 presented 3 three or more.

The *interaction modes* feature indicates the possibility of the games to support different hardware (mobile, computer, console) and controllers (e.g., VR headsets, joystick, mouse and keyboard, etc.) potentially opening up different setups and configurations for experiments and educational activities. User-generated content repositories such as the 'Steam Workshop' enable players to submit their creations for others to download, adding screenshots with strategies for community discussion, etc. This social hub provides a largely untapped resource for researchers—from analysing publicly available content to creating and sharing levels or challenges for data collection on the platform. Yet another possibility is using these resources in educational activities as evidenced in [38]. Level-editors allow the creation of specific challenges or maps to better control the variables and measurements. Researchers employed them for creating experimental setups [18]. Custom game servers, mods and changes to game code have also been pursued to provide more control over the activity [38]. Naturally, multi-player support opens the possibility of investigating collaborative design processes, communication aspects and related matters in computer-mediated settings.

In an attempt to gauge the popularity of the analysed games and the size of their communities, the total number of reviews that each game received on Steam and the percentage of positive reviews were retrieved. Overall, the games were very well regarded (over 54% had more than 90% positive reviews). The number of reviews registered for the games ranged from a few dozens to over a hundred thousand.

The relevance of game evaluation (i.e., percentage of positive reviews) is that it can be seen as a proxy for how well designed the game is—potentially helping researchers to focus on easy-to-learn, user-friendly games. The total number of reviews can be seen as an indication of the overall size of the game's community (to review a game, players must have acquired it). Interestingly, game reviews on the platform are "peer-reviewed"—users can vote or recommend the best reviews, earning badges and prestige in the community. The social aspect of the reviews could support community building and strengthen other community-related activities such as sharing content through the platform. Finally, other metrics such as average active users in the last 30 days, could be employed for assisting the selection of games in cases where researchers plan to interact directly with players. A summary of the game analysis is available in the supplementary material.

Discussion

In the previous sections, we presented an overview of current uses of games in research, and the most relevant features of COTS games. We now discuss the core issues and opportunities identified so as to delineate future pathways for employing games in design creativity.

One issue highlighted in the reviewed literature is related to the disconnect between **game representation and the real-world**. This issue encompasses instances where researchers mentioned the challenging aspects of creating a game that accurately depicted the phenomena of interest, while being reasonably easy to learn and play—for instance [19, 20, 39]. It also includes times when real world data was adapted for incorporation in the game, e.g., [22]. This is a relevant discussion where the trade-off is clear, but its resolution is challenging and context dependent. In the *BioP-C* game [20] researchers simplified the subject-matter to better adapt it to the game format, and evaluated its validity afterwards, comparing game results to randomly generated results and to "gold-standard" results from existing literature. The *SIM MV2*, a seaport simulation game, used data gathered directly from the port company business processes to better represent activity durations, costs, etc. [39]. While using a COTS VR game, researchers observed that game physics differed from that in the real-world, but this difference did not disrupt player engagement nor appear to affect the outcomes of the study which focused on the design process itself [19].

On the other hand, COTS games can also incorporate real-world data: *Fly-Corp*, a transport network simulation game, uses real-world geographical information and population data; *Simple Rockets 2*, a space simulator game, incorporates orbital physics principles and rocket performance metrics analogous to those of real rockets; *Logic World* is a digital circuit simulator that enables players to build circuits running on the same principles as real-world computer chips. The core difference here is the researchers' lack of control over the simplifications and adaptions made by the developers.

From this brief discussion we see that COTS games could be suitable for contexts requiring higher levels of fidelity with their real-world counterparts. Conversely, depending on the phenomenon of interest or purpose of the game, fidelity to the real-world might not even be required: a game that has consistent rules and processes could be enough, as suggested by [19] or even more desirable to further free participants to be creative [38].

Considering the issue related to the **different types of activities** and how they may affect research outcomes, COTS games can provide play opportunities along the whole continuum of play-based versus game-based gameplay. On the play-based end of the spectrum, games that focus on unconstrained, undirected play could be employed (e.g., *Cloud Gardens*, a dystopic garden landscape design simulator or *Atlas Architect*, a free-flowing, relaxed world-building game). On the opposite end of the spectrum, games can provide heavily goal-oriented experiences (e.g., *Mini Motorways*, a minimalist city simulation game in which players manage traffic to develop the most resilient traffic network). Some games can provide both free and directed experiences, positioning them in between the extremes (e.g. *Minecraft* as reported by [30] and *Trailmakers* with its explore-and-build story mode and unbounded sandbox mode). Investigating how these different type of games affect creative outcomes could further advance insights previously reported [30] and uncover novel implications.

Furthermore, still considering the issue of different types of play, it is worth investigating how varying game genres relate to research outcomes. The literature reported on the use of games ranging from a massive multi-player sandbox game (*Minecraft*) to an 'exergame' (*Dance Dance Revolution*). Research topics that might be pursued further include understanding the differences in using puzzle-focused or design-oriented games for creative outcomes. The theme of the games and their suitability for the intended public can also be investigated: *Logic World* focusses on digital circuit design, while *Poly Bridge 2* focusses on structural truss design, the limitation of a bridge-building game to a domain-specific design activity has already been noted [18].

Finally, **capturing gameplay activities** is a relevant issue both for custom and COTS games. Detailed game logs, registering player actions, parameters and outcomes, have been employed by researchers who developed their own systems [22, 39]. However, game log use was not verified across all custom games, nor do such logs necessarily capture the social and psychological aspects of game play. Researchers have successfully employed screen and activity recordings of users playing with COTS games, for subsequent qualitative data analysis [18]. While this approach yields a thorough understanding of players' choices and design procedures during the game, it is a relatively time-consuming method, which would hinder its scalability.

In terms of the opportunities, **teaching and learning** of design creativity were frequently reported to possibly benefit from the increased motivation and experiential learning that games can offer. In particular, some COTS games even offer systematic support for educational initiatives: *Minecraft* has an "Education" edition; *Fortnite Creative* has readily available course materials and *Eco* (a sustainability-focused ecosystem simulation game) has an educational version. Regarding further **research opportunities**, besides the varied data gathering or data source possibilities, researchers could employ COTS games for increasing research reproducibility. Not only the datasets and results but also the levels and 'mods' created for running the experiments could be shared through game platforms themselves.

Despite the potential benefits and opportunities highlighted, some inherent challenges related to game use persist, such as the cost of acquiring the games and the development of scalable data collection and analysis approaches. Ensuring an automatic, streamlined process that minimizes data overload and data analysis disruptions must be sought when using games at scale. Additionally, the effect of factors external to the game must be further investigated, i.e., environmental conditions such as room comfort, internet connection, computer hardware capabilities, etc. Figure 2 summarises the discussions presented in this section.

Conclusion

We started this paper with a brief account of the Poly Bridge Olympics, just to highlight that game players are spontaneously participating in creative design activities, documenting their process, and making the outputs available for all to see. As we hope to have demonstrated through our reports on the published literature and the available games, the Poly Bridge Olympics is just a small corner of the game universe that could be potentially relevant for the design creativity field.

Our synthesis of the challenges and opportunities of game use reported in the literature provides a starting point for researchers and educators who are considering the possibility of using games in their own work. Similarly, the most relevant game

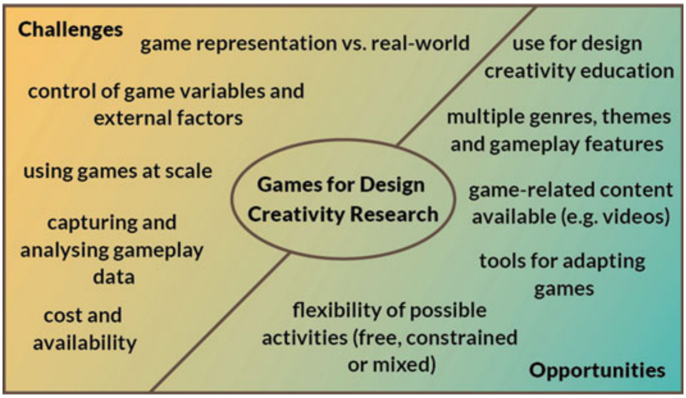

Fig. 2 Summary of the challenges and opportunities of employing games in the design creativity field

features identified can inform custom game design decisions or the adaptation of COTS games.

The systematic search for potential COTS games revealed the most relevant genres, features and metrics that can inform researchers and educators when deciding on which game(s) are suitable for their needs. Even more—the list of games we identified attests to their variety; it ranged from simple abstract games in which players create gardens to more complex simulation games in which players can express their creativity while designing and managing an entire city.

The possibility of employing games for design creativity education was verified in the literature we surveyed. This is noteworthy and warrants further investigation, particularly given the enduring tendency of the design creativity field to overlook educational problems or opportunities [4].

Two limitations of the current study are the narrow scope of papers included in the review, and the restriction to (mainly) simulation games on the Steam platform. These limitations arise from the need to create a relevant yet manageable pool of (re)sources that could be thoroughly analysed. Expanding the pool of journals to those of other fields and including conference proceedings could lead to the identification of more instances of game use and discussions from diverse perspectives. In terms of the games, the restricted scope builds upon existing literature that already employs this type of game. Further explorations of different game genres and a more in-depth analysis of those other games might yield further insights on features and gameplay opportunities for design creativity research.

Future work should be conducted on the formalization of evaluation strategies for using games in design creativity research, and the systematic investigation of the effect of games from different genres in design creativity activities. A systematic evaluation of game mechanics and their relationships with particular creative processes could also provide more detailed insight into how games can be employed for design creativity studies.

Empirical studies should be conducted comparing different games to each other and to traditional approaches for design research. This would assist in the definition of best practices and increase methodological robustness. Tapping into game-related materials, such as reviews and user-generated content (similar to the Poly Bridge Olympics) could also provide insight on design creativity phenomena happening in relatively controlled environments that have been established independently of the researchers who might study them. Finally, game use for design creativity education also appeared as a potentially fruitful research avenue.

In this study we aimed to raise researchers' and educators' awareness of the opportunities and challenges of using games in the design creativity field. We also aimed to provide an overview of the variety of potentially relevant games that are available for exploiting those opportunities and addressing those challenges. In pursuing this, we hope to have provided a useful starting point for employing computer games in the field of design creativity, whether that is for planning research projects or educational interventions.

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Exploring Designers' Encounters with Unexpected Inspirational Stimuli

Elisa Kwon, Vivek Rao, and Kosa Goucher-Lambert

Abstract In prior work on designers' search for inspirational stimuli, random discovery of stimuli through passive search processes has been underexplored. This paper primarily investigates how unintentionally discovered stimuli influence design outcomes, and why designers select these stimuli despite not meeting their initial expectations. In the present work, designers' search for inspirational stimuli is explored through their use of a multi-modal search tool developed by our team. Fifteen designers used the search tool to find inspirational stimuli to solve an open-ended design challenge. During this study, many search results were found not to meet designers' expectations. Nonetheless, designers incorporated a portion of these unexpected stimuli into their design ideas, resulting in the design outcomes: introduction of novel features, fulfillment of needs in an unanticipated way, and acceptance of readily available stimuli. This work suggests that encounters with unexpected stimuli can be beneficial, suggesting implications for future design tool development.

Introduction

For designers to become inspired, encounters with external stimuli are often needed. These encounters may occur when designers search for inspiration through processes that are both active and deliberate, or passive and random [1]. While active search implies an intention to find a stimulus to fulfill a specific goal, passive search is related to the random discovery of results [2], which can be beneficial for designers [3, 4]. The aim of this paper is to further understand how designers engage with

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passive search processes and the impact of inspirational stimuli discovered through these processes on design outcomes.

Prior work on search for inspiration has focused on what designers tend to look for through the specific search queries they initiate [1, 2]. However, as designers search for inspiration, they may not always have a fully defined search query or be able to retrieve exactly what they are intending to find through searching. While past work (e.g., by Goncalves et al.) has shown how unexpected stimuli can be fortuitous for designers [2], the results of passive search procedures have rarely been studied systematically. Insights about these processes are especially valuable for informing the development of design tools. While the discovery of unexpected stimuli through passive search is a phenomenon known to assist designers with idea generation, design tools are not typically made to support this process and focus rather on improving the retrieval of desired stimuli [5].

In this work, we present examples of how the unintentional discovery of unexpected results can affect design outcomes. These examples are drawn from a cognitive study we conducted in which designers used an AI-enabled tool we developed to support search for inspirational stimuli using multiple modalities of input. The results outlined in this paper present opportunities for future work to better understand and support designers' use of inspirational stimuli they do not explicitly intend to discover.

Related Works

In this section, we provide an overview of prior work on designers' search for inspiration. First, we introduce designers' inspirational and informational search processes and, second, the features of inspirational stimuli designers tend to prefer.

Processes Designers Use to Search for Inspiration

There are many aspects of the search process that are important to consider to understand how designers search for inspiration. Highly important are the intention and goal of the designer engaged in the search process [2], which have been suggested to include both specific detail and resolution of stimuli [6] and contextual, perhaps less-defined information contained in stimuli [7]. Also relevant to the present work is how designers initiate the search process. Goncalves et al. studied how designers select keywords to initiate the search process [2]. Several behaviors were discovered, including searching for closely related terms to the design problem earlier in the task and more distantly related terms later in the task [2]. These search strategies are supported by related research on inspirational stimuli that suggests the importance of both analogically near and far stimuli on promoting beneficial design outcomes [8].

However, Ware suggests that the goal of a designer is not always defined, leading designers to use different search processes [9]. When a goal does exist, designers engage in active search, and otherwise passive search processes are used. Passive search is defined as the process during which designers have a goal to solve but do not have a fully defined search query [2, 9]. Though not intentionally searched for, stimuli discovered through passive search can be recognized by the designer as beneficial to their design and somehow related to the current problem [2]. In this work, we define active search as the goal-driven process of intentionally searching for a specific stimulus. Passive search instead results in the discovery and selection of stimuli that were not explicitly searched for.

In investigating designers' information seeking behaviors more generally, Damen and Toh found that information evaluated as helpful did not necessarily mean that designers leveraged this information during idea generation [10]. Later work by Damen and Toh suggested that designers are adept at *effectuating* readily available information sources, even those that may not evidently influence the outcome [11], and that designers applied diverse organizational strategies to best leverage information towards design goals [12]. These findings are useful for understanding why designers may select unexpected information: selected information may afford effectuation (i.e., use of existing resources) even when causal links to an outcome are not clear, or it may support organizational strategies that facilitate the designers' goals.

The present work extends upon the prior research reviewed here in two ways. First, we consider search processes using a multi-modal search tool. Prior work has focused on inspiration processes initiated by keyword or text-based searches, which require designers to engage in active search. By introducing non-text-based search inputs, as afforded by our multi-modal search tool, different ways of expressing search intent and pursuing a search goal can be explored. Second, while prior work focuses on the retrieval of inspirational stimuli that designers explicitly search for through active search, this work also considers designers' passive inspirational search processes leading to discovery of unintended stimuli. A deeper understanding of why designers select such stimuli could help illuminate how and why passively encountered inspirational stimuli shape design outcomes—or not.

Designers' Preferences for and Use of Inspirational Stimuli

Different features of inspirational sources can determine whether they are preferred or found useful by designers to support their design processes. For instance, the modality in which stimuli is presented can impact whether they are influential on the design process, such as in the difference between 2D versus 3D stimuli [13]. Designers tend to prefer visual information [14], which can lead to the generation of creative ideas [15] and increased idea novelty [16]. Further describing the nature of visual information, Wallace et al. suggested that students sought and were most influenced by highly resolved sketch stimuli rather than rough sketches [6]. Cai et al. suggested that while experts valued sketch stimuli for their contextual content, students valued sketch stimuli for their real-life resemblance and direct connection to the task in question [7]. The analogical distance of the external stimuli to the designer's current problem or design space is also a relevant factor to consider, where far-field stimuli, despite being less obviously relevant to the problem at hand, can lead to idea novelty [17, 18]. Seeking distantly related stimuli is a strategy that designers intentionally employ to become "struck by inspiration" [2].

This paper extends on previous work by exploring how designers' preferences for inspirational stimuli may differ when stimuli is discovered *unexpectedly*. Much of previous work has described stimuli preferences when stimuli selection was intentional; here, we aim to uncover and understand motivations behind designers' selection of stimuli that are discovered randomly and unintentionally. The preferences designers have for unexpected inspirational stimuli can help explain designers' selections of inspirational stimuli. Designers' preferences for, e.g., visually represented and analogically distant design stimuli may give insight into their selection of stimuli that do not directly satisfy their search intentions. An understanding of how established findings describing designers' stimuli preferences and selections in active, intentional search align with their preferences in passive, unintentional search could offer deeper insight into the nature of search processes in design inspiration.

Methods

In this section, the cognitive study we conducted is presented, including details about the participants recruited, the design tool we developed, and the design task completed.

Participant Information

Participants were recruited via email solicitation among graduate students at the University of California, Berkeley, and industry professionals. Participants were required to have at least 1 year of Computer-aided design (CAD) experience. In total, 15 participants volunteered for the study, including 8 professionals and 7 students. Self-report experience with CAD tools ranged among students (3 males and 4 females) from <1 year to 9 years, and professionals (7 male and 1 female) from 3 to >10 years. Compensation of $20 was offered for participation in the 1-h study, consisting of a 30-min. design task and 30-min. interview. Findings from the interview are not reported in this paper. This study was approved by the Institutional Review Board (IRB) at the University of California, Berkeley.

Multi-modal Search Tool

Participants engaged with an AI-enabled multi-modal search tool during the cognitive study to complete a design task. The search tool uses a deep-learning approach to retrieve inspirational stimuli in the form of 3D-model parts based on the user's input query. To develop the search tool, deep-neural networks were used to model semantic, visual, and functional similarities between various 3D-model parts from the PartNet dataset [19], which consists of 24 object categories and 26,671 3D-model assemblies.

The result is a design tool that allows flexibility for designers to discover inspirational stimuli using several input modalities, including: (1) by text-based query, (2) based on another 3D-model part, and (3) based on the designer's current 3D-modeling workspace, composed of previously retrieved parts. Examples of keyword and part search inputs and results are shown in Fig. 1. In this example, the keyword search enables active search for the query "container", while the part search supports passive search, where the intention to encounter functionally related parts is made without specifically intending to find chair legs. Additional details regarding the development of this tool are described in our prior work [20].

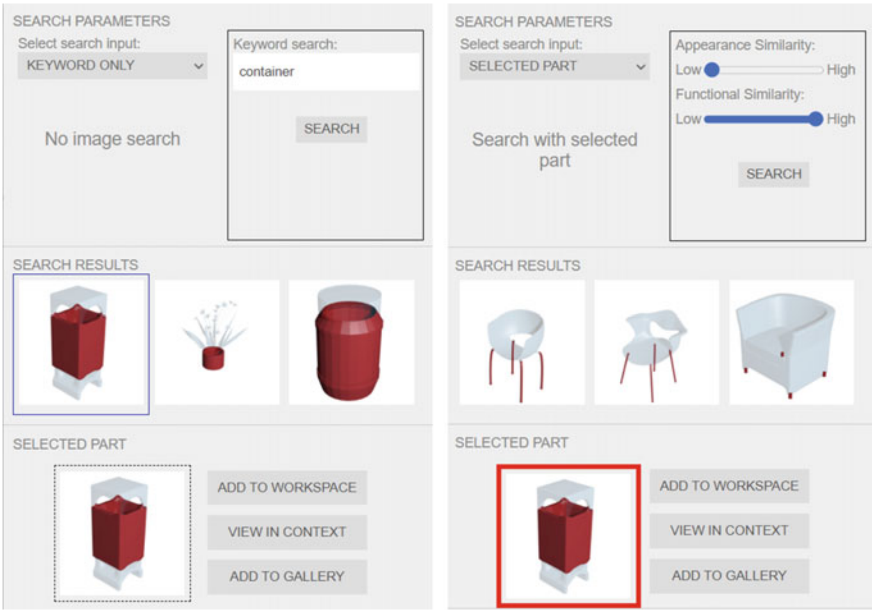

Fig. 1 Multi-modal search tool interface: Search results for (left) the keyword input "container" and (right) a part search of the selected container

Design Task

In the design task, designers were instructed to use the search tool to search for 3D parts to inspire solutions to the design of a "multi-compartment disposal unit for household waste". Designers began the task with a text-based query to retrieve parts to perform non-text searches. The study was facilitated using Zoom, which enabled screen and audio recording of participants' progress throughout the task. Screen recordings were used to capture how participants engaged with the search tool.

Instructions for following a think-aloud protocol were also provided, which directed participants to explain their interactions aloud, with particular attention to: (1) why the specified search type and input were used before executing a search and (2) whether the returned result is what was expected, or not, after executing a search. From prior work where the same design task was completed without think-aloud instructions, these prompts were specified to elucidate motivations behind previously observed search behavior during the task.

Identification of Search Behaviors from Task and Think-Aloud Data

The design task and think-aloud data were analyzed and classified into search behaviors based on definitions derived from Goncalves et al.'s description of the inspirational search process [21]. This process includes the formulation of search inputs, the (successful or unsuccessful) search for and selection of a stimulus, assessment of its correspondence to the designer's expectations, and the designer's choice to incorporate and adapt the stimulus to the problem at hand [21]. In the present work, the behaviors we are interested in identifying are how designers *evaluated* search results as expected or unexpected, and *selected* search results to be accepted or rejected from their designs. The criteria used to assign these behaviors are presented in Table 1 with representative examples from think-aloud data.

Two coders, each with at least three years of postgraduate design research experience, assessed the data using the classification scheme outlined in Table 1. Coder 1 manually transcribed think-aloud data from screen and audio recordings of the design task sessions. Coder 1 identified user interaction behavior and think-aloud quotations pertaining to the defined behaviors. A total of 235 searches were made throughout the study, an average of 15.7 searches per participant. To validate the framework, Coders 1 and 2 independently applied the defined codes to 15% of the data set. An interrater reliability of 84% was determined, suggesting that the developed coding framework was relatively consistent across coders. After resolving differences, Coder 1 coded the remainder of the dataset.

By identifying how search results were *evaluated* and *selected* by designers, we can explore the unexpected stimuli that designers accept and use in their designs. The

Table 1 Search behavior classification scheme from task and think-aloud data

Search behavior	Criteria for classification	Representative example
Evaluation (Expected)	Explicit acknowledgement that the result *is* what was searched for or preceded an 'accept' selection if no accompanying verbal statement given	"Yes, I like these features. This is providing what I'm looking for" (**P10**)
Evaluation (Unexpected)	Explicit acknowledgement that the result *is not* what was search for or preceded a 'reject' selection if no accompanying verbal statement given	"This is not what I was expecting – I was expecting to see more lids, whereas these are tabletops" (**P4**)
Selection (Accept)	Result is added to the designer's developing design in the 3D workspace or saved to their gallery of parts	"This is a shape that could possibly be used in my design. So, I'm going to add it to my gallery" (**P12**)
Selection (Reject)	Result *is not* added to the designer's developing design in the 3D workspace or saved to their gallery of parts. Designer continues to search again	"This is not what I was thinking, but this is a trashcan, for sure… I'm maybe more looking for a cabinet" (**P5**)

impact of incorporating unintentionally discovered stimuli on the design process is discussed through specific examples that emerged during the design task.

Results and Discussion

In this section, we present our preliminary findings related to the selection of unexpected inspirational stimuli and the effect of these stimuli on the design process. First, we identify these instances of design behavior by coding the data according to the classification scheme detailed in the previous section. Second, we present and discuss the high-level themes that emerge from these examples to propose motivations for designers' selection of unexpected inspirational stimuli.

Selection of Unexpected Inspirational Stimuli

Combined across all 15 designers, the numbers of searches categorized under each evaluation and selection behavior are reported in Table 2. In total, 156/235 (66.4%) searches retrieved results that were identified as unexpected. The high proportion of unexpected search results appears to be disproportionately true for searches made with 3D-part inputs (41/58, 70.7%) and 3D-workspace inputs (24/28, 85.7%), in

Table 2 Summary of search evaluations and selections by search input used

	Search input			
Search behavior	Keyword	Part	Workspace	**Total # of searches**
Evaluation (Expected)	*58*	*17*	*4*	*79*
Selection (Accept)	50	11	4	*65*
Selection (Reject)	8	6	0	*14*
Evaluation (Unexpected)	*91*	*41*	*24*	*156*
Selection (Accept)	11	4	6	*21*
Selection (Reject)	80	37	18	*135*
Total # of searches	*149*	*58*	*28*	*235*

comparison to keyword searches (91/149, 61.1%). Across search types, 149/235 (63.4%) searches produced results that were rejected by designers. Of the 156 searches with unexpected results, 135 (86.5%) were rejected and not incorporated into designers' ongoing work or saved for future inspiration.

Given the large proportion of rejected and unexpected results, two areas of further investigation are proposed. First, methods to improve the retrieval accuracy of AI-enabled design tools should be investigated, including the tool's ability to recognize the designer's search intent and goal from their input. A less obvious contribution is to encourage, through engagement of features within the design tool, the incorporation of these unexpected stimuli into the designer's ongoing idea. In the present study, 21/235 (8.9%) of searches were unexpected, but accepted by designers and integrated into their design ideas. As we showcase in the following sections, though they represent a small subset of the total searches conducted, these examples demonstrate the opportunity for unexpected stimuli to introduce exciting and beneficial design features during ideation.

Motivations for Selecting Unexpected Inspirational Stimuli

Introducing a Desirable, but Unanticipated Design Feature

The first motivation observed for selecting an unexpected result retrieved by the search tool was that it introduced a desirable, but previously unanticipated feature to the designer's concept. In two cases, designers were inspired to add wheels to their designs, though this is not what they initially sought. Participant P8, looking for different forms of containers through a part-based search with high functional similarity and low appearance similarity to a container lid, received the parts shown in Fig. 2a, including two sets of wheels. These were returned by the search tool because lids and wheels are visually dissimilar but share a common functional context in object assemblies including containers. Discovering the wheels, participant P8 noted:

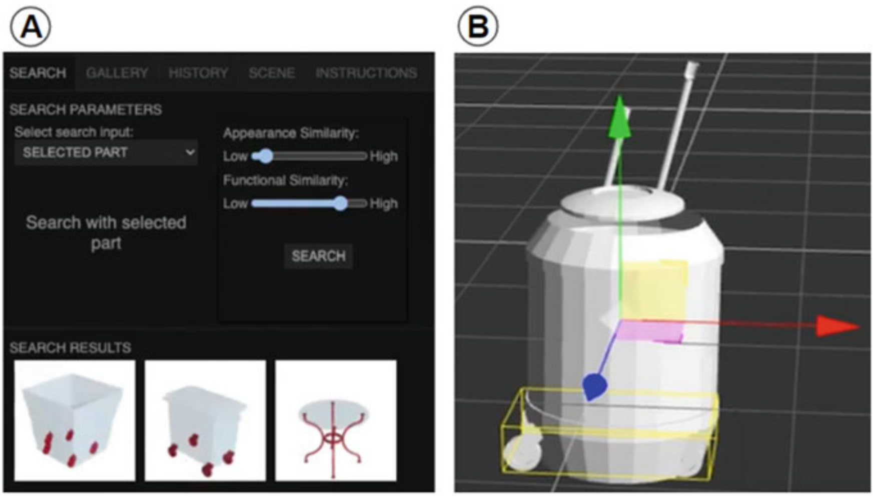

Fig. 2 An example of unexpected results introducing an unanticipated desirable feature (P8): **a)** unexpected wheel results returned by the search tool (left) and **b)** addition of the middle result to Participant P8's design (right)

"*Well now that I see it, I think it may be a good idea to have the unit movable, so I think castors would be something useful*". The resulting influence on their design can be seen in Fig. 2b, displaying that the wheels were subsequently added to the base of their disposal unit. In a second instance, participant P7, when looking for "*something similar to this drawer*" using a workspace-based search, was returned chair wheels (Fig. 3a). The search tool, recognizing visual similarity of the drawer to the seat in the chair assembly, returned chair wheels due to their shared context with the seat. After first remarking, "*well that's kind of funny*", the chair wheels were added to their design (Fig. 3b) after similarly acknowledging: "*Now we can add wheels to this and make it mobile, which is good*!".

In both examples, the effect of retrieving wheels was to introduce an unanticipated feature to their design, i.e., mobility. In the first example, wheels from an analogically near-field (as defined by Fu et al. [8]) object assembly (a different kind of container) were added, which may represent a more obvious transfer of unexpected stimuli to the design. The second example is striking as it demonstrates how even unintentional stimuli from a far-field domain (a chair) can be effectively applied towards introducing a desirable, but unanticipated feature to the design. The use of contextually unrelated stimuli is further relevant to the next motivation discussed.

Fulfilling a Searched for Purpose, in a Different Way

The second motivation identified for a designer's use of an unexpected stimulus was that it fulfilled the same purpose originally intended, but in a different way. Participant

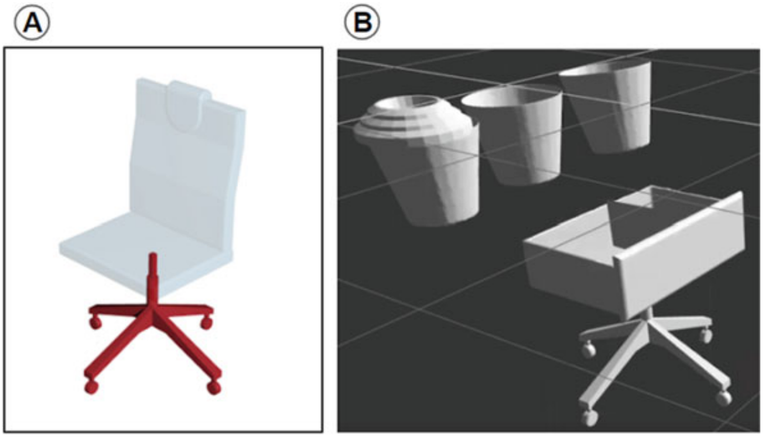

Fig. 3 An example of unexpected results introducing an unanticipated desirable feature (P7): **a)** Unexpected chair wheel results returned by the search tool (left) and **b)** addition of the part to Participant P7's design (right)

P4, upon retrieving three tabletop results (e.g., Fig. 4a) when searching for a lid to place on a rectangular trashcan found that "*Nonetheless, it's actually fitting what I'm looking for exactly*". In this example, although the object did not match what was searched for, its visual form suited the designer's needs for a cover they could scale to the size of their trashcan. In a similar example, Participant P7 searched for a "can" and was given a round base of a candle holder, as shown in Fig. 4b. While expressing that this is not what they were looking for due to its scale, they also stated, "*This one is maybe promising, I can maybe make it bigger…this looks like it has an opening*". Despite the size of the result, an acknowledged ability to scale it to the correct size made it useable to the designer. Finally, when looking for cylindrical shapes, Participant P14 was returned a chair seat (Fig. 4c). This result was identified as being potentially useful because, "*worst case, I can flip it… if I don't find anything, I can work with this shape which is resembling something that I might be looking for.*" Reorientation has been proposed in prior research as a strategy to aid creativity [22]. In general, encouraging designers to consider object transformations such as rescaling or reorienting may assist their ability to discover more useful sources of inspiration from passive search processes.

Satisficing for a Result that Does not Meet Expectations

A final motivation discovered for designers to accept unexpected stimuli is a sense of satisficing for a result. Two distinct scenarios were observed: in the first, designers' search results included a previously rejected part, which may have strengthened the belief that a more relevant match did not exist. Secondly, even when acknowledging that a result is "*not quite what I was looking for*" (P15), the result was accepted. These

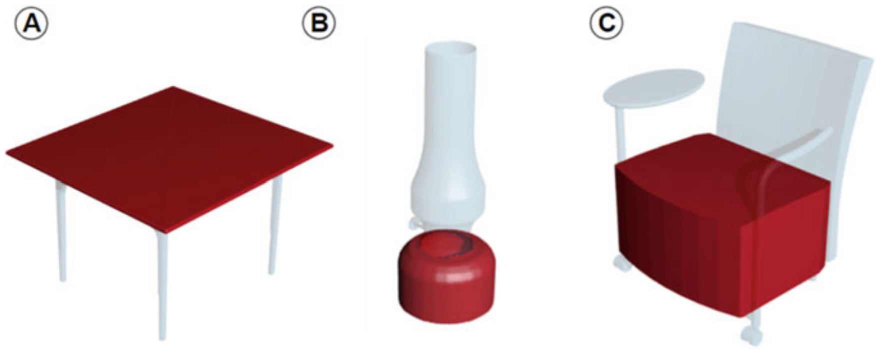

Fig. 4 Examples of unexpected results that fulfill the purposes of intentionally searched for parts: **a)** Tabletop scaled down to fit the top of a trashcan **b)** Candle holder base scaled up to serve as a can, and **c)** Chair seat reoriented to a container

examples reinforce that designers use readily available stimuli without knowing how they will directly influence ideas [11], suggesting that designers can tolerate an acceptable threshold of accuracy when using inspiration-retrieval tools.

Conclusion

In this paper, we presented the results of a cognitive study where designers searched for inspirational design stimuli to complete a design task. While searching, designers encountered many stimuli that did not meet their expectations. However, we also observed instances of designers using these unexpected stimuli in their design ideas to add new design features, fulfill their intended needs in a different way, or because designers satisficed for results. This work reveals the importance of the role of passive search in uncovering unexpected stimuli that can benefit designers' idea generation and proposes that design tools should encourage and support these unintended discoveries.

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Collaborative Design: Evolution of Project's Information and Role of the Graphic Interactions

Gaëlle Baudoux and Pierre Leclercq

Faced with challenges of new collaborative and digital design processes, it is necessary to understand how to support architectural design to articulate the information from the collaborative ideation (first creative moments of idea deployment) to the digital design phases that follow (such as BIM models specifications).

The study presented here lies within the fields of design theory and computational design as our research question is to analyze collaborative design processes to qualify the evolution of the information characterizing the project and the design activities generating this evolution, notably through the role of graphic interactions.

To achieve this goal, we changed the paradigm by considering the designers as transmitters of information, and the information as the heart of our questioning.

As result, we highlighted some typical design activities to characterize the project, recurrent associations of information and finally the importance of graphical traces as a support of this characterization.

Motivation

Background

The current modes of design show little articulation between their multiple actors, called to manage the increasing complexity of building projects. Building information modeling (BIM) technologies and integrated processes are seen today as the

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promising path to increase exchanges between actors and to improve the buildings' performances [1, 2]. If it undoubtedly brings benefits during the implementation phases, this digital approach for information sharing is not really adapted to ideation phases, creative moments of idea generation and deployment.

Thus, it is essential to address the issue of the transition from architectural design to BIM by integrating the collaborative, contextualized and designer-oriented processes. This involves tracking, collecting and articulating information from the collaborative ideation.

These questions relate to the fields of design theory and computational design, addressing the notions of design activities, external representations and graphical traces.

Existing Research

Many researchers have already studied design theory.

Since 1990, Gero has been studying reflective practices in design and has developed a situated Function-Behaviour-Structure ontology model [3–5]. In the wake of Schön and Wiggins [6], he integrated the notion of situation and separated reflective practices into two types of reflection, self-reflection or reflection with the environment. This model will also allow the development of a situated Function-Behaviour-Structure co-design model [7].

Design thinking is also discussed in recent studies by Gero and Milovanovic, who go as far as defining a framework of analyses which includes design cognition, design physiology and design neurocognition [8].

Collaborative design activities have also been widely studied by Falzon, Darses, Détienne and Visser [9, 10] from the point of view of ergonomic cognitive psychology, developing several recommendations for collaborative design assistance.

Thereby, there are already many analyses on the collaborative design activity but they often focus on the actor. It is thus important to emphasize that in our study we did a change of paradigm by considering the designers as transmitters of information and the information as the heart of our questioning.

We also consider that the media, i.e. the mediator objects between the designer and the design activity [11, 12], are specifically chosen by the designers [13] and that they are combined with each other, forming patterns [14]. By pattern we refer to a recurrent association of media used in combination with each other. We therefore analyzed patterns within the usage of media. We thus differ from Yu and Gero [15] who studied patterns in the designer's activity by observing sequences of moves in the Function-Behaviour-Structure ontology.

Aim

Faced with the challenges outlined above, our study aims to understand how to assist architectural ideation by collecting and articulating projects' information. To do so, we seek to understand how precisely this information appears, evolves and is shared.

We therefore analyze:

- what information is generated and shared, and by which media;
- whether patterns emerge in the media usage;
- and what role graphic interactions play in the evolution of this information.

Method

Environment

Our study takes place in the very particular context of Liege University's Architecture and Building Engineering Master's educational design workshop.

This workshop reproduces similar conditions to architectural competitions and presents the opportunity to observe an integrated collaborative design process consisting, in this case, in the realization of a 7000 m^2 musical complex with various functions (two concert halls, artists' spaces, restaurant with production kitchen, etc.). We are studying this process in its entirety, i.e. over a period of 14 weeks long. The observed design is thus analogous to an agency process.

The attending subjects form 6 teams of 3–4 actors, each team designing a unique project of the music complex. We are therefore studying 6 different processes in parallel.

These 20 subjects are all expert designers. They differ from novice designers by their global approach of the project, more focused on the solution space than on the problem space [16–18].

In addition, these 6 teams of expert designers interact during review sessions of the projects with 2 senior architects and 2 engineers, all having long-term professional and agency experience.

In this type of process, there are two typologies of design:

- the design which we will call "long design", which combines individual and collective design activities spread over several days in various work environments;
- the design which we will call "episodic", which constitutes short design moments, sorts of episodes of design conversations, for the instantaneous resolution of a problem, involving all the actors on a given focus, i.e. a discussion subject.

The analysis of the evolution of information on a large scale, i.e. from week to week, to understand long design activities, has already been covered in a previous publication [13]. In this study, we seek to characterize specifically live information evolutions appearing in episodic design moments.

Fig. 1 Critical review environment and SketSha software

To study these moments of live episodic evolution across a 14-week continuous design process, we choose to focus our observations on the moments of review sessions. These are design moments [19] which offer the double advantage of being moments of explicit project characterization and of being easily time-taggable and instrumentable for data collection.

The discussions are supported by the graphic communication software SketSha (for Sketch Sharing). This software is based on the sharing, between several remote workstations, of various graphic documents such as plans, photos, texts, etc. These shared elements can then be annotated in real time with a digital pen [20, 21]. It is therefore a collective review tool allowing remote as well as co-presence review sessions [22].

In the present configuration, the review sessions took place face-to-face but also remotely due to the sanitary crisis. SketSha was therefore used both as a large graphic table supporting collaborative architectural drawing in co-presence (Fig. 1) and as a multimodal environment for remote collaboration.

Data Collection

We observe the project review sessions as non-participants in order to capture the documents used as well as the verbal and graphic interactions. For this purpose, we record the exchanges using a camera mounted on the ceiling, collecting the sound of the room and the image of SketSha (Fig. 2). This allows us to collect the necessary data without disrupting the subjects' design activities.

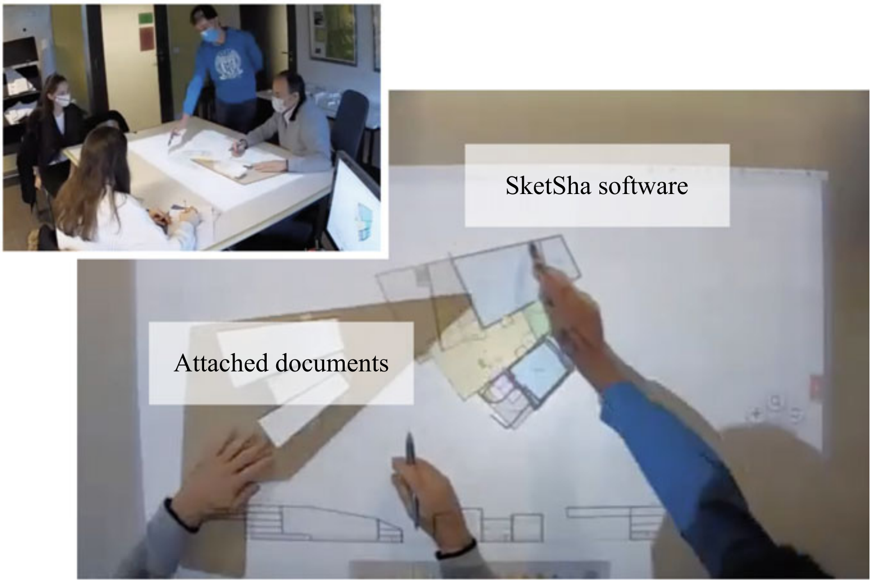

Fig. 2 Experimental space—camera shot

In terms of data corpus, this allows us to collate one hour of interaction for each of the 6 designer teams during 6 formal reviews, 3 of which presented episodic design sequences. We thus collect about 36 h of verbal and graphic interactions.

The analysis of these design episodes is done by 15-s steps. We characterize the evolution of the information through a free description as well as through four criteria (Fig. 3) (developed in previous publications [13, 23]):

- The typology of the information mentioned (e.g. concept, facade or structure): classification of building's attributes constructed from the grounds up according to the Grounded Theory [24].
- The type of means of design used to generate this information (e.g. hand drawing, 3D CAD or prototype): type of instrumented action used to conceive the project and to produce the desired representation (design instruments are associated with a pattern of use and material or methodological resources).
- The type of external representation used to communicate this information (e.g. reference image, plan or perspective): possibilities of information figuration on visual documents.
- The presence or absence of a graphical trace materializing this information.

For example, when a designer, in the observed design episode, adds by drawing a water basin in the urban space on the layout plan, he evolves an "*implantation*" type of information through an instrumented activity of "*hand-sketching*" on an external representation classified as "*plan and section*".

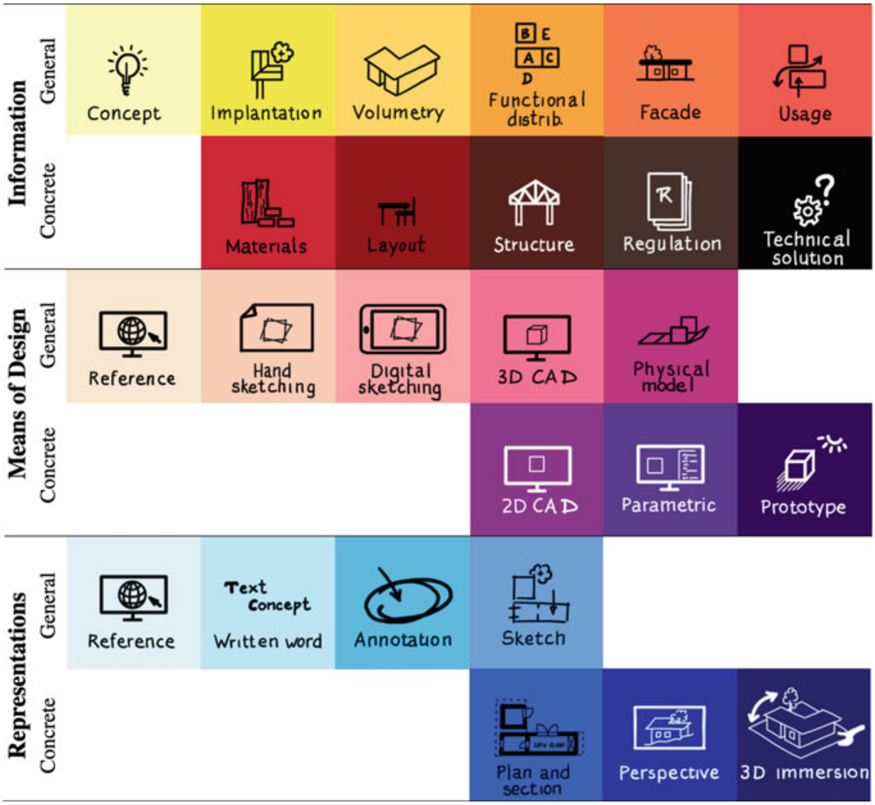

Fig. 3 Diagram of the information, means and representation typologies

The coding of these design moments is then imported into the data visualization software CommonTools [25], which allows the generation of several types of graphs such as, among others, timelines illustrating the evolution of the information.

This coding (Fig. 4) provides a reconstruction of the chaining of project information, and thus its evolution, during the 64 design episodes identified. As a result, in a longitudinal reading, for each team and for the three project review sessions observed, we can analyze the fluctuations in the information, means and representations used.

In addition, in a transversal reading, for each team of participants, each piece of project information expressed by a designer is characterized using the triplet of properties stated above (type of information, means and representation).

Fig. 4 Data modeling for teams 2, 3 and 5

Results

In this section, we will present the different results emerging from our observations.

Typical Design Activities

In order to determine whether there were typical design activities in this episodic design context, we calculated the occurrence of use of each class of means and representation, regardless of the participants, for each episodic design sequence observed (Fig. 5). Strikingly, we note a widespread use, all along the process and for every team, of the means "*digital sketching*" and external representations of "*annotations*" and "*sketch*" type. In some sequences, the model or 2D CAD is used as a complement.

To refine our analysis of design activities, we intersect the different means and representations used with the type of information conveyed by them (Fig. 6).

This graph highlights the means and representations most commonly used and for which type of information as illustrated by the red boxes.

In conclusion, we can see that, whatever the information generated or conveyed during these 64 design episodes, design activities take place largely through annotations and sketches and, in a second stage, through physical models and CAD plans or sections.

It is interesting to note that these results, specific to the analysis of "episodic" design moments, diverge from the results obtained when analyzing "long" design activities, in the same experimental context. These studies on long design [13, 14]

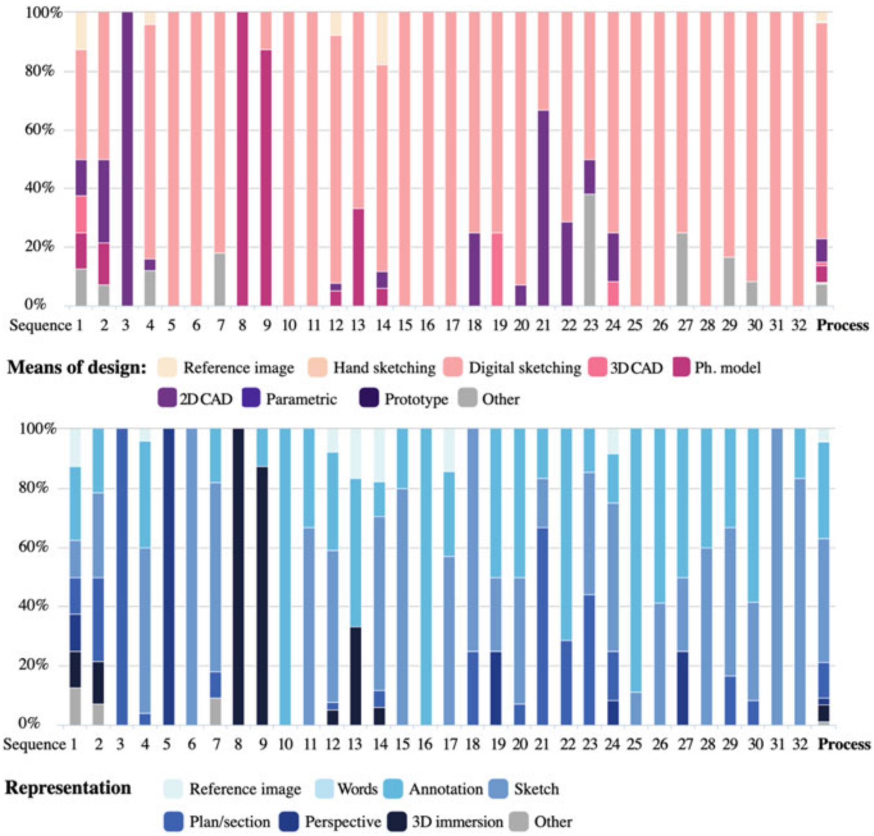

Fig. 5 Proportion of use of different classes of information, media and representation throughout the process, all teams combined

showed a diversified use of design media and an intentional and specific choice of media depending on the situation.

Our explanation hypothesis is based on the statement that the design activities observed here are not free individual design activities, carried out over several days, but rather short moments of project's critical point resolution where all the actors choose to carry out their design activities in a single physical space and in a shared space of reflection, recognizing Ben Rajeb's "*We-space*" [26]. Therefore, the cognitive economy encourages designers, in their activities, to use the medium and representation already present, in this case SketSha, to design [22]. This phenomenon has been more widely studied and validated in the recent studies of Calixte [27].

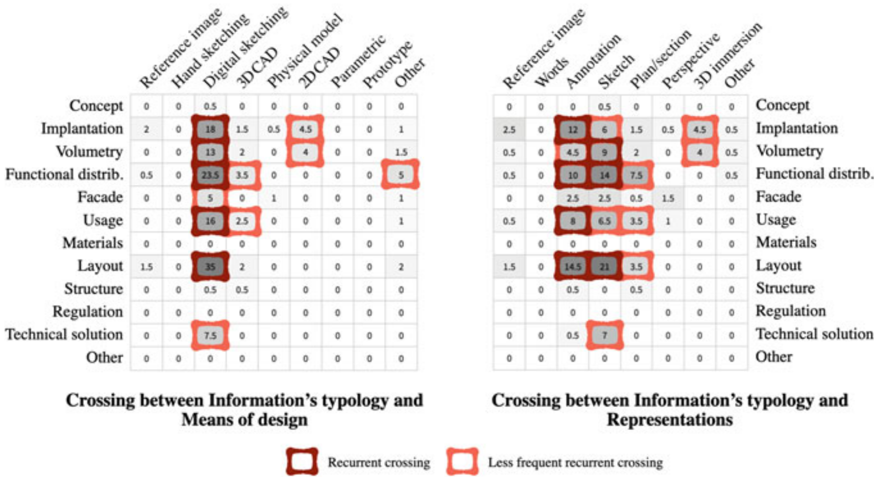

Fig. 6 Proportion of use of the different Information-Medium and Information-Representation crossings, throughout the process, all teams combined

Recurrent Information Associations

This experience also revealed recurrent information associations.

Let us recall that by "information" we refer to a specific characteristic of the building such as the material of a floor, the height of a window, etc. Thus, for a given focus, for example the main entrance door, we can find different typologies of information such as the position of the opening in the main facade (*facade* type), the shape of the pathway leading to the door (*layout* type), the trajectory of visitor flows through this door (*use* type), the width of the passageway required in case of fire (*regulation* type), etc.

By crossing the typology of each successive piece of information with the typology of the information that follows this one (Fig. 7), we can observe that pieces of information are mostly followed by another piece of information of the same type (most important occurrences are on the diagonal). Moreover, when a change of information type occurs, three preferential associations are observed:

- *Volumetry* and *Layout*;
- *Volumetry* and *Functional Distribution*;
- *Use*, *Functional Distribution* and *Layout*.

The observed associations between information of the same type show that these design moments in a review session, which aim to address invalidated architectural proposals, are focused on a unique and precise focus, i.e. on one single and detailed discussion topic. When we went back to watch these recorded moments, we actually witnessed that an invalidated solution is continuously worked on until a satisfactory compromise between the different constraints is reached and thus the proposal is

	Concept	Implantation	Volumetry	Functional distrib.	Facade	Usage	Materials	Layout	Structure	Regulation	Technical solution	Other
Concept	0	0	0	0.5	0	0	0	0	0	0	0	0
Implantation	0	18.5	2.5	1	0	1	0	0	0	0	1.5	0
Volumetry	0	2.5	13	2	0	0.5	0	0.5	0	0	0.5	0
Functional distrib.	0.5	1	1.5	17.5	1	4	0	6	0	0	0	0
Facade	0	0	0.5	0.5	3	0.5	0	1	0	0	0	0
Usage	0	1	0	5	0.5	5.5	0	2.5	0	0	1	0
Materials	0	0	0	0	0	0	0	0	0	0	0	0
Layout	0	0.5	0	3.5	0	4	0	27.5	0.5	0	1	0
Structure	0	0.5	0	0	0	0	0	0	0	0	0	0
Regulation	0	0	0	0	0	0	0	0	0	0	0	0
Technical solution	0	0.5	0.5	0	0.5	1	0	1.5	0	0	3	0
Other	0	0	0	0	0	0	0	0	0	0	0	0

Crossing between Information's typology and Following information's typology

Fig. 7 Occurrence of crossing between typologies of each piece of information and the following one, along the whole process, all teams combined

validated. For example, in the 8th episodic design sequence, team 5 is challenged, in the central building atrium, by the lift battery which blocks the circulation on the platform and by the irregular distribution of the columns surrounding the atrium. The expert suggests placing the lifts a little further away and redistributing the position of the columns. This leads to changes in the shape of the landings to remove some of the columns from the passage. These modifications are then reflected on the upper and lower floors. Finally, the new layout is validated and the columns are determined to be circular sections.

Furthermore, the preferential associations appearing in second stage between different types of information suggest that, in their thinking patterns, designers have preferential cognitive pathways between the different possible focuses and have associative ideas reasoning logics.

Importance of Graphical Traces

Finally, we observed that a graphical trace accompanies on average 78% of the project information generated and communicated (Table 1). This high percentage of presence and the low standard deviation between the different teams reflects the importance of graphical traces in "episodic" design activities.

Table 1 Percentage of information supported by a graphical trace

Teams	1	2	3	4	5	6	Total
Information nb	102	334	91	113	83	110	833
Graphical traces occurence	78	225	75	93	68	86	625
Percentage (%)	76.5	67.4	82.4	82.3	81.9	78.2	78.1

Graphical traces seem to be the preferred means used by teams to support these design episodes. This can be explained by its potential to support communication between designers, to reinforce oral comments, to concretely illustrate the proposed solutions or to crystallize the evolution of the artifact.

Conclusion

The study presented in this article aims to qualify the so-called "episodic" evolution of the information characterizing the architectural project and to better understand the design activities that generate this information. For this purpose, we observed the design episodes present in the project review sessions of a 14-week integrated design process. This allowed us to highlight the following:

- design activities are largely achieved through annotations and sketches and, in a second stage, through physical models and CAD plans or sections, which is explained by the cognitive economy that encourages designers to use the medium and representation already present to quickly and directly design the new architectural solution;
- the design focus is unique and precise for each sequence of architectural problem solving and once the solution is validated there are preferential paths to move from one focus to another;
- the graphical traces are an important support for the generation and communication of successive information characterizing the evolving project.

These results provide a better understanding of how information appears, evolves and is shared, we can better grasp the issue of collecting this information and we know that it will have to be done by using graphic traces made up of annotated sketches and CAD plans.

Replicating this experiment in a different work environment would isolate the influence of this environmental factor and exclude a potential bias related to the use of SketSha as a design tool [20, 21].

Having studied the evolution of project information during the collaborative design of an architectural project, we will now study how to, concretely, collect this information. Micro-experiments on specific focuses in a laboratory will allow us to set up a specific and operational method to collect and formalize this information in a more detailed way.

We also intend to study more in-depth the specific role of graphical traces in episodic design moments.

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Collaborative-Knowledge Construction Activity Method to Analyse Design-Learning in VR Co-design Crits

Hadas Sopher and Tomás Dorta

This paper introduces and explores the "Collaborative" Knowledge Construction Activity (Co-KCA) method as means to describe design learning and teaching activities performed during codesign critiques using a collaborative VR system. In codesign critiques, students and tutors develop together a design solution. Students learn through active design practice and teacher demonstrations. However, since most existing learning assessments are project-based, learners and teachers are not provided with enough feedback concerning each participant's activity, which may hinder the learner's progress and teacher support. The Co-KCA method aggregates observable design decisions of each participant, together with the type of design activity practised, into measurable units. Links between units describe design development applied to former decisions or a collaborative development of a peer's decision, allowing for tracking individual and collaborative performance. Examples from twelve codesign critiques done in a collaborative VR system demonstrate the potential of the method in identifying elements of codesign learning processes.

Introduction

Design learning processes in the codesign studio comprise a close-coupled student–teacher activity aimed at the mutual development of a design solution. Following the constructivist approach [1], students learn through the active practice of design activities and teacher demonstration [2]. However, their learning assessments are mostly project-based and subjective, failing to provide relevant information concerning the

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learning activities performed, what may hinder the student's progress and careful teacher support.

In this paper, we propose the Co-KCA method as means to assess design learning and teaching activity performed in codesign learning sessions, known as "critiques" (Or "crits"). The method provides a detailed description of the performance of each participant. This is a development of the former KCA method [3, 4] that enables assessing the design learning performance of individual learners under the conventional (non-codesign) studio approach. The strength of the method is in assessing longitudinal learning processes. We propose that the description provided by the Co-KCA method can reveal a longitudinal performance of multiple participants and thus support design pedagogy in codesign settings. The method successfully tracks both learner's performance and tutor support, an underexplored topic that holds promise to improve teaching strategies. We applied the Co-KCA method to codesign sessions performed using a multi-user codesign VR system that allows multiple designers to experience a sense of presence in their design representations and actively design through 3D sketching. Collaborative VR systems were found advantageous for codesign learning in terms of active designing and ideation, showing potential in becoming an important tool in design pedagogy that increasingly utilises digital representational tools during design activity [5].

This paper aims to introduce the Co-KCA method and to explore its use to measure design-learning in tutor–student codesign situations at the studio. We applied the method to the learning processes of three students, comprising twelve codesign crit sessions. The results point to a tutor's dominancy in design performance and clear evidence of the learners' active design practice. The analyses yielded fine-grained information and provided evidence of the method's capacity in analysing design-learning processes in the context of codesign studios, which tend to become highly complex as many participants are involved.

Design Activities Through Codesign

Design can be described as an iterative process of skilful activities meant to achieve a desired solution that will create a change in an existing setting. It is a complicated process that encompasses a large variety of considerations and calls for the orchestration of multiple design activities. These activities include *analysis*, *synthesis*, and *evaluation* [6]. Accordingly, *analysis* activities concern exploring and framing the problem, setting goals, and identifying shared traits or anomalies. *Synthesis* activities use information already analysed to create a solution, expressed as a new form or as changes made to one of its components. By transforming problem situations into solution situations, synthesis activities prove to be of considerable value to design endeavours. *Evaluation* activities consist of various queries made by the designer regarding the ability of an artefact (or a specific component) to achieve the desired goals or arrive at a satisfying state. In response to evaluation activity, goals can be changed. Consequently, new goals can be set and lead to another cycle of design activity. Throughout the process, reasoning rules that result in modifications in the artefact are applied to a former design decision, considered a design *development* activity [7]. Design development is considered to consist of *divergent-convergent* modes of activity [8], often associated with creativity and design progress [9]. *Divergence* refers to associative thoughts or creating alternatives able to expand one's attention. *Convergence* refers to thoughts that focus attention [10]. In the context of design, divergence refers to the development of a single design decision in more than one trajectory, resulting in additional decisions. Convergence forms a new decision from two or more existing decisions, resulting in greater detail or a new relationship [8].

Design is considered a constructive activity that relies on prior knowledge and discovery [11]. In codesign, knowledge is co-constructed, as multiple participants are simultaneously engaged in the situation, applying design activities, and developing the design issues made by peers [12]. When the participants work closely to progress the design, the process is considered a close-coupled codesign. The knowledge of each participant plays an important role in the design progress [12]. Accordingly, each participant applies design activities individually, relying upon personal knowledge, allowing other participants to change their understanding according to the added knowledge.

The Representational Ecosystem for Supporting Codesign

Communication allows all participants to become informed of the proposed design issues and evaluate them to achieve further progress. For that purpose, the design process occurs over a Representational Ecosystem [13] that includes various representational tools, allowing designers to communicate concepts or information (Fig. 1).

Design representations convey the relevant and essential characteristics of a particular message concerning the artefact's features. They thus form the essential "glue" that connects the activities of design one with another [14]. Examples demonstrate

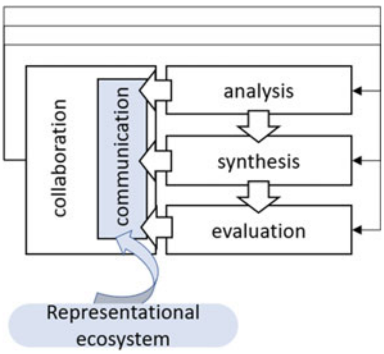

Fig. 1 Design activities applied during codesign with the use of a representational ecosystem. After Kalay [14]

the role of representations in stimulating design ideas and design progress [15, 16] and in the performance of divergent-convergent activities [8]. Conversational and representational design activities intertwine in relation to the representational tool [17].

The representational ecosystem is more than a medium for communication. They reflect the designer's capacity to apply design activities, operating design tools, and visual literacy. Comparing non-designers, novices, and expert designers revealed that experts triggered more issues from design representations than the other participants, expertise that assisted them in further design development [18]. This suggests that in codesign situations, each participant's capacities can be reflected in the design representations created during the session while also affecting further progress.

Digital representational tools are advantageous for codesign by expanding the traditional tools to allow real-time communication with other participants. In this scope, VR systems comprise unique characteristics that make them adequate for supporting codesign situations. VR systems enable users to experience an illusion of being present in the design project (alone or together with others) during a situation as conveyed by the computational display [19], making it possible to navigate in a digital representation or to create and develop 3D artefacts by modifying them. 3D sketching enabled by collaborative VR systems was found particularly important for codesign, for allowing multiple users to rapidly represent design ideas in 3D and better discuss them with others [5]. These characteristics make collaborative VR systems highly suitable for constructivist learning that relies on active practice through real or simulated ad hoc situations [20].

Design Learning Through Codesign Critiques

Design crits form an eminent part of the learning process of the design studio. Crit activity includes tutor–student social modalities of interaction in which the learner's artefact is being assessed (e.g., group crit or a one-to-one desk crit) [21]. Thoroughly described by Schön [2, 22], learning occurs through the active practice of design activities, and active listening and seeing a tutor's demonstration of design activity, which lead to learning through imitating the tutor. Representational activities during design crits were found to support the development of concepts and learners' comprehension [23]. In this sense, the tutor's representational activity has considerable value in the learning process. The studio was criticized for being teacher-centred [24] and for ambiguity in the teaching methods [25]. These arguments have support as studies found the tutor's verbal dominance in design crits [26, 27].

Facing these shortcomings, the codesign approach emphasizes a social modality of a close-coupled tutor–student collaboration during crits [28]. Dillenbourg [29] describes collaborative learning as a small, ad hoc educational situation where collaboration is seen as a pedagogical component responsible for effective learning. In this sense, learning through codesign entails a co-construction of knowledge for both tutor and student, taking place through the mutual development of a design solution. It follows that the use of design representations during codesign crits has an important educational purpose, as it allows students to learn through active practice and tutor demonstration in a close-coupled codesign process. In addition, tutors use their proficiency to decode the information embedded in the representations designed by the student, identify errors, and stimulate further progress. This suggests that *the production of a representation or its modification* can serve as evidence of knowledge construction activity. Accordingly, activities produced by students indicate learning through active practice, and activities produced by the tutor indicate learning through active tutor demonstration. The development of a participant's design issue (e.g., a tutor develops the student's issue) indicates that a close-coupled activity took place.

Learning at the studio is a longitudinal process that lasts several weeks to several months. A student may develop a design issue after several crits, demonstrating the practice of iterative design activity. A similar activity performed by the tutor serves ground for learning through imitation. Tracking learner-tutor design activity throughout multiple sessions is therefore essential to assess close-coupled learning activity.

Design-Learning Assessment Through Co-KCA: A Proposed Method

Methods of Design Learning Assessment

The abovementioned studies show that feedback concerning the performance of different participants during codesign crits and throughout the learning process is essential for providing adequate tutor support and learning progress. However, since most learning assessments at the studio are project-based [21], students and tutors do not receive such feedback. This is consistent with De la Harpe et al. [30], who reviewed studies on the architectural studio, art, and product design. Project-based assessments mainly concern the quality of the artefact developed during the learning process. A successful artefact may imply one's general state of competency, yet it does not show which design activities require further practice, thereby limiting the tutors' ability to address the student's strengths and weaknesses as they support learning. In addition, project-based assessments do not provide information concerning each participant's performance, resulting in a lack of feedback on how a close-coupled performance was achieved.

In contrast to project-based learning assessments, research proposes methods designed to study the activities applied during the design process and not specifically to design-learning, making it possible to assess one's proficiency in applying certain activities. Nevertheless, these methods offer high-grained feedback concerning the activities and processes occurring mostly in professional practice and some studies during studio crits while providing limited information regarding longitudinal design processes that commonly happen during design learning.

Linkography

Linkography [31, 32] provides a high-grain description of design activity through a *move* and *link* structure. A recognised idea or its modification introduced during the design process is identified as a *move*. A link between moves represents design development. Moves and links are identified in the design exchanges explained through think-aloud and protocol analysis techniques. Applied to the studio setting, Linkography was used to trace critical moves (carrying numerous links), revealing the contributions of the different crit participants, establishing teaching profiles [26], and identifying the interactions that took place under different representational tools [33]. Van der Lugt [34] and Hatcher et al. [35] proposed categories describing moves and links, making it possible to trace the performance of specified activities. Designed to analyse the design process to its micro-steps of changes, a Linkograph depicts a single design event or very few ones. It does not show how a certain move may affect moves in other sessions, as often occurs in design-learning processes.

The Function-Behaviour-Structure (FBS) Ontology

The FBS ontology identifies the cognitive activities formalised verbally during the design process [36, 37]. The method identifies the domains of a design issue and processes applied to these domains involving their modification. It is widely used to analyse design studio crits, including diverse expertise of industrial design and mechanical engineering students [38] or tutor–student communication in architectural studio crits [27]. An explorative study compared the distribution of FBS issues generated by tutors and students using the conventional representational ecosystem and a collaborative VR system during codesign [39]. The findings highlighted the tutor's conversational dominance during VR sessions while also pointing to increased student engagement. Recently developed, the situated FBS model expands to account for different participants and their activity over their peer's design issues [40]. Like Linkography, the FBS method focuses on high-grained activity, thereby limiting the ability to track longitudinal learning processes. A single code, "Design description", refers to the moment in the exchange when the designer mentions a representation or produces one. This code does not distinguish between a verbal mentioning and an observable representational activity, making it impossible to track active practice and a tutor's demonstration.

Design Conversations

The method identifies verbal exchanges and collaboration patterns formalised in codesign, showing how ideas become mature [41]. The method conducts in-depth analyses accounting for verbal exchanges, gestures, and active representations. Five elements are defined as measurements for tracking the conversation, including verbal *naming, constraining, negotiating, proposing and decision-making* and representational illustrating or gesturing, coded as *moving* [41]. Focusing on the learning process through codesign studios, Boudhraâ [28] added the learner's *observation* in the tutor's demonstration and *presentation*, seeing them as relevant educational components. The study showed that observation played a dominant role during crits, indicating the value of tracking the teacher's demonstration. Evidence of gestures accompanying verbal exchanges and moving while using different representational contexts allowed identifying the context's role in supporting students during codesign activity [42]. Designed to analyse high-grained activities in codesign, the method has limited capacity for analysing longitudinal learning processes.

Knowledge Construction Activity (KCA)

The KCA method [3, 4] provides detailed feedback on the design activities performed during the learning process, namely design-process and design-development activities. The method aggregates the design activities presented during crits with the educational settings used into measurable KCA units, including the crit's social modality and the representational ecosystems used in the spatial educational setting. Figure 2 (Left) illustrates the multiple properties coded in each KCA unit. With respect to Linkography [31, 32], links between KCAs describe design development as illustrated in Fig. 2 (Right). The learner's design decision in the form of a design representation is identified as a KCA unit. A modification of an existing representation is identified as design development and coded as a link between the source of a former KCA and the target of a new unit, allowing to measure progress through the number of links generated. The method allows measuring the number of source KCAs that carry multiple links, considered design divergence, and the number of target KCAs considered design convergence. The method generates a graph that describes the learning process practised through a single design project. Seen in Fig. 3 is a graph of the learning activities presented at each crit by a single student during a four-month studio course that used two different representational ecosystems (VR setting and non-VR setting), demonstrating the method's capacity to analyse longitudinal learning processes.

The KCA method is independent of the educational setting used during the learning process, making it possible to use the method for studying design learning in different settings. Studies using the KCA method coded the activities occurring during an entire semester in a course that used two different spatial settings,

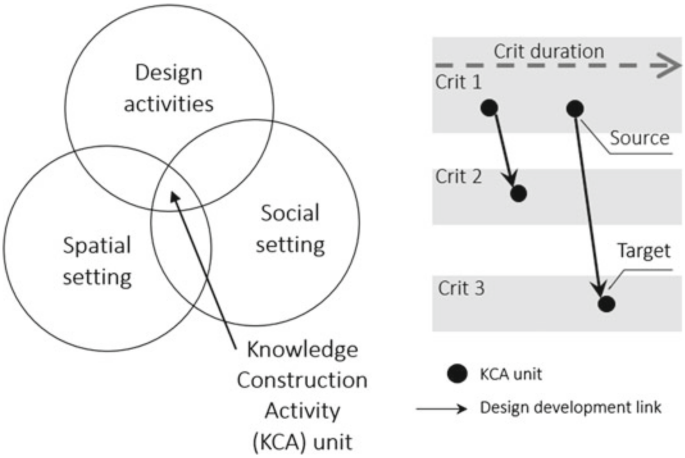

Fig. 2 A knowledge construction activity unit (Left) and design development links (Right)

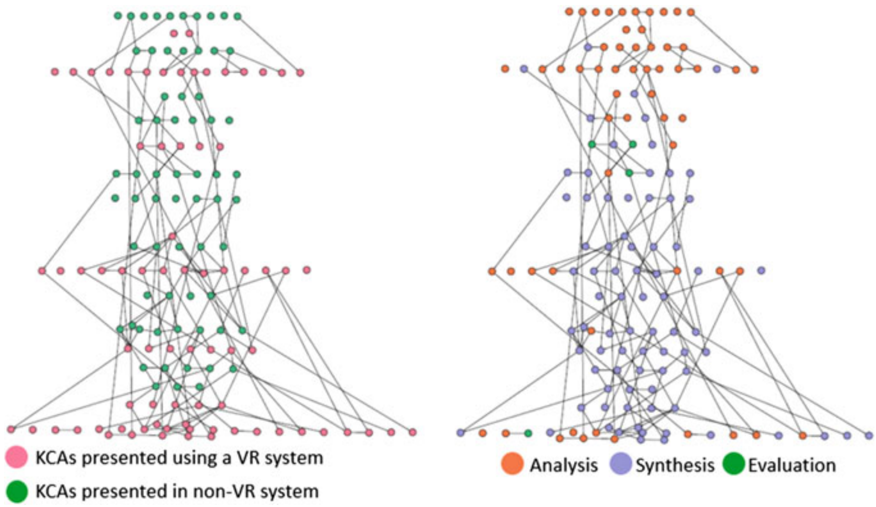

Fig. 3 A single learner's KCA learning graph coded in a full semester course that used VR and non-VR. The graph presents the KCAs generated in each setting (left) and the type of design activity coded in each KCA (right). *Source* [4]

revealing increased learning activity performed in the VR setting compared to the traditional setting in terms of synthesis design activity [3] and design convergence [4]. Evidence of iterative cycles of divergence-convergence activity in students' performance measured [43] provides detailed feedback of each learner's achievements, information that can assist the tutor in encouraging learners for further practice. Designed to assess how different educational settings affect learners' performance, the KCA method focuses on the activities prepared by a single student to be presented in a particular setting, being unable to track active practice occurring during crits, nor the performance of different participants as happens in codesign.

The Co-KCA Method

This paper proposes the Co-KCA method, as means to provide feedback on design learning and teaching activities through codesign. The Co-KCA method expands the KCA method by coding each participant's performance of KCAs and links, making it possible to track individual and collaborative activity during codesign crits. Observable evidence of a design issue in the form of a design representation, presented and created during crits by each participant, is used to identify Co-KCAs and developmental links. A newly introduced design issue or a modification of an existing one, performed during a crit, is registered as a Co-KCA. Figure 4 illustrates the properties coded in a Co-KCA unit (Left) and design development links (Right). Each Co-KCA unit includes three domains (Fig. 4 (Left)). A modification of an existing unit, seen in the form of a modified representation, will be coded as a link between the new and the modified units (Fig. 4 (Right)). Vertical links (directing right or left) represent a modification applied to a Co-KCA from previous crits, allowing for tracking the activity during the crit and throughout the course, as often happens in studio courses.

The method allows for tracking the properties that characterize each *Design issue* (Table 1): *Social setting* refers to the participant that actively generated the design

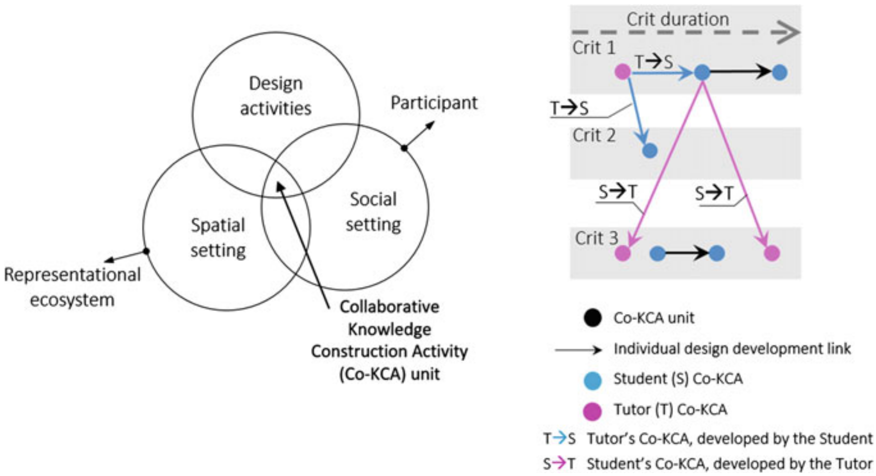

Fig. 4 A Co-KCA unit (Left). Each unit includes the activity performed by a specified participant, and the representational ecosystem involved. Links represent the design development made by each participant (Right)

Table 1 Co-KCA coding properties in a single Co-KCA unit

Co-KCA properties	Description	Code
Unit identifier	Chronological identifying number	Co-KCA-1
Design issue	Description of the issue presented, or created during the crit and the modification applied to an existing issue	
Social setting	The participant who performed the activity	Student (S) Teacher (T)
Spatial setting	The representational ecosystem used	System X
Design activity	The design activities required to be learned through practice and taught through demonstration	Analysis, Synthesis, or Evaluation
Session identifier	The crit number where which the activity took place	1, 2 …. *n*

issue. Differing from the KCA method, Co-KCAs can be produced by different participants, generating a graph of a close-coupled activity. *Spatial setting* refers to the representational ecosystem used. *Design activities* refers to the educational content that is expected to be practised in the studio course, namely design-process activities [6]. The types of design activity are identified according to the purpose of the representation, as described by the participant who generated it: (a) Representing the existing context, problems or goal are identified as an *analysis* activity; (b) Representing a solution in the form of an artefact, or one of its components, is considered a *synthesis* activity; and (c) The assessment of the existing context or whether the proposed artefact meets its goals (e.g., size) is identified as an *evaluation* activity. Describing each design issue and the modification applied to existing issues allows for determining links (Table 2).

The coding method of links codes information about collaborative development (Table 2):

- T → S is coded when a student develops the tutor's activity, serving evidence of a learner's active practice of collaborative activity.
- S → T is coded when a teacher develops the student's activity, serving evidence of a tutor demonstration.

The strength of the method is found in the capacity to track the design activities occurring during codesign crits as well as the development occurring in a discontinuous order after several crits.

Table 2 Links' properties

Links	Description	Code	Comment
ID	Chronological identifying number	1	
Source	The chronological number of the source Co-KCA unit	Co-KCA-1	Registered automatically
Target	The chronological number of the target Co-KCA unit	Co-KCA-3	Registered automatically
Individual development	An observable modification of an existing Co-KCA done by the same participant	Null	
Collaborative development	An observable modification of an existing Co-KCA done by a different participant	S → T	Is registered when the tutor develops a student's Co-KCA
		T → S	Is registered when the student develops a tutor's Co-KCA

Case Study

To demonstrate how the Co-KCA method can be applied to assess learning processes in codesign, a case study is given from a codesign studio, taught at the 3rd year, School of design, University of Montreal (Canada). Following the codesign approach, all sessions encouraged active tutor-learner designing. Three students were monitored in twelve codesign crits. A single tutor participated locally in all sessions and one tutor from the domain of Ergonomics at the University of Lorraine-Metz (France) joined remotely as a guest during three sessions. All sessions had a similarity in crit duration (around 30 min).

All sessions took place at the collaborative VR system, Hyve-3D [44] (Fig. 5), which allows for multiple users, local and remote, to actively codesign through the use of 3D sketching using handheld tablets. The guest tutor joined remotely through another equal system. The Hyve-3D allows for a life-size representations and active participation through affine transformations of imported 3D geometries (copying, pasting, moving, rotating, scaling) and sketching in 3D. Designed to support codesign, the system allows for rapid 3D sketching in a similar manner to 2D hand sketching while expanding it to include 3D sketching and endless navigation possibilities. 3D sketching is enabled as users change the tablet's position, which serves as a 3D cursor drawing area and add complementary orthogonal 2D views to the drawing on the tablets [44]. Navigation is done with the tablet used as a 3D trackpad [Ibid] (Fig. 5).

We used Gephi [45] software to code the multi-criteria information described in Tables 1 and 2 into Co-KCA units and design development links, and analyse the learning graphs generated. In this case study, coding was done by a single coder.

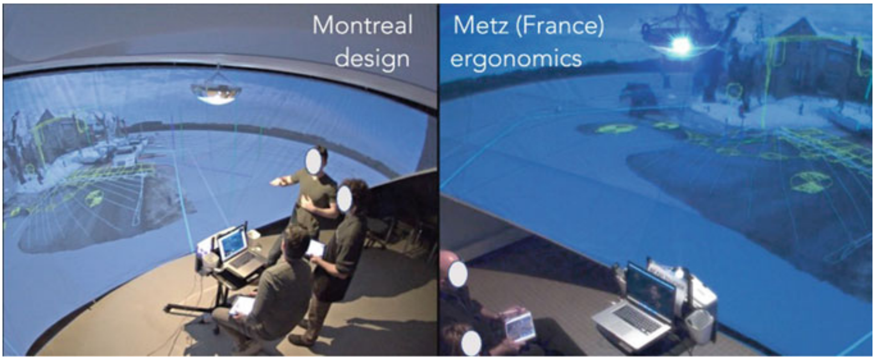

Fig. 5 A Codesign crit at the collaborative VR system (Hyve-3D) in Montreal (left) and Metz (right)

Preliminary Results

This section presents examples that demonstrate the capacity of the Co-KCA method in tracking design-learning and teaching activities in codesign. Figure 6 depicts the full graph of representational activities generated in student S.03's sessions.

The method's capacity to describe longitudinal learning processes is demonstrated in capturing design development occurring across crits. Seen in Fig. 6 is a single unit (Co-KCA-08), generated in Crit no. 1 that is developed after two crits, indicating iterative activity practised by the student. As the tutor (T) generated the original unit, it is possible to see that the tutor's design issue stimulated further learner activity, filling its role in the learning process. A similar example is tracked as Co-KCA-32 (Crit no. 3) is developed by the student to Co-KCA-37 in the following Crit no. 4.

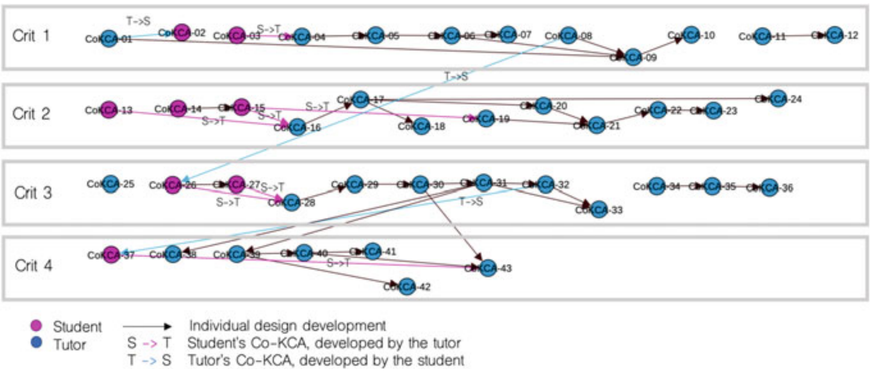

Fig. 6 A Co-KCA graph of Student S.03. Analysis of a longitudinal learning process is demonstrated through tracking design development over multiple crits

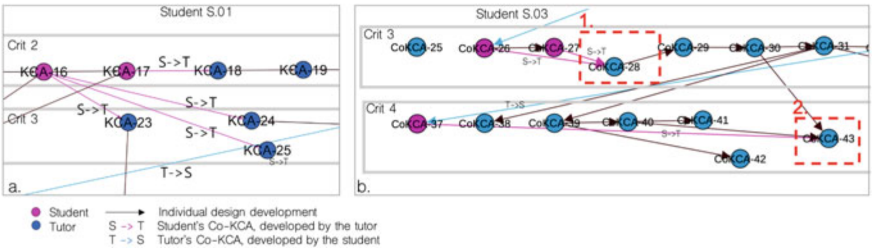

Fig. 7 Tracking design divergence, **a** made by the tutor from a single student unit (student S.01, Crit no. 3). Co-KCA-16 is developed to Co-KCAs 23, 24, and 25. Tracking design convergence in student S.03 sessions, **b** made by the teacher from two student unit during a single crit (1), and design convergence involving Co-KCAs from the previous crit (2)

Figure 7 demonstrates evidence to track the collaborative practice of divergence-convergence development, considered essential for design progress. Seen in Fig. 7a is divergence, identified as a single unit (Co-KCA-16), generated by the student, is developed into four additional units (Co-KCA-17 and 23–25). Co-KCA-17 was developed by the student applied to his former unit (Co-KCA-16), demonstrating practice in design development, and Co-KCA-23–25 were developed by the tutor, indicating a tutor demonstration of design divergence. Figure 7b depicts two examples of design convergence as a single Co-KCA is generated out of several former units. The first (no. 1) is done by the teacher (Co-KCA-28), who converged two of the student's decisions (Co-KCA-26 and Co-KCA-27), indicating a teacher's demonstration. The second (no. 2) depicts a unit (Co-KCA-43) that is converged out of former units generated during a former crit (Co-KCA-30) and the current (Co-KCA-37 and Co-KCA-40), demonstrating an iterative activity performed over more than a single crit, commonly expected during a learning process.

Co-KCA Analysis

The amount of 137 Co-KCAs and 114 design development links were coded in three Co-KCA graphs, one for each student. Table 3 depicts the percentage of Co-KCAs generated during the learning process of each student and the teaching support given in the process. Evidence of Co-KCAs generated upon each other's Co-KCAs indicates that a close-couple activity took place. As shown in Table 3, the tutor is dominant in all sessions in terms of applying Co-KCAs, indicating tutor demonstration. Different from a conversational tutor dominancy, widely seen in previous studies and considered undesired tutor-centred learning, these new results present a dominancy in the tutor's representational performance (Table 3), considered an essential educational component [22, 23]. The low student participation, seen particularly in students S.02 and S.03s' results, may indicate the need to encourage additional practice.

Table 3 Co-KCAs generated during the learning process of each student

Student	Co-KCAs	Student (%)	Tutor (%)
S.01	44	34.1	65.9
S.02	37	21.6	78.4
S.03	43	21.6	78.4

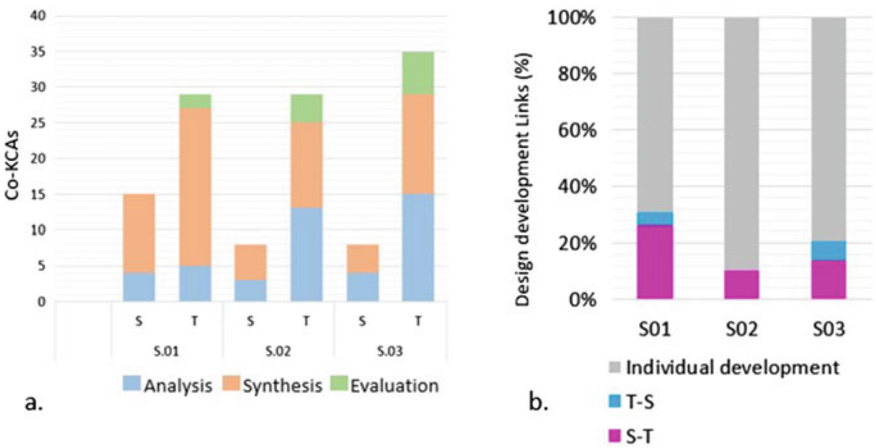

Fig. 8 Co-KCA analysis **a** distribution of Co-KCAs according to the type of design activity practised during each student's learning process. S-student. T-teacher. Design development analysis **b** distribution of design development links generated by each participant

We measured the type of design activity (Fig. 8a), and the design development (Fig. 8b) practised during the learning process of each student. Students S.02 and S.03 practised a few synthesis and analysis activities. None of the students practised the evaluation activity.

The tutor's generation of Co-KCAs of the three types of design activity (Analysis, Synthesis and Evaluation) serves as evidence of demonstrating these essential skills to the students. Seen in Fig. 8b is the distribution of links developed during the learning process of each student. The results point to dominance in individual development, implying the need to encourage collaboration considered important in codesign learning [28, 29]. Evidence of S → T and T → S indicates a close-coupled process. The results seen in students S.01 and S.03 show that the students developed the tutor's design issues, indicating the active practice of collaborative development. On the other hand, student S.02 had no T → S links, which may indicate the student's tendency for individual practice rather than a close-coupled one. The remote guest tutor that attended three crits did not introduce any representational activity, resulting in no Co-KCAs from his part. Although the guest tutor contributed to the learning process through verbal exchanges activity, the method reveals a lack of active demonstration through representation, which is considered an essential teaching component [23]. This can be explained by the fact that the guest, arriving from the domain of

Ergonomics, had no representational skills. The issue demonstrates the limitation of the Co-KCA method in describing the knowledge constructed during crits, derived only from the focus on representations.

Discussion

This exploratory study presented the Co-KCA method as means to analyse design-learning processes in codesign crits on three students.

The preliminary study demonstrated the design-learning and teaching activities that can be analysed and measured with the aid of the Co-KCA method, including design-process activities, design development, and divergence-convergence modes of development, all considered essential in gaining design knowledge. The method's capacity to represent each participant's performance on self and peer-generated design issues provides detailed feedback on the different roles of participants in codesign, such as tutor demonstration or learner's active practice. The use of design representations as evidence for design activity limits the coding of design activity done through verbal exchanges or gesturing. However, it expands the limitations of existing Linkography [31, 32], FBS [36, 37] and the Design Conversations [41] methods by describing the type of representational activities generated by each participant and their development during a particular crit or across a few crits.

The small number of sessions monitored in this study provides limited feedback concerning the learning process in codesign. Furthermore, in this exploratory study, since only one rater was coding Co-KCAs, no interrater reliability test was done. In future works, a kappa statistic will be used for such interrater test to provide more consistency to this method, extending that the data are correct representations of the variables observed, and so, by more than one coder. However, the preliminary results show the premise found in using the Co-KCA method to achieve this target. The results showed evidence of the learners' active practice of synthesis and analysis types of design activity, supported by a tutor's demonstration of all activity types. The dominance found in the tutor's activity demonstrates its important role in active demonstration, considered essential in studio pedagogy [22, 23]. The mutual tutor–student development seen in all the learning processes serves as evidence for co-construction of knowledge, considered important in collaborative educational settings [29] and the codesign studio [28]. Evidence of learner Co-KCAs and developmental links during crits seen in all three learning processes demonstrate an active practice of design activities, considered essential for gaining design proficiency. Only a few of the tutor's Co-KCAs were developed by the students. Such feedback can help the tutor to better engage a student in the activity to achieve better practice, serving thus as an educational tool to foster customised learning.

The focus on a collaborative VR system, done in this study, is derived from the educational potential these systems hold for supporting constructivist learning [20], design learning [3, 4], and codesign between collocated and remote participants [5], which expand the possibilities for inter-disciplinary and inter-university collaborations. Future steps should develop the method to account for knowledge arriving from non-design disciplines during design crits, through verbal exchanges and gestures, to allow the integration of these systems in multi-disciplinary codesign situations.

Conclusions

The Co-KCA method provides a detailed description of the design-learning process through codesign. The strength of the method is found in its capacity to analyse longitudinal learning processes, as it can represent the development of particular design issues throughout multiple crits.

The method's use of representational design activities as evidence of learning corresponds with the educational approach of the studio [2]. It responds to the shortcoming of existing learning assessment methods used in design pedagogy [21] and research [31, 32, 36, 37, 41] by providing an additional layer of information concerning the learning performance at the studio, depicting the activity during design crits and throughout multiple crits. Considering that the introduction of new representations or their modification is essential for design progress and learning comprehension [23], the method's capacity to analyse such performance demonstrates a relevant value in supporting customised and learner-centred teaching. The expansion of the formerly developed KCA method [3, 4] to account for the performance of multiple users enables analysing individual and collaborative learning processes, demonstrating a potential to analyse more complex codesign situations that comprise multiple participants carrying different roles. Considering the small sample in this exploratory study, no representative conclusions can be drawn regarding the learning performance in codesign. Due to the demonstrated success of the method in describing such performance, future research will apply the method to a larger scale experiment.

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Revisiting Darke: Tracing the Emergence of Design Generators in Architectural Design

Yu Cao, Yuval Kahlon, and Haruyuki Fujii

The notion of a 'primary generator' (PG), proposed by Jane Drake, refers to a self-imposed broad objective that drives designing. PGs are important for designers as conceptual compasses for navigating design problems. Therefore, it is essential to understand how they are employed in designing. As most accounts of PGs are retrospective, they may exclude momentary events which are central to explaining human designing. Capitalizing on Darke's hint regarding the interactive nature of formulating and using PGs (consistent with recent studies on situatedness in design), we examine the ways in which PGs drive design in real-time. A close analysis of a design task results in an elaboration of the original concept, revealing a set of action patterns that are potentially generalizable to other design tasks. These serve as a step in systematically modeling such processes, towards their implementation in computational design systems.

Introduction

In the 1960s, the first generation of design research focused their efforts on creating frameworks for understanding designing as a rational activity [1]. Consequently, non-rational aspects of designing, such as subjective evaluation, took a minor role in design research [2]. In a pioneering attempt to account for the ways in which non-rational subjective factors shape architectural design processes, Darke [3] has proposed the concept of a primary generator (PG). Generally speaking, PGs are sets of goals or concepts that architects derive, on the basis of value-judgements. For example, an architect may see the site of a future building and say that he/she would like to 'preserve its quality of openness'. Adopting this perspective as a basic

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motivation for designing may have a strong, global impact on the resulting design, pushing it in a certain direction. In this image, design is seen as a linear process, which goes from requirements to an artifact. Yet, since real-world design processes are generally non-linear, the course of designing often shifts based on the current situation. Therefore, in human design processes certain redirection is often needed. Our research question is – how can we model and understand the dynamics of using primary generators, in design? We explore this question by carefully tracing PGs, in the context of architectural design activity.

Considering the complexity of such processes (see next sub-section), we set out to visualize them, as a means for making sense of this phenomenon. To do so, we documented couples of designers as they engaged in a simple architectural design task of designing a building façade. Our analysis enabled to trace certain sources and effects of PGs, from which we derived patterns of reasoning in design. This has enables us to begin and elaborate the concept of PG into sub-types, as originally hoped by Darke.

Primary Generators and Design Interpretation

Primary generators are widely discussed and differently interpreted in design literature [2, 4]. This work draws on Darke's original definition, in her famous 1979 article [3], which stipulates that a PG is: (1) a broad initial objective which drives designing; (2) self-imposed by the planner; (3) usually strongly valued on a subjective basis; (4) can be explicit or implicit.

PGs are deeply rooted in human design activity, as beautifully reflected in Frank Lloyd Wright's famous work—Fallingwater. The client requested Wright to design a weekend house with a view of the waterfall, however Wright placed the house above the waterfall. He thought it would be better to merge the house with it, so that it can be experienced through sound (rather than visually). Since the desired manner of experiencing the waterfall is a value judgement (facilitating further actions) which depends on a self-imposed interpretation of the latent need in the client' s original request, the above instruction can be read as a prompt for choosing a PG and acting upon it.

The power of PGs as a driving force in design activity can be readily understood from the perspective of interpretation, which is a major sub-process in designing [5]. First, since PGs can be seen as a reflection of the designer's standpoint with respect to the design problem, they facilitate further interpretation, which then drives seeing and action [6]. Second, the mere formulation of a PG implies a certain view of the design problem, which in-itself can be seen as an interpretation of the design situation. Due to this tight relation with interpretation, approaching PGs from this perspective may yield deep insights into the ways in which they are formulated and used. Considering the complexity of interpretation processes (see next sub-section), tracing the actual usage of PGs is obviously a challenging task. To approach it, we draw on state-of-the-art models for situated design and design visualization, as explained below.

Modeling and Visualizing Interpretation as a Situated Activity

Our goal is to visualize and understand the dynamics of PGs in design. Various approaches to design visualization exist, such as a tree-structures consisting of 'creative segments' [7] and timelines consisting of activities, sketches and problems/solutions [8]. Linkography [9], for example, suggests visualizing design processes using graphs of 'design moves' (operations on knowledge that change the situation) and 'links' (connections between moves). As a basis for forming such graphical representations for design visualization, researchers commonly use protocol analysis [10] by employing a codification method of choice [11]. This enables the construction of a shared vocabulary for recognizing critical patterns. In this study, we draw on the idea of design moves and links from linkography, and codify events based on the situated function-behavior-structure framework (situated FBS) [12], introduced below.

We view the formulation of a PG as an event which is interpretive in nature. According to Tversky et al. [13], the formation of an interpretation can be decomposed into two main steps: (1) perceptual reorganization in which we mentally represent the artifact under a certain gestalt; (2) finding meaningful interpretations that may be assigned to the artifact or its component based on this representation, thus relating external and internal reality. How can we model the complex dynamics between the designer's mental world and external reality, which the usage of PGs entails?

One of the three major paradigms for studying cognitive processes in design is the situated cognition paradigm [14]. The famous descriptions of designing as a 'see-move-see' process [6] or as a 'conversation' between the designer and the design representation [15] fall under its umbrella [16], which emphasizes the interactive nature of the activity. The essence of studies on situatedness in design is nicely captured in Gero's saying: "where you are when you do what you do matters" ([16], p. 236). Note that, rather than a mere indication of the physical space one inhabits, 'where' should be understood in a broader sense which includes the totality of the actual circumstances that the designer is found in.

It assumed that the formulation and utilization of PGs can be seen as a sequence of situated acts [17], and thus modelled using frameworks for situated design. More specifically, in the situated FBS framework, Gero and Kannengiesser proposed to distinguish external from internal reality in design, by positioning the activity within three worlds: external (concerning things outside of the designer) versus interpreted and expected (both concerning the designer's views with relation to the former) [12]. We draw on their work in codifying and organizing our data, as a basis for visualizing the dynamics of PGs.

Motivation

This research seeks to deepen our understanding of the way design processes are navigated by human designers, towards the enhancement of computational design systems. The work presented here focuses on PGs as interpretive devices, and the ways they affect the course of designing. We are motivated by Darke's implicit suggestion that the formulation of a PGs should be understood as a continuous process rather than as an isolated event: "By becoming aware of ideas that are acting as generators, the designer may be able to evaluate them and widen their range if necessary" [3] (p. 39). By this view, understanding PGs requires a close examination of the dynamics which characterize their formulation and usage, attempted in this study.

Objectives and Scope

Our main objectives are: (1) collect evidence for PGs which emerge during the design process, (2) visualize how these drive the interpretation and design result, (3) extract patterns of using PGs in design, (4) identify types of PGs based on their contribution to the design process.

As this is an initial inquiry into this topic, we concentrate on PGs' relations with structures and functions (see the 'Method' section), which are central to processes of interpretation. Consideration of the concept of behavior (another component of situated FBS [12]) is thus suspended to reduce complexity, with the aim of integrating it into further studies.

Significance

This research contributes to our understanding of PGs by extending previous work through the lens of situated cognition [18]. The importance of this study is twofold: (1) it deepens our understanding of design cognition, by elaborating the important concept of PGs, and (2) it provides a list of behavior patterns associated with PGs, which may be applicable to other design tasks. As such, the work may contribute to research on design cognition, which is important from a theoretical perspective.

Method

Preliminary Trial

We set out to devise a task which will enable to closely observe the formulation of PGs. As a preparatory test, we asked two designers to work together and develop a building complex of design offices and residences. The expected output was a set of sketches concerning the general layout etc. We encouraged them to talk freely and recorded both their conversations and their sketching process (the setting of two designers collaborating was assumed to be more natural for capturing utterances than the traditional 'think aloud' method, which requires pre-training from participants; [9], p. 28).

The preparatory test was helpful in several aspects. First, it helped to focus our efforts on a specific aspect of interpretation – we observed that often one shape or a group of shapes in a drawing were associated with more than one function, by linking it with an architectural element [12]. For example, doors can both separate rooms and preserve people's privacy. Second, several shortcomings were identified: for example, the design task was overly complex and time-consuming, and the lack of constraints made comparing the designs difficult. Based on these observations, we devised our task, as explained below.

Task

We utilized the findings from the initial trial to carefully devise our design task (see Fig. 1). Specifically, the task was designed so that we can observe how certain elements (structures) are interpreted by assigning them with meaning (in the form of function).

To minimize the workload of the designer, we simplified the design tasks. The task demanded participants to work together and design a façade of an architectural office, given some initial information such as site conditions, design requirements, and so on. Our subjects were encouraged to imagine an actual site, the architects' relations, and so on at the start of the design, to establish a sense of a realistic situation.

Additionally, to decrease the complexity of the design while still leaving room for creativity, designers were required to design using a set of predetermined modules. The initial modules were basic shapes without any given meaning, and the designers were allowed to give the modules any meaning they see fit. The modules were available in four different sizes, two different hues of gray, and two different orientations. The designable area consisted of a site segmented by a 10×21 grid. Finally editable tags and lines were given for annotation purposes.

Further, 'façade' and 'modules' helped us to focus on the interpretation of visual representation as architectural elements, as these can be seen as 'function bundles'. Concentrating on façade design allowed the designers to consider both visual and

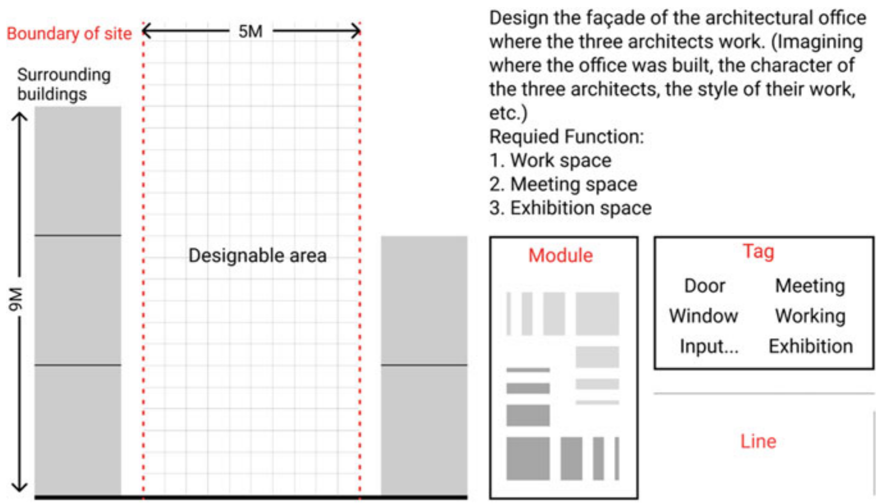


Fig. 1 Interface of design experiments in Figma (English version)

functional aspects, as the façade consists of architectural elements that reflect the visual appearance of the building, which then hint at functional aspects. Accordingly, the design task provided a rich setting for interpretation, in which specific elements which were interpreted could be directly related with specific referents by using modules (as opposed to sketches which have unclear boundaries etc.).

Finally, the abstract building façade composed of these modules aided to reduce the discussion of 'behavior' in the design process. Since 'behavior' in FBS ontology [12] is often related to concrete measurements or performative aspects which are derived after an interpretation has been established, it was seen as less central to such an initial study, which can be attended to in more advanced phases (compared with 'structure' and 'function' that are directly linked to the interpretation process itself).

Participants and Setup

Since participants are expected to have some shared knowledge of architectural design and a capacity to externalize their ideas, students with at least three years of architectural education we recruited for the study. We requested participants to work in pairs to complete a design in 45–60 min, so as to allow them to express their thoughts naturally and develop more innovative ideas. The experiment was carried out with the cooperation of 18 participants (in 9 groups).

Since the initial trial was conducted at the outbreak of COVID-19, we resolved to conduct later experiments remotely. We chose to utilize Figma (a co-design platform) for real-time designing and Google Meet for conversation. Participants took part in the experiment using their computers in a stable online environment. The flow of our experiment was (1) invite participants to Google Meet and Figma; (2) conduct a 5-min tutorial on how to place modules in Figma; (3) conduct a 10-min introduction on the design task; (4) start the experiment and video record the participants' design process and conversation; (5) conduct an interview on the design process and the motivation behind the design after the design session.

Data Processing

First, recorded sessions were converted into transcripts, cleared from irrelevant utterances for simplification (such as "hm"), and anonymized. The transcripts were then broken down into sentences based on the architectural elements and specific functions proposed by participants.

Second, we cross-referenced the transcript with the video and searched for the occurrence of PGs. Since there is no formal definition of PGs, to improve accuracy, we identified PGs by matching events in the design process with the description of PGs given by Darke. For example, in our 7th experiment, the designer suddenly said that 'how about we make all the things vertical?' and the idea of 'vertical' fitted the 4-point description of PGs introduced earlier in this paper. Furthermore, we checked the interviews with designers after the design session to validate our judgments.

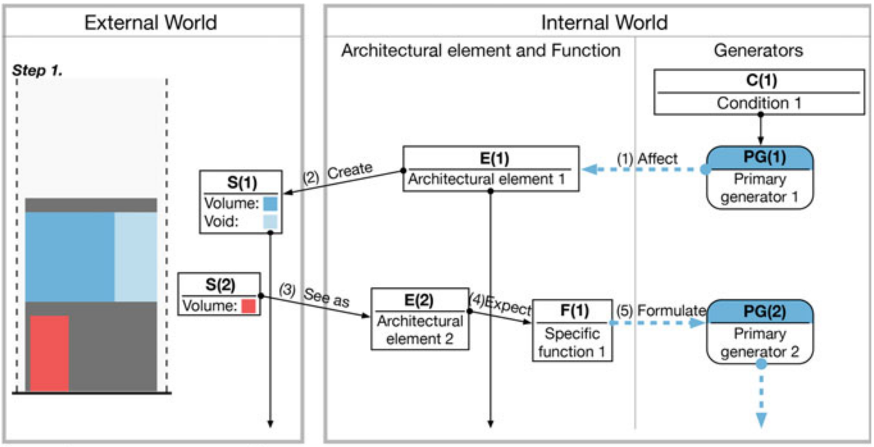
Third, to provide a rich (yet concise) account of PGs, we selected four representative episodes by reviewing the PGs contained in each. Our selection was made in such a way that: (1) the impact of PGs on the design process is clear; (2) we have different levels of complexity to present the diversity of PGs in a limited space. For example, episode 2 (in the 'Results' section) clearly demonstrated not only the 'spatialized' PG but also the complex interaction between the two PGs, and was thus selected.

Finally, we coded the design events in representative episodes. Based on the insight of the preliminary test and Gero's initial definition [12], we further defined 'structure' as a visual representation including a module or a group of modules and 'function' as an architectural element with multiple sub-functions such as 'a window', or a specific function, such as 'I can see the mountains through this'. We followed this process: (1) extract the events about architectural elements and specific functions in the transcript; (2) extract the visual representations corresponding to the events in the video; (3) arrange the events and the visual representations in chronological order; (4) relate them by arrows and annotate the arrows with descriptive words.

Visualizing the Effects of PGs on Interpretation and Designing

Interpretations link the internal and external worlds. PGs are contained in the interpreted world but serve as drivers of design at a holistic level, in such a complex situation, building a basis for discovering patterns can benefit from visualization of their relationships. Accordingly, we made a distinction of internal and external worlds, and divided the internal world into two subcategories, ‘architectural elements and functions’ and ‘generators’. In Fig. 2, ‘S(x)’ in the external world is a structure, and ‘x’ in ‘S(x)’ is a serial number. In the internal world, ‘E(x)’ is an architectural element, and ‘F(x)’ is function. To show an interaction between entities over a longer time span, we used ‘P-E(x)’ as previous element and ‘P-F(x)’ as previous function. In the subcategory-generators, ‘PG(x)’ stands for primary generator [3] and ‘C(x)’ stands for initial condition.

Lines were utilized to indicate the connections between entities. The possible path of causation was highlighted with arrows. Notice that the descriptions on the lines (create, see as, etc.) were auxiliary for explaining the connections between entities. We did not prepare these descriptions in advance. Rather, while creating the diagrams, once we a useful descriptions was found we used it and gradually refined



Label	Term	Definition
S(x)	Structure	Shape or a group of shapes which is a visual representation of design.
	e.g. S(1)' in Ep. 1:	*Reduce eight 1m*1m modules from S(1) (derive form video).*
E(x)	Architectural element	Collection of functions which is an internal presentation of Structure.
	e.g. E(1) in Ep. 1:	*“And then, on the third floor are the rooms of three architects (contains many potential functions).”*
P-E(x)	Pervious element	Architectural element that appeared in the previous design process.
F(x)	Function	Specific function which is an internal presentation of the Structure.
	e.g. F(1) in Ep. 1:	*“Its function is not to work, but to be a living space for the architect (a specific function).”*
P-F(x)	Pervious function	Specific function that appeared in the previous design process.
C(x)	Condition	Piece of information from the beginning of the design process.
	e.g. C(1) in Ep. 1:	*“The site is in Ikuta (a suburb area in Kanagawa, Japan).”*
PG(x)	Primary generator	Self-imposed broad objective that drives designing.
	e.g. PG(1) in EP. 1:	*“Isn’t Ikuta a suburb? I think it should be a “field” in the suburbs (in coherence with surrounding).”*

Fig. 2 Visual representation of an episode using our mapping approach; the division into design worlds as well as the structure–function distinction follows the situated FBS framework [12]

our coding scheme. Each line was tagged with a number to show the sequence in which it appeared (identical numbers represent events that occur at the same time). When entities influenced or were influenced by a PG, the connection between them was emphasized by dashed lines. Additionally, screenshots by groups of shapes near each 'structure' entity were remade for a clearer viewing, and special colors were used to indicate different parts of visual representation.

Simplifying Diagrams and Extracting Patterns

After visualizing the changes in interpretation and the influence of PGs during the design process, we could obtain a very rich picture of the designer's cognitive process. To further focus on the influence of PGs on the design, we simplified the original diagram of the episode.

In the simplified diagram (see the middle of Fig. 3), we referred to all designs, including visual representations, architectural elements and specific functions, as D. PG stood for the primary generator and C stood for the initial conditions including site conditions, the design task, initial objectives and so on. Both D and C could be the sources for the formation of PG. When D was changed because of PG, we added a new component D' to represent the modified design. Then, we placed each component in chronological order, from top to bottom, as in the original diagram. Finally, we used arrows to indicate the source and target of the impact and added serial numbers on the side of the arrows to indicate the order of occurrence. In addition, we used customized visual elements to show the unique characteristics of PGs in a simplified diagram.

The simplified diagram enabled to easily see the general influence of a PG on the design. However, since all the components were scattered across time, it was difficult for us to visualize the continuous interaction between the components. Therefore, we decided to emphasize the relationship between the components (especially the design D and PG) by omitting the process of iteration from D to D', thus unifying the design D and the modified design D' into one component in the same space–time. Then, we extracted the relationships and order represented by the arrows in the simplified diagram and made the pattern of the episode (see the right of Fig. 3).

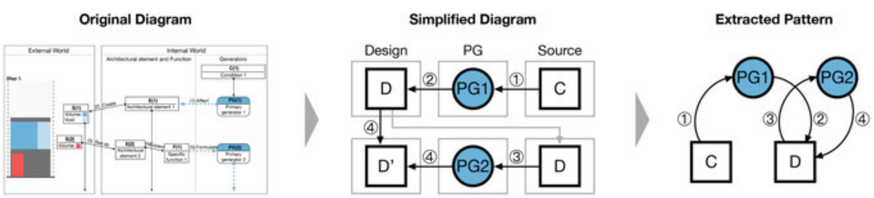


Fig. 3 The process of simplifying diagrams and extracting patterns

Results

We explain various episodes in some detail, and by focusing on the way in which the final structure (appearing at the bottom left of each figure) resulted from previous interpretations, and in turn how these can be related to the PG in the design process. Following this, to further focus on the influence of the PGs on the design and show the unique characteristics of PGs, we present simplified diagrams from the original diagrams of each episode and the extracted patterns.

Episode 1—Rooftop Field in Suburb

As a first example, see Fig. 4 in which the designers began by setting the site in a place called Ikuta C(1) found in Kanagawa, Japan. In a retrospective interview, one designer reported that Ikuta gave him a suburban feel, and made him want to make the building in coherence with its surroundings PG(1), which played an implicit role in his design process. He did not mention the PG(1) and did not propose any architectural elements or specific functions related to it at the beginning. However, when they considered the specific function of the rooftop garden E(2)', he suddenly proposed to cultivate plants F(2) on the rooftop, and to name the roof garden as 'rooftop field' E(2)". The observer inquired about this change during the retrospective interview, in which the subject revealed that his decision to create the rooftop field was driven by a latent image of idyllic landscape associated with the suburb.

In the simplified diagram of episode 1 (Fig. 5, left), in the beginning of the design process, the concept of 'coherence with its surrounding' was formulated as the PG from the site condition, but did not influence the design immediately, and remained somewhat implicit (represented by a PG with dotted circle). Later, the PG suddenly became explicit (a PG with solid circle) and drove the designers to convert the rooftop garden D to a rooftop field. Based on the simplified diagram, we extracted a pattern of the transformation of PG from implicit to explicit. (Fig. 5, middle).

Episode 2—Vertical and Horizontal Windows

As a second example, see Fig. 6. The designers saw the previously designed door E(2) as 'vertical', so one designer came up with an idea to make all the architectural elements 'vertical' PG(1). The designers were strongly influenced by this concept when designing the columns between the windows on the 1st floor E(3) and the vertical windows on the 1st floor E(1)'. After some time, when the designers designed the vertical windows on the 2nd floors E(4) and saw the windows on the 1st floor E(1)' again, they decided to go for a window that was 'different from the others' F(1),

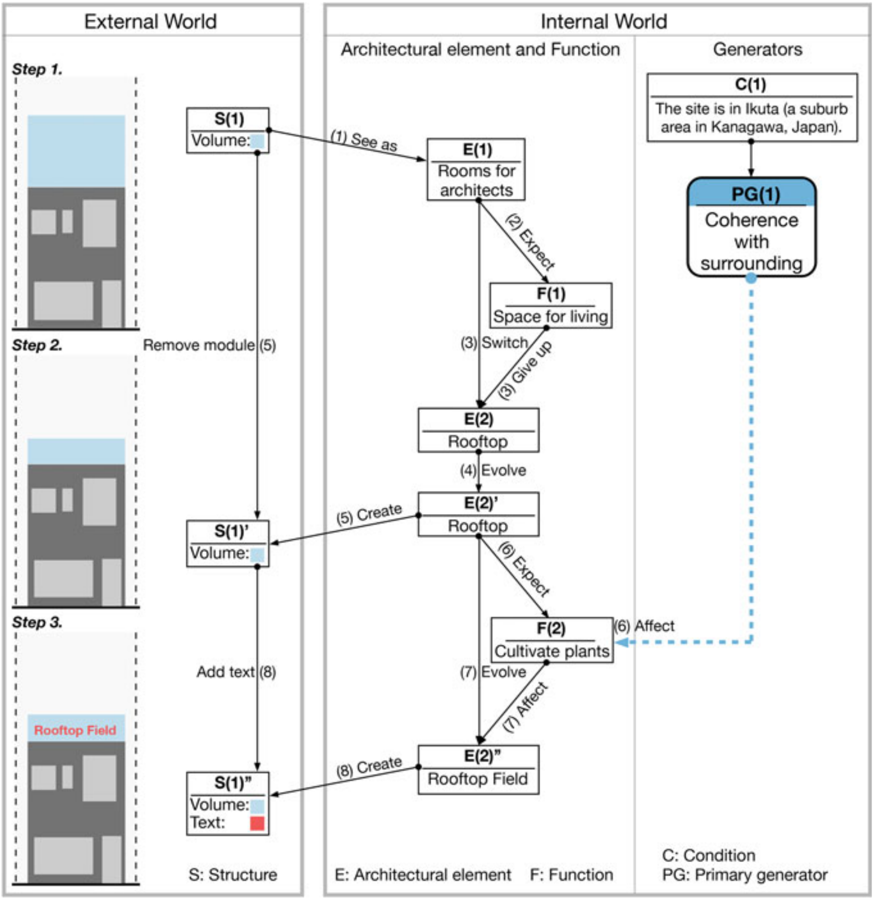


Fig. 4 Episode 1—rooftop field in suburb

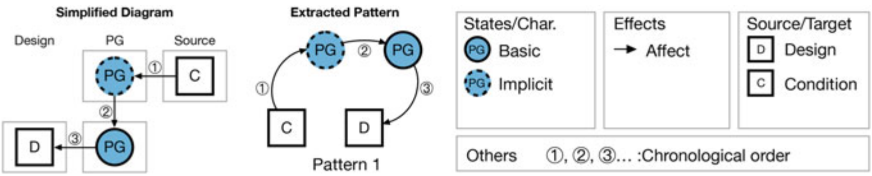


Fig. 5 Simplified diagram and extracted pattern in episode 1

and came up with a new concept 'horizontal' PG(2). Driven by this new concept, the designer made the horizontal windows on the 3rd floor E(5).

In the simplified diagram of the first half of episode 2 (Fig. 7, left), the concept of 'vertical' was formulated as the PG from the vertical door in the design D. Unlike broad, abstract concepts, this PG was concrete and focused on spatiality (represented

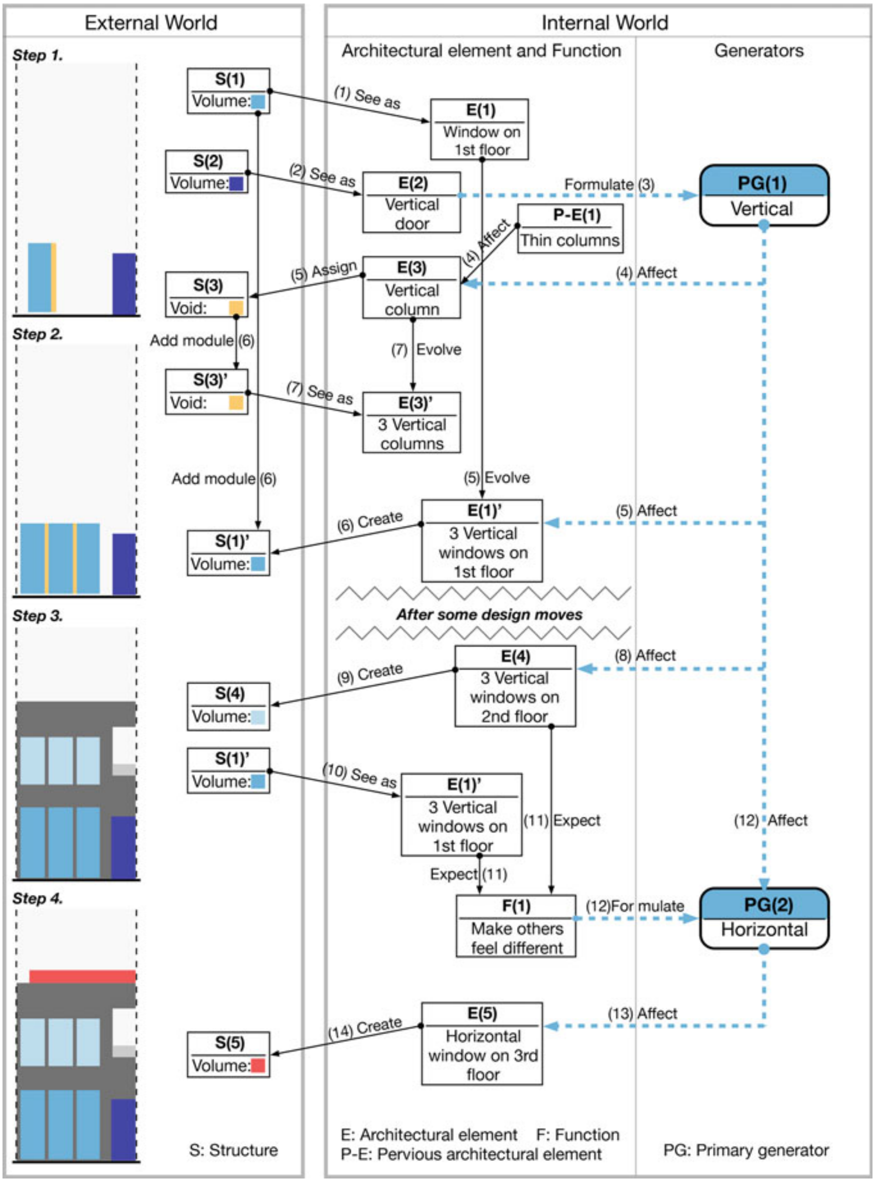


Fig. 6 Episode 2—vertical and horizontal windows

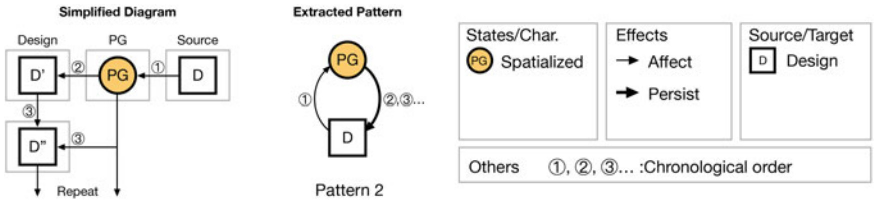


Fig. 7 Simplified diagrams and extracted patterns in the first half of episode 2

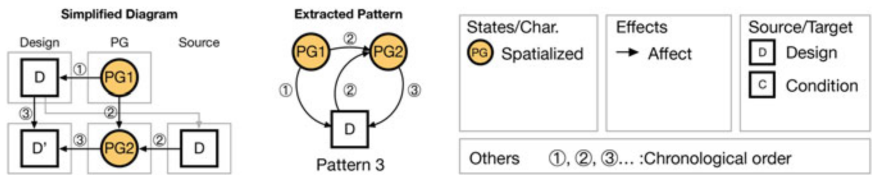


Fig. 8 Simplified diagrams and extracted patterns in the second half of episode 2

by a PG in yellow). This PG served as a strong driving force (represented by a thick line) which influenced design repeatedly and continuously, driving the designers to design the vertical columns and the vertical windows and so on, creating the new design D'. Based on the simplified diagram, we extracted the pattern of PG influencing the design repeatedly and continuously (Fig. 7, middle).

In the simplified diagram of the second half of episode 2 (Fig. 8, left), the PG1 'vertical' influenced the design D and made almost all elements become vertical. Therefore, the designers wanted to do something new in design, coming up with the new PG2 'horizontal' based on PG1. Both PG1 and PG2 were concrete and focused on spatiality (represented by a PG in yellow). The PG2 drove the designers to design a horizontal window on the 3rd floor, creating the new design D'. Based on the simplified diagram, we extracted the pattern of one PG influencing the formation of another (Fig. 8, middle).

Episode 3—Frame-like Terrace

As a third example, see Fig. 9. At the beginning, the designers found that there was a height difference between the two buildings around the site C(1), and suggested to take advantage of the site's features PG(1). Following this, it was suggested that a terrace E(1) could be designed on the third floor to connect the different heights of the left and right buildings. Then, the designers found that the columns on the left and right side of the building E(2) looked like a frame, and formulated a new concept 'frame-like' PG(2). Influenced by this concept, they proposed that a horizontal roof could be added to the terrace E(1)' to form a closed frame.

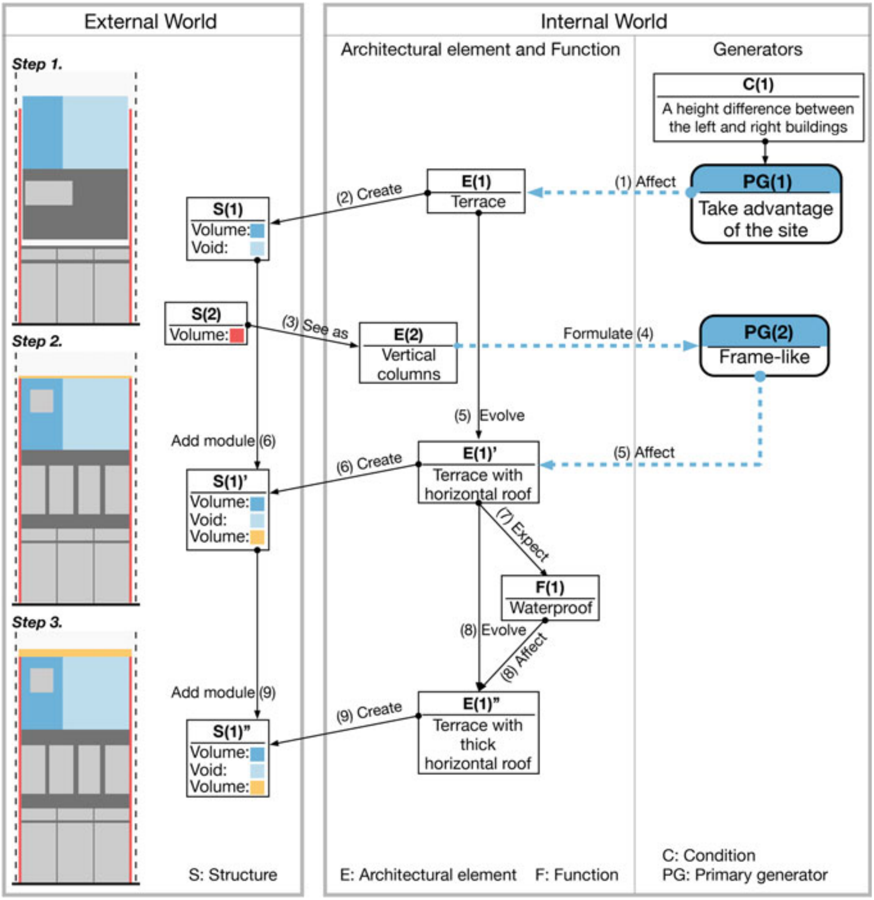


Fig. 9 Episode 3—frame-like terrace

In the simplified diagram of episode 3 (Fig. 10, left), the concept of 'take advantage of the site' was formulated as the PG1 from information of the design task. The PG1 drove the designers to add a terrace in design D. Then the PG1 became dormant (represented by a PG with gray circle) and stopped affecting the design. The concept of 'frame-like' was formulated as the PG2 from vertical columns in the design D, focusing on spatiality (represented by a PG in yellow). The PG2 drove the designers to add a horizontal roof on the terrace, forming new design D'. The terrace in design D' still retained the influence of PG1, so it could now be seen as PG1 co-contribute (represented by a dotted line) to the design with PG2, even though PG1 was dormant. We extracted the pattern of one PG influencing the design and another also contributing to the design, in a collaborative manner (Fig. 10, middle).

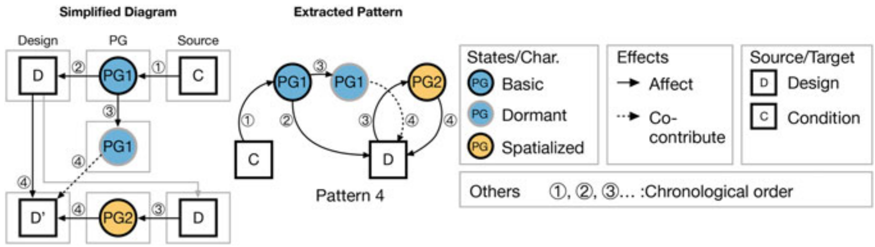


Fig. 10 Simplified diagram and extracted pattern in episode 3

Episode 4—Vertical Windows Coherent with Surroundings

As a fourth example, see Fig. 11. Here, the designers were driven by the concept 'vertical' PG(1), which lead them to design a vertical window on the 2nd floor E(1). However, when examining it as a part of the building E(1)', they found that the window would reveal the true height of the 2nd floor, in contrast to their initial objective 'making the building coherent with its surroundings' PG(2). To hide the true height of the 2nd floor F(1), they designed a square window E(1)". After some design moves, the designers realized that this square window was not in line with the concept of 'vertical' PG(1), so they wanted to find a way to make the window vertical F(2) and also hide the true height of the 2nd floor F(1). Finally, the designers chose to extend the window in a different direction than before, and designed a vertical window on the 2nd floor E(1)"'.

In the simplified diagram of episode 4 (Fig. 12, left), the PG1 'vertical' which focused on spatiality (represented by a PG in yellow) drove the designers to design a vertical window in design D. The concept of 'coherence with its surroundings' was formulated as the PG2 from the designer's initial objective, which did not match the design D influenced by PG1, driving the designers to create a new design D'. However, the new design D' did not match the PG1, pushing the designers to create a solution D" that matches both PG1 and PG2. Based on the simplified diagram, we extracted a pattern of two PGs actively influencing the design in a competitive manner (Fig. 12, middle).

Modeling PGs in Designing

We extracted the characteristics of PGs and the transformation process of PGs from the five patterns. Then we constructed our visualizations with condition and design as the PGs' source and target, to show a rich picture with the least number of components.

In the model, we used different circle-shaped elements to represent the four states/characteristics of PG. Then we used squares to represent the possible sources

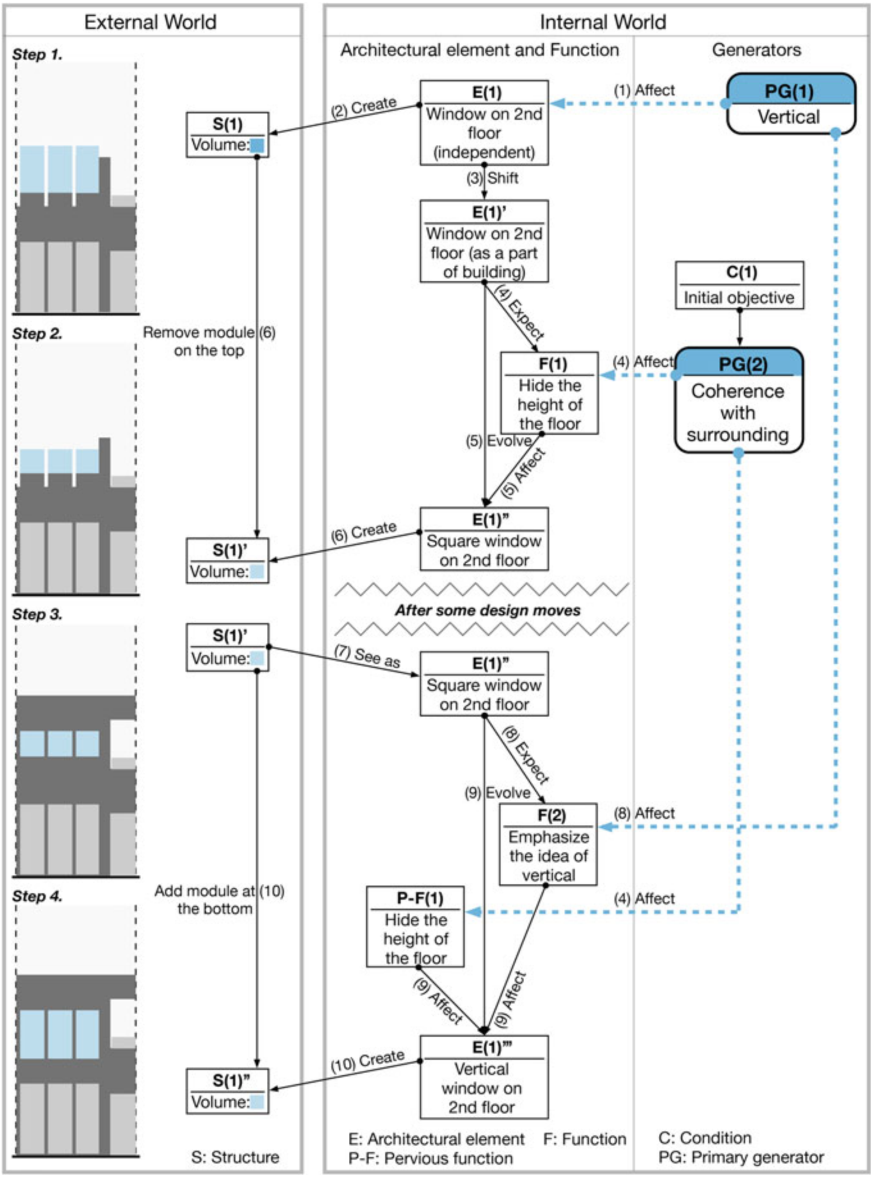


Fig. 11 Episode 4—vertical windows coherent with surrounding

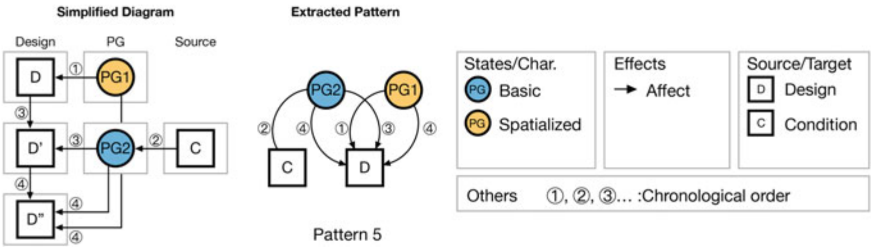
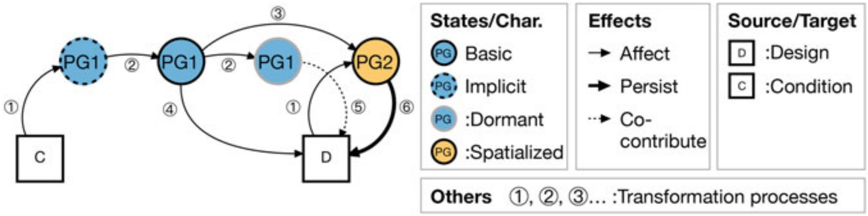


Fig. 12 Simplified diagram and extracted pattern in episode 4



Category	Term	Description
States/ Characteristics	Basic	PG is consciously employed by the designer to drive design activity
	Implicit	PG exists in the background but is not noticed by the designer for some time
	Dormant	PG has influenced the design in the past, and can potential to influence in the future (was not eliminated by designer)
	Spatialized	PG that has an spatial aspect when formulated
Source/ Target	Design	Product of the designer's thinking in the form of a visual representation, describing functions/behaviors/structures
	Condition	Initial information, including site conditions, design tasks, initial objectives, etc.
Processes	①Formation	PG is formed from design or condition
	②Shift	Change of state of a PG
	③Propagate	One PG contributes to the formation of another PG
	④Affect	PG influencing the design in a noticeable manner
	⑤Co-contribute	Several PGs affect the same design element in a non-contradictory manner
	⑥Persist	PG that repeatedly influences the design

Fig. 13 Model of PGs in the design process

of PGs and arrows with different lines to show transformation processes between source-PG, PG-design, and PG-PG (Fig. 13).

Discussion

Based on our analysis, Darke's original notion of a PG was elaborated into:

- four characteristics of PGs (basic, implicit, dormant and spatialized)
- two possible sources (condition, design)

- six transformation processes (formation, shifting, propagation, affecting, co-contributing, persisting).

Further insights are now drawn from our inquiry, and on the basis of the above. First, with respect to the sources of PG, two categories were derived from the empirical data: (1) conditions, i.e. initial information, including site conditions, design tasks etc.; and (2) design, i.e. current situation, including the existing visual representations, architectural elements, and specific functions which designers focused on. We observed that PGs which came from initial conditions tended to be more abstract and broad (e.g. 'coherence with its surroundings') whereas PGs which emerged from the design (during the design process) tended to be more concrete and spatialized (e.g. 'vertical' and 'frame-like'). This poses a question regarding the relations between the time of appearance and the nature of the PG, which begs for further inquiry.

Second, in a related study, Suwa et al. [19] have empirically established a two-way relation between unexpected discoveries and the invention of issues or requirements in design, noting that requirements "invented" in specific situations may become central to the design process. In our study, complex interactions between PGs were observed in our patterns consisting of multiple PGs (patterns 3, 4, 5). For example, pattern 3 revealed that one PG influenced the formation of another. Since this was not pre-planned, and due to the contribution of PGs for framing (and thus for setting requirements), such an event may be seen as an invention on-the-fly. It is important to point out that various such relations between PGs can be observed already in this initial study. For example, pattern 4 reflects a "collaboration" of two PGs while pattern 5 shows a sense of "competition". Due to its unexpected nature, we believe that such interaction between PGs may be one source for reinterpretation (since concepts are triggered), which is of great importance to creative discovery in design.

Third, while the generator-conjecture-analysis model proposed by Darke [3] was described as iterative, it was nonetheless sequential and thus somewhat linear. However, this view is challenged by our observations regarding how PGs emerged, transformed and contributed to the design process in quite complex ways, as discussed above. On this basis, we believe that the original generator-conjecture-analysis model may be reconsidered, such that it includes multiple conjectures which are developed and tested in parallel, and interact in various ways.

Finally, this study may help to clarify the relationship between Darke's PGs and Dorst's related concept of a 'design frame' [20]. Dorst considers a PG as a kind of initial frame which the designer possesses. However, rather than an initial frame, the authors suggest that a PG is better seen as an *abstract type* of frame (or 'meta-frame'), for several reasons: (1) as hinted by Dakre, PGs do not have to appear at the beginning of the process—and in fact, as demonstrated in the findings, they may result from one's actions and perceptions; (2) since PGs relate with personal judgements, preferences etc. that rest on subjective grounds regarding things that the designer generally values, they tend to be much less concrete than what is usually referred to as a frame; (3) finally, a PG seems to enable one to select many possible frames to look at the design problem through it. For example, if a PG is a desire for 'coherence with surrounding', as we saw in episodes 1 and 4, the designer may employ a frame of a ‘building which enables to cultivate plants’ (episode 1) or ‘keeping the floors at the same level with other buildings’ (episode 4). Both frames fit well with the original PG, and therefore the PG can be seen a larger container in which other frames are nested and selected.

Conclusion

An approach for systematically tracing and visualizing PGs was proposed and demonstrated. By visualizing the relations between PGs and their sources we: (1) elaborated the original notion into four states/characteristics, and (2) described several patterns of formulation and transformation between them. We suggest that future work focus on: (1) exploring the interactions between the proposed types of PGs, as well as identifying additional ones; (2) evaluating the generalizability of the proposed patterns in broader contexts, on the basis of empirical data from different design tasks.

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Design Cognition—2

Inspirational Stimuli Attain Visual Allocation: Examining Design Ideation with Eye-Tracking

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Inspirational stimuli may be used to support the design process. This article aims to elicit new insights on the impact of inspirational stimuli on design ideation with eye-tracking technology. We replicated a design ideation experiment's methodology [1] but collected eye-tracking data and a think aloud protocol. Preliminary results of eye-tracking data demonstrate that inspirational stimuli influence participants' eye movements and visual allocation. Specifically, participants examine inspirational words significantly more than neutral words—and participants examine design problem statements significantly more in absence of inspirational stimuli. We also observe distinct individual visual search strategies. Experimental procedure, data, and code are openly available to facilitate further replication efforts.

Introduction

Visual stimuli affect designers during concept generation [2], facilitating [1] or hampering [2, 3] design ideation depending on the visual stimuli's type and timing. To support design processes, visual stimuli may e.g., serve as "inspiration", which is often sought by designers. If visual stimuli are "inspirational," how does it affect designers' visual allocation? Will designers devote more visual attention to inspirational stimuli?

This work uses eye-tracking technology to obtain further insight into visual stimuli's effect on idea generation by replicating the task, stimuli, and experimental procedure of a design ideation experiment [1] (referred to as "the original study"

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throughout this article) that investigated whether inspirational stimuli of varying analogical distance to the problem space influence design concept generation.

The original study tasked participants to generate concepts for open-ended design problems and found that inspirational stimuli increased idea fluency [1]. Compared to control stimuli, inspirational stimuli both nearer and farther from the problem space facilitated participants to produce more ideas, and the effect was most prominent after a period of time. Moreover, functional magnetic resonance imaging (fMRI) data suggested two different activation patterns of brain regions. Two search strategies were coined accordingly: The *inspired internal search* activates brain regions associated with memory retrieval and semantic processing—herein, participants likely recognize the inspirational stimuli as helpful or applicable to the design problem. The *unsuccessful external search* increase activation in brain regions associated with directing attention outwards and visual processing—participants likely continue searching the problem space for an inkling. Control stimuli generally produce unsuccessful external search while near stimuli produce inspired internal search. Far stimuli exhibit features from both strategies.

While inspirational stimuli evoked different brain regions and facilitated participants to generate a greater number of ideas, it remains unknown whether these ideas were different from ideas produced in control conditions and which words were most conducive to the "inspired ideas." These unknowns constitute the research objectives of this work, warranting the collection of two new data sources. To learn whether ideas are different with and without inspirational aid, we added a think aloud protocol to the experimental protocol. To determine the most conducive (or "inspirational") words and investigate if they impact the visual allocation of participants or participants' perception, we used eye-tracking.

This article investigates designers' eye movements during ideation; it addresses the following questions; if visual stimuli are "inspirational," how does it affect visual allocation; will more visual attention be devoted to inspirational stimuli?

This article aims to provide new insights from eye-tracking; it presents a preliminary analysis of eye-tracking data, specifically, the differences in visual allocation between stimuli. The results show that participants examined inspirational words significantly more than control words; and that design problem statements were examined significantly more in the absence of inspirational stimuli. We moreover observe distinct individual visual search strategies. Exhaustive analysis of eye-tracking data and transcription of the think aloud recordings will be presented in future publications.

Background

Scientific advancement relies on the core principles of reliability, repeatability, and ultimately reproducibility, as do experiments. However, more often than one might think, experimental results are not replicated, or they fail to replicate due to a lack of information or other unforeseen factors. In the Open Science Collaboration's replication efforts, 32% of original results yielded insignificant results in combination with new data [4, 5]. This is a part of science's broader problems, further exacerbated by publication bias [5, 6].

Replication is a challenge to design cognition's future, a future that simultaneously holds repeated testing of predictions (or results) as a key opportunity [7]. These are closely related, and when taken together, they actualize replicability. Replication is both an opportunity to- and necessary for improving reproducibility, since irreproducible results may occur even within studies of exemplary quality due to random or systematic error [4].

We advocate for minimizing a potential replication crisis in design research and for providing replication studies with a positive connotation (our impression is that replication studies are frowned upon). Thus, this work replicates previous research's methodology [1] while gathering new data sources, and is thus a replication and extension study.

Eye-Tracking Technology

Eye-tracking measures record eye movements and gaze location over time and task [8]. The first record of eye-tracking dates back to 1823, and it was until recent technology advancements an expensive and effortful method. Today, eye-tracking is more affordable and accessible due to video-based eye-trackers [8, 9]. There are two main types of video-based eye-trackers: table and head-mounted configurations [8].

These eye-trackers shine an infrared light at the eye, not visible to humans, and illuminates it. Eye-facing cameras record the infrared light's reflection, which produces a corneal reflection and the pupil center through a bright or dark pupil effect [10]. The corneal reflection appears as a glint on the eye. When the infrared light is aligned with the camera's optical axis, the pupil's reflection is directed towards the camera producing the bright pupil effect. When the infrared light is not aligned with the camera's optical axis, the pupil's reflection is directed away from the camera, thus producing the dark pupil. The gaze position can be calculated by using the location of the corneal reflection and the pupil center.

Eye-Tracking Data

Eye-tracking data are time-series data sampled at a given frequency yielding the gaze position [8]. When the gaze rests (or fixates) at the same target for a period of time, these gaze points can be aggregated into a *fixation.* Fixations consist, therefore, of both a duration and gaze position. Fixation lengths vary and are usually within the range of 180–330 ms [11]. The rapid eye movements between fixations, occurring when scanning the visual space and moving the eyes, are called saccades. Herein, the visual input is suppressed [8, 11]. Some eye-trackers can also measure pupil dilation.

Eye-Tracking in Design Ideation Research

Design research uses eye-tracking to investigate visual reasoning in design activities [12]. Similar design ideation tasks with eye-tracking have explored differences between beginning and advanced design students during idea generation using stimuli of varying distance from the problem space, but used images as stimuli [13]. The Alternative Uses Test (AUT) has been used to investigate the relation between eye movements and idea output (creativity); participants were presented with images of 12 objects, and listed alternative uses of the object (i.e., ideated) for 2 min [14]. Eye-tracking and AUT have also been used to explore differences between designers and engineers in idea generation [15]. We have not found other studies investigating the effects of inspirational word stimuli during design ideation with eye-tracking.

Experimental Method

This experiment differed from the original [1] in using head-mounted eye-tracking technology and the think aloud protocol as an additional task. Here, participants were seated at a desk in front of a monitor, equipped with a conventional computer mouse and keyboard to indicate new ideas and submit questionnaire ratings. Participants in the original experiment lay supine in the fMRI, used a response glove to indicate ideas and provide questionnaire ratings, and did not think aloud.

Participants were tasked to develop as many ideas as possible for 12 different open-ended design problems and instructed to "think aloud" by briefly explaining their idea in a think aloud protocol. Five words were presented along each problem in two blocks for 1 min each, totaling 2 min of ideation time per design problem. The three first words were presented in the first block (called Wordset1), whereas the remanding two words were also presented in the second block (called Wordset2), i.e., the second block displayed all five words. A 1-back memory task was performed between blocks. Participants were exposed to three conditions: Near, Far, and Control. Words near or far from the problem space served as inspirational stimuli in the Near and Far conditions, while the Control condition reused words from the problem statement. See the original paper for an exhaustive description of the task, design problems, and word stimuli [1].

Participants were sequentially assigned to one of three counterbalanced groups of specific problem-condition pairs in the experiment's repeated measures design.

After each problem, participants rated the words' usefulness and relevancy, and the developed solutions' novelty (uniqueness) and quality. The number and timing of generated ideas were collected continuously.

Participants

None of the N = 24 healthy adults (18 male/6 female, 22 right-handed/2 left-handed ages 23–35, mean = 25.8 yrs., SD = 2.9 yrs.,) participating were native English speakers. Since glasses might interfere with the head-mounted eye-tracker, no participant wore glasses, but eight used lenses. We recruited through internal channels and contacts at the Norwegian University of Science and Technology (NTNU). Participants were graduate-level students or higher (minimum 4th year MSc, PhDs) at the Department of Mechanical and Industrial Engineering (MTP) and the Department of Design (ID) to ensure similar educational background as original participants. Monetary compensation was not given.

Experiment Procedure and Calibration

First, participants received general information in Norwegian about the experiment, its procedure, and the task, and gave informed consent. Then, after fitting participants with the eye-tracker, it was 3D calibrated according to manufacturers' "Best Practices" [16]. Thereafter, the experiment commenced by providing information, explaining the design ideation task, and the 1-back again. Finally, participants answered a demographic survey after completing the 1-h experiment.

Hardware

The experiment ran on a conventional desktop computer with a 24 in. monitor, a conventional keyboard and mouse, and a head-mounted eye-tracker from Pupil Labs [17] with binocular setup (cameras on both eyes). See specifications below. Participants were seated in a chair approximately 70 cm from the monitor, see Fig. 1. A microphone was placed on a tripod in front of participants.

Higher accuracy in eye-tracking data may be acquired by using a chin rest. We were interested in areas, words, and patterns as a whole, which means sub-word accuracy was not necessary. We thought a chin rest might restrict participants and/or increase or induce a Hawthorne effect or other expectancy biases. A chin rest was therefore not used.

Hardware specifications:

- Desktop computer: Dell OptiPlex 7050, OS: Windows 10 Education 64-bit, CPU: Intel Core i7-7700 @ 3.60 GHz, RAM: 32 GB
- Monitor: Dell UltraSharp U2412M, Size: 24″ (61 cm), Resolution: 1920 × 1200 pixels, Refresh rate: 60 Hz
- Microphone: Zoom H1 Handy Recorder, fs: 48 kHz, Bit rate: 16 bit, Channels: 1 (mono recording)

Fig. 1 Experimental setup

- Eye-tracker: Pupil Core, World cam. Resolution: 1280 × 720 pixels, fs: 30 Hz, Field of view: 99 degrees × 53 degrees, Eye cam. Resolution: 192 × 192 pixels, fs: 120 Hz. Gaze accuracy 0.6 degrees, gaze precision 0.02 degrees.

Software

The experiment was recreated in an open-source software, PsychoPy v2021.1.4 [18], with wordsets presented as black text on a white background in font OpenSans. Letter height was set to 5% of the screen's height in PsychoPy, which is 60 pixels on the monitor, or approximately 17 mm, which corresponds well with the fovea's 1.5–2-degree visual field at 70 cm viewing distance [19] and the eye-tracker's 0.6 degree accuracy. Pupil Capture collected and recorded eye-tracking data. To synchronize eye-tracking data, audio data, questionnaire responses, timestamped ideas, and stimuli annotations, we used Pupil Network API. By using this API, we sat Pupil's clock to the global experiment clock in PsychoPy, and thereby ensuring time synchronization of PsychoPy and Pupil Capture. This API was also used to implement automatic data recording, ensuring that Pupil Capture began recording once the PsychoPy experiment was launched. Pupil Player,[1] Pupil Labs' software, exported eye-tracking recordings from Pupil Capture.

Surface Tracking

To recorded participants' gaze relative to the monitor and not only the video frame we used Pupil's Surface Tracker plugin in combination with AprilTags (small binary markers) fastened on the monitor's bezel. We designed and 3D printed custom monitor mounts to ensure no changes in marker setup during the experiment period.

[1] https://docs.pupil-labs.com/core/software/pupil-player/raw-data-exporter.

The planar monitor's surface was mapped out with Pupil's Surface Tracker and the exact size of the monitor was marked in the recording software.

Processing and Analysis of Eye-Tracking Data

To summarize, the following data modalities were recorded: eye-tracking data, audio recordings, number and timing of generated ideas, and subjective ratings via a questionnaire. The two latter have been preliminary analyzed; these results largely corroborated the original and are presented in its entirety elsewhere [20]. This article's scope is a preliminary analysis of eye-tracking data. A comprehensive analysis of all data will be published later.

Data Processing

Exporting Eye-Tracking Data

Raw eye-tracking data were exported to CSV files with Pupil Player and stored in participant-specific folders.

Apart from fixations, all eye-tracking data export without selecting and setting any parameters. Duration and dispersion thresholds must be selected before exporting fixations, since fixations spread out temporally and spatially. Pupil Player uses a dispersion-based algorithm [21] that maximizes the fixation duration within the given parameters and outputs non-overlapping fixations. Pupil Capture calculates the gaze position using the dark pupil effect [17].

Our assumptions: The aim is to obtain an overview of which words were examined, not fixations within the words themselves. We recognized that participants could potentially fixate on a word for several seconds, i.e., a long fixation; we therefore wanted to prevent long fixations from being separated into a series of fixations. On the other hand, participants could also pay little attention to a word, e.g., recognize a control word, not find it interesting or helpful, and thus not spend any more time fixating on it. Such fixations have a short duration, but we want to capture them nevertheless.

The dispersion threshold was set to Pupil Player's maximum of 4.91 degrees. Pupil Labs states that there is no gold standard for setting fixation thresholds.[2] By exporting fixation data with different thresholds, we found that setting maximum duration too low caused a considerable number of fixations passing the threshold, which split long fixations into one or more shorter fixations. We found that we could capture fixations of a wide range of lengths by setting maximum duration to 4000 ms.

[2] See the following section in their "Best Practices": https://docs.pupil-labs.com/core/best-practices/fixation-filter-thresholds.

Although similar ideation research used a lower bound of 150 ms [22], we set the lower fixation bound to 100 ms (see e.g., Wass et al. [23]) to include potential short fixations.

Fixation files with other parameters can be exported since the raw data is publicly available.

Data Concatenation

To ease data handling, a script using the Pandas library [24, 25] iterated across exported files of the same type (e.g., annotations, gaze, fixations) and concatenated the files into one larger file per data type. Assigning participant ID to each row in the concatenated data ensured each row's uniqueness.

Data Analysis: Are Participants Paying More Attention to Inspirational Words?

This article aims, as mentioned, to provide a preliminary analysis of eye-tracking data. We sought "the bigger picture; an overview of which words were examined; and an investigation of whether there are differences in visual allocation for the different wordsets. We hypothesize the following; participants spend significantly more time examining inspirational words (i.e., words presented in Near and Far) than neutral words (i.e., compared to Control). We, therefore, evaluated eye-tracking metrics mostly on an aggregated level.

For data analysis and statistics, we used open-source Python libraries Pandas [24, 25], NumPy [26], SciPy [27], and Pingouin [28]—for visualization methods and plotting we used Seaborn [29] and Matplotlib [30].

Data Quality

The eye-tracking software Pupil Capture appends a confidence score between 0 and 1 for each data point based on the quality of the pupil detection. To ensure high-quality data, we included only data with a confidence score above 0.8, thus discarding data with low confidence scores, e.g., blinking.

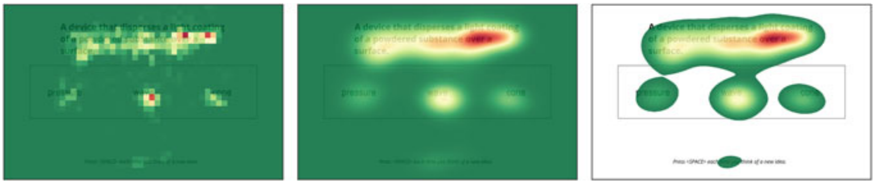

Fig. 2 Heatmap generation process from left to right: (Left) 2D histogram binned to the monitors' pixels (here visualized with large bins for visibility); (Center) Heatmap binned at each pixel with a Gaussian filter; (Right) Lower values filtered out of center heatmap

Heatmaps

Heatmaps provide a visual overview of gaze positions. First, our custom code implementation made two-dimensional histograms with each gaze data point binned into bins similar to the pixels of the monitor (1920 × 1200 pixels)—then, we smoothened the values with a Gaussian filter. Afterward, to increase visual differences between heatmaps, we filtered out values below a lower bound. The lower bound was the mean of the histograms' non-zero values, divided by 2. Figure 2 illustrates the heatmap generation process. The color indicates the relative gaze distribution from green to red with increasing gaze density.

Fixation Distribution

To obtain descriptive data of fixation distribution to test differences between stimuli, we split the monitor into four areas of interest (AOI) and calculated the ratio of time participants spent examining each area. The AOIs were: *problem*, *words*, *off-screen* and *other*. *Problem* represents design problem statements, and *words* represent wordsets; these AOIs indicate how interesting the words are and how one might draw inspiration from the problem statement itself; they were selected to investigate differences between words and problems. We included *off-screen* since we observed some participants gazing outside the monitor when ideating in the experiment. *Other* represents the remaining parts of the monitor.

The Surface Tracker plugin does not map the monitor perfectly (as seen in Fig. 3) due to distortion from the world camera's fisheye lens. Upon preliminary inspection of heatmaps, we noticed a slight vertical offset relative to the text on the screen. We, therefore, extended the boundaries for the box encompassing the words, particularly for wordset 1, see Fig. 4. This distortion explains offsets when plotting heatmaps and scanpaths over a screenshot.

Fixation distribution data was made by first assigning a label with corresponding AOI to each fixation based on the fixation's position on the monitor. Second, AOI distribution ratio was calculated by summing up fixation duration for each label and

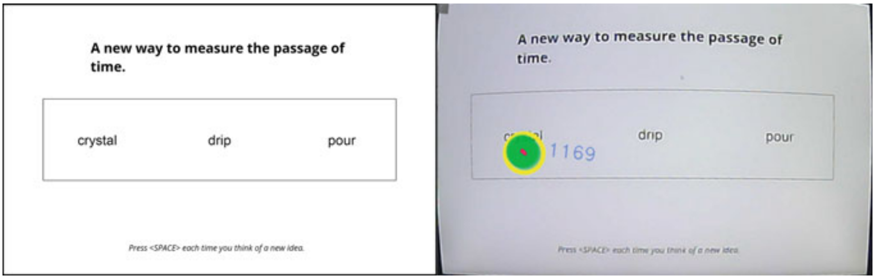

Fig. 3 (Left) Frame as shown on monitor. (Right) Monitor as mapped out by Pupil software

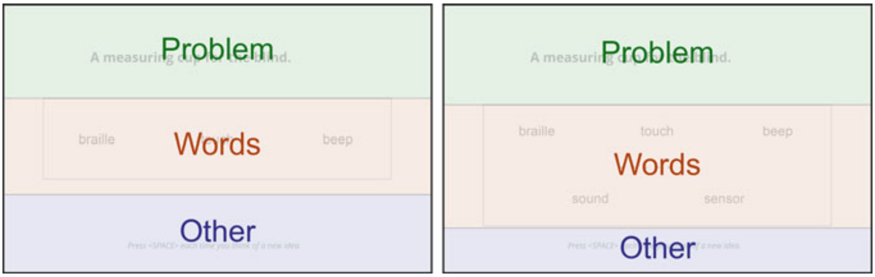

Fig. 4 Areas of interest (AOI) borders defined within the monitor for Wordset1 (left) and Wordset2 (right). Off-screen is outside the monitor

wordset (totaling 100%), and dividing by each label and wordset's fixation duration sum, respectively.

Statistical Analysis of Fixation Distribution Data

Friedman's test (a non-parametric test) assessed differences in fixation distribution between conditions due to violation of ANOVA's normality assumption for several subsets. Wilcoxon signed-rank test with a Bonferroni correction for multiple comparisons assessed pairwise comparisons post hoc. Hedges' g is used as effect size [6]. A significance level of $p < 0.05$ was selected for all tests.

Scanpaths

Scanpaths visualize fixation data in a scatterplot where the dots are connected by lines. A dot indicates a fixation; the dot's size varies with the fixation's duration, i.e., larger dots indicate longer fixations. The lines connecting the fixations indicate saccades. The first and last fixation is indicated by a green and cyan point, respectively. This custom scanpath implementation plots the line between each fixation with chronologically varying opacity from transparent to opaque, meaning that the visualization retains the temporality in the eye-tracking data, whereas heatmaps only aggregates the position of gaze data.

Due to the temporal aspect of scanpaths, they are difficult to compare directly on an aggregated basis, which is possible with heatmaps.

Results

Heatmaps

Aggregated heatmaps for all combinations of conditions and wordsets are presented in Fig. 5. Firstly, we observe a strong tendency of gaze allocation towards the monitor's center for all conditions, which we attribute to the *central fixation bias* [31]; the "marked tendency to fixate the center of the screen when viewing scenes on computer monitors." In other words, the monitor's center is a natural place to rest the gaze when not actively scanning for new visual input.

Despite the *central fixation bias*, there is a clear visual difference between the inspirational stimuli and control words in the time participants spent looking at the different AOIs, as seen in Fig. 5. Gaze is allocated more to the problem statement in control conditions, whereas the gaze distributes more evenly over the entire monitor and more on the wordsets in Near and Far condition.

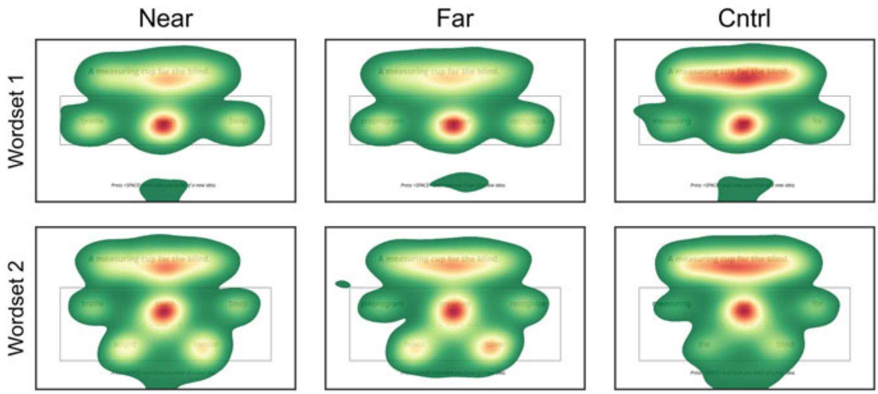

Fig. 5 Aggregated heatmap across all conditions

Table 1 Friedman test of AOI ratio

Wordset	AOI	DOF	χ^2	p
1	Problem	2	7.583	0.023*
	Words	2	18.250	< 0.001**
	Off-screen	2	4.750	0.093
	Other	2	2.333	0.311
2	Problem	2	7.583	0.023*
	Words	2	14.333	0.001**
	Off-screen	2	2.333	0.311
	Other	2	0.083	0.959

* $p < 0.05$, ** $p < 0.01$

Fixation Distribution

Friedmans test evaluated differences in fixation distribution between conditions and wordsets, i.e., objectively testing whether participants spent more or less time in any AOI. Table 1 presents the results, which were significant for AOI *words* and *problem* for both wordsets.

Pairwise comparisons with Wilcoxon tests are presented in Table 2. For AOI *problem,* there were significant differences between Control and Near for Wordset1 and between Control and Far for Wordset2. Moreover, the difference between Control and Near for Wordset2 obtained a $p = 0.051$, close to the significance threshold and thus noteworthy. Participants spent more time examining problem statements in control conditions compared to inspirational conditions.

For AOI *words*, there were significant differences between Control and Near, and Control and Far for both Wordset1 and Wordset2. Participants spent more time examining the inspirational words than control words. These findings align with our heatmap observations: when receiving control stimuli, participants spend time on the problem and less time on the words, compared to receiving inspirational stimuli, in which case participants spend more time on the words and less on the problem. This effect is apparent in Fig. 6 as well.

Discussion

The effect of inspirational words on participants visual allocation was significant. Inspirational words both near and far from the problem space received greater visual attention, i.e., participants spent more time visually fixating on the inspirational words, compared control words, throughout the entire ideation session. Further, participants visually examined the problem statement significantly more in control ideation sessions' second halves (Wordset2) compared to far inspirational ideation,

Table 2 Wilcoxon signed-rank test with Bonferroni correction

WS	AOI	Between		W	p	Corr. p	Hedges' g
1	Problem	Control	Far	79.00	0.044	0.132	0.378
		Control	Near	45.00	0.003	0.008*	0.482
		Far	Near	138.00	0.742	1.000	0.117
	Words	Control	Far	35.00	0.001	0.003**	−0.608
		Control	Near	19.00	<0.001	0.001**	−0.620
		Far	Near	143.00	0.853	1.000	−0.001
	Off-screen	Control	Far	75.00	0.033	0.100	0.311
		Control	Near	92.00	0.100	0.301	0.178
		Far	Near	111.00	0.271	0.814	−0.146
2	Problem	Control	Far	47.00	0.003	0.010*	0.592
		Control	Near	66.00	0.017	0.051[n]	0.570
		Far	Near	147.00	0.943	1.000	0.000
	Words	Control	Far	22.00	0.000	0.001*	−0.695
		Control	Near	56.00	0.008	0.023*	−0.510
		Far	Near	111.00	0.271	0.814	0.149
	Off-screen	Control	Far	107.00	0.225	0.674	0.256
		Control	Near	148.00	0.966	1.000	0.092
		Far	Near	107.00	0.225	0.674	−0.188

* $p < 0.05$, ** $p < 0.01$, [n] noteworthy, AOI *Other* is not included since its Friedman test was insignificant

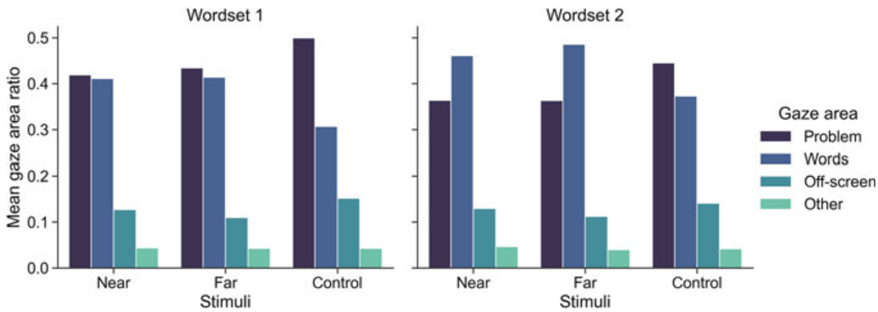

Fig. 6 Fixation distribution of AOIs for all conditions

and significantly more in control ideation sessions' first halves (Wordset1) compared to near inspirational ideation. The difference between control and near inspirational ideation sessions' second half (Wordset2) obtained a $p = 0.051$, close to the significance threshold. It may have turned out significant with a larger or slightly different participant pool. Because its effect size ($g = 0.570$) is comparable to that of the

Control-Far (Wordset2) ($g = 0.592$), we take this as an indication of the effect also occurring in the second half.

To summarize, this preliminary analysis of eye-tracking data yield two main findings/conclusions. One, participants allocate more visual attention (time) to word stimuli when receiving inspirational stimuli of any kind (both near and far from the problem space) compared to neutral (control) words throughout the entire ideation session; two, in the absence of inspirational stimuli (control condition) participants devote more visual attention to problem statements, an effect whose magnitude might depend on the inspirational words' distance to the problem space.

Finding one may be related to the *inspired internal search* from the original study, which suggested that participants found/recognized the inspirational stimuli as helpful or applicable to the design problem. Participants did rate inspirational stimuli as more useful both in the original study [1] as well as in this replication [20], which we suppose is why participants spent more time examining inspirational words than neutral words.

The second finding can be related to the strategy *unsuccessful external search* employed in the absence of inspirational stimuli where, originally, it is suggested that participants continue to search for clues in the design problem space [1]. The eye-tracking data confirm that participants continue trying to use the problem statement as a source of inspiration when they are not provided with any inspirational stimuli.

Scanpaths

The scanpaths presented here visualize a difference in how participants move their gaze around, possibly using different strategies during ideation. We selected an example illustrating participant 3 (in Fig. 7) versus participant 6 (in Fig. 8) for all problems in Wordset2 (both from group C).[3] Participant 3 stays fairly central at all times, exhibiting the central fixation bias to a greater extent than participant 6, who moves vigorously around the visual space, looking for inspiration in almost every stimuli word, to us in a pattern strikingly similar to a hexagon. Although both participants show lacking interest in control stimuli words for problem 10, it appears that individual participants have different search strategies; this will be investigated further in future work. Further conclusions regarding search strategies are therefore not drawn here.

[3] While only presenting a selection in this article, scanpaths were generated for all problems and participants.

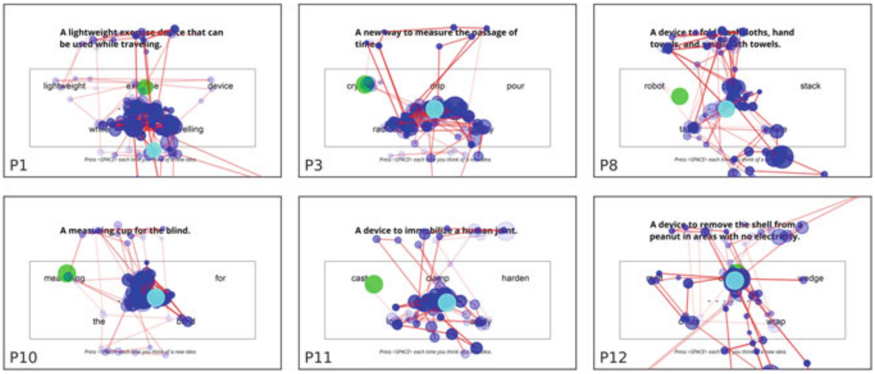

Fig. 7 Scanpaths for participant 3 for selected problems in Wordset2

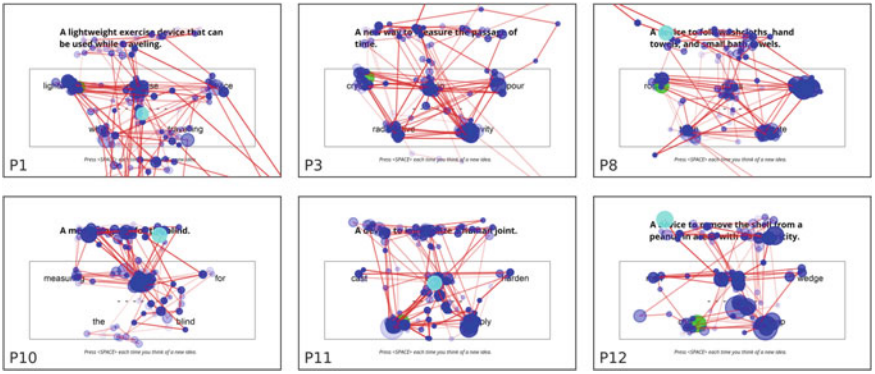

Fig. 8 Scanpaths for participant 6 for selected problems in Wordset2

Limitations

The study is limited by the central fixation bias, which could have been corrected for by randomizing the visual stimuli's position (problem statement and words etc.) on the monitor. However, randomization of positions was not possible since the study employed existing stimuli. Therefore, results are presumably influenced by the central fixation bias with *words* receiving disproportionately greater visual attention than other AOIs, as seen in Fig. 5. If we assume that the central fixation bias says consistent across conditions it is not affecting statistical results; if, however, it varies from condition to condition the statistical results are influenced.

Since this paper presents a preliminary analysis of eye-tracking data only the research objectives are not exhaustively answered; for this an exhaustive analysis is necessary. Further studies—collecting new and additional data modalities, in settings with higher ecological validity or in situ—are necessary to fully understand design ideation, visual- and inspirational stimuli.

Future Work

Future work intends to present an exhaustive joint analysis of eye-tracking data, the think aloud protocol's transcription, the behavioral-, and subjective data measured.

The illustrated scanpaths appear to indicate that there may exist individual visual search strategies amongst participants, although we do not draw any conclusions here. Scanpaths are interesting descriptive data that we will use to inform future analysis. Currently, we do not know how nor if scanpaths will be useful or not, but this will be investigated in future work.

Conclusion

We used eye-tracking and a think aloud protocol in a replication and extension of a design ideation experiment with and without inspirational stimuli [1]. This article provided a preliminary analysis of eye-tracking data and aimed to provide new insights from eye-tracking technology. Results show clear influence from inspirational stimuli on visual allocation; participants examine (or gaze) significantly more on inspirational words than neutral words; in inspirational stimuli's absence, participants examine design problem statements significantly more. Finally, we facilitate further replication with the openly available experimental procedure, data, and code.

Published Code Repository and Data

The code, raw data, and results from this study are publicly available:

- Code repository [32]: https://doi.org/10.5281/zenodo.5130090
- Pre-processed data [33]: https://doi.org/10.18710/PZQC4A
- Raw eye-tracking data [34]: https://doi.org/10.21400/7kq02wjl.

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Using Eye Tracking to Measure Cognitive Load of Designers in Situ

Christoph Zimmerer, Thomas Nelius, and Sven Matthiesen

The cognitive load of design engineers is a promising metric to get a deeper insight into cognitive processes of design engineers while designing. Previous findings regarding cognitive load are often based on intuitive rather than analytical thinking processes, which is also a large part of the design process. Thus, they are not directly transferable to the design process. Therefore, a study was conducted in which engineering design students and design engineers worked on a selection of typical tasks from the design process. Subsequently, it was investigated which eye parameters show a correlation to cognitive load obtained via a questionnaire. The results show that the eye parameters studied are more strongly influenced by the task than by cognitive load. This is probably due to the diversity of design tasks causing different patterns in gaze behavior. Therefore, ways and parameters are needed with which cognitive load can be measured in various tasks.

Introduction

The cognitive processes of designers while designing are an important topic in design research. To better support researchers understand cognitive processes of designers, measures are needed to assess cognitive processes in situ, i.e., right during the design process. Current research methods are not able to capture cognitive processes in situ and thus need to be developed further [1]. Quantitative data acquisition provides the most promising approach to achieve this, as it enables both an automatable data analysis and a more objective evaluation than would be possible with qualitative research methods. At the same time, this allows larger studies to be conducted with more participants, resulting in more statistically significant and reliable results [2].

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For the development of new research methods and tools that make cognitive processes of designers measurable, suitable data collection methods on a quantitative basis are required as well. Physiological signals like eye movements, galvanic skin response, and heart rate variability are suitable ways to use for measuring design thinking via quantitative parameters [1]. Eye tracking is particularly well suited for this purpose. There are also already existing metrics, like the cognitive load, from other disciplines that can be used to establish a link between eye tracking parameters and cognitive processes.

There are already a large number of studies on correlations between eye tracking parameters such as the pupil diameter and cognitive load in the state of the art [3–5]. In addition, the types of cognitive processes considered must also be considered here. Kahneman [6] distinguishes between a fast, intuitive and a slow, more analytical cognitive process. Existing studies largely use tasks that specifically elicit fast, intuitive thinking. Examples are tasks in driving simulators or Stroop tests. Therefore, the findings are not directly transferable to the design process. A more detailed overview of existing studies is compiled in Table 1. However, the design process is only in rare cases and for experienced designers an intuitive cognitive process as described by Kahnemann. Instead, in the majority of cases, cognitive processes while designing demand mainly slow, analytical thinking.

For this reason, findings on correlations between eye tracking and cognitive load from the current state of the art should first be verified in the design process in order to demonstrate suitability in principle.

Background

Cognitive Load Theory

The Cognitive Load Theory originates from educational research and describes the extent to which the available mental capacities are used. The basic assumption behind the concept of cognitive load is that humans have a limited amount of working memory. Working memory is a limiting factor for information-processing and problem-solving processes [7]. The cognitive load must be prevented from exceeding the capacity available in the working memory, as performance will otherwise decrease. To be successful in these processes, it is important to reduce the cognitive load as much as possible [8].

The resulting cognitive load is determined by three different factors: intrinsic cognitive load, extrinsic cognitive load and germane cognitive load. Paas et al. [9] describe these as follows:

> *Intrinsic cognitive load* is determined by the interaction between the content and type of information available and existing prior knowledge. In the process, comprehension is built up.

The design and structure of the available materials influence the *extrinsic cognitive load*. A high number of repetitions, cross-references as well as many alternating ways of providing information result in an increased extrinsic load.

The *germane cognitive load* represents the learning-related contribution to the cognitive load. It describes the additional effort required to permanently internalize the knowledge currently built up in the form of processes or schemata. If the intrinsic and extrinsic load become too high, there is not enough capacity left to internalize what has been applied.

The individual components can be combined additively to form the total cognitive load. If the cognitive load increases beyond the capacities of the working memory, this leads to a complete or at least partial failure of the cognitive system. The consequence is that the processing of necessary information can no longer take place [10].

The principles of cognitive load presented originate from the field of educational research, but are relevant to information processing and problem solving processes. Since the design process is also a complex problem solving process [11], it could be very valuable to investigate the cognitive load of designers in more detail.

Survey Based Methods to Assess Cognitive Load

There are many different survey-based techniques for measuring cognitive load. These are widely used and can be classified into uni-dimensional and multidimensional survey methods. It is already known that such methods are very reliable and valid and that they even detect relatively small differences in cognitive load. In addition, the participants are influenced to only a very small extent by the survey [12].

Hill et al. [13] compared different questionnaires for the assessment of cognitive load. They compared the Modified Cooper-Harper Scale (MCH) and the Overall Workload Scale (OWS) as unidimensional and the Subjective Workload Assessment Technique (SWAT) and the National Aeronautics and Space Administration Task Load Index (NASA-TLX) as multidimensional approaches.

The NASA-TLX achieved the highest level of sensitivity and acceptance. In addition, Hill et al. [13] conclude that the NASA-TLX is the most appropriate questionnaire to record data on cognitive load in more detail.

The NASA-TLX by Hart and Staveland [14] is a questionnaire that determines cognitive load via a six-dimensional survey. The individual dimensions of mental demand, physical demand, temporal demand, subjective performance, effort, and frustration are each assessed on a scale of 1–20. To determine the overall cognitive load, there are two different approaches: In their original approach, the cognitive load was determined using a weighting approach. The weighting of the individual dimensions was determined by pairwise comparison between all dimensions. In an alternative approach, Hart [15] describes that it is also possible to determine the cognitive load with high precision even without weighting. Since it has not yet been conclusively proven which method of calculation is more precise [15], both methods can be considered suitable.

In addition to survey-based approaches, there are also measurement approaches that are based on performance or behavior. However, these will not be discussed in more detail here as both are hard to measure continuously and automatically. Furthermore, there is the possibility to measure the cognitive load via physiological signals [16]. Besides the galvanic skin response and the heart rate, eye-based measures are particularly interesting here.

Eye Parameters to Assess Cognitive Load

In other research areas, such as human–computer interaction (HCI) or research on fatigue behavior in driving, a relationship between cognitive load and eye parameters has already been investigated.

Many different parameters were identified as appropriate. These can be traced back to the pupil diameter and the three basic movement types fixations, saccades and blinks.

However, Halverson et al. [17] stated that there is no consensus in the community on which parameters exactly are best suited to capture cognitive load [17]. No evidence has been found by the authors to disprove this statement.

Table 1 provides an overview of existing studies on correlations between cognitive load and eye movement types in other fields.

Chen et al. [20] use all four eye movement types with a range of measures. For the pupil, they use area, measured in pixels, rather than diameter. For fixations, it is the duration and number, and for saccades, it is additionally the angle as a measure of the moved distance. Blinks are expressed by the value PERCLOS, the percentage of eye closure. This describes the temporal proportion during which the pupil is at least 80% covered. The highest rate of agreement on cognitive load is obtained by PERCLOS and is 36%. By combining several parameters using machine learning approaches, the accuracy could be further increased to about 40% [20].

In a review of various studies in the field of driving simulators, Marquart et al. [4] identified the relationships between cognitive load and various parameters. It was found that an increased cognitive load is accompanied by an increasing pupil diameter and an increase in fixation duration. At the same time, gaze variability and blink duration decreased.

Halverson et al. [17] also use machine learning to determine the cognitive load with parameters similar to those mentioned above. The parameters are calculated in certain time windows. It has been shown that for different parameters, different window sizes provide the best results. For example, pupil diameter gave the best results for 5s windows, while PERCLOS gave the best results using a window length of 30s. [17]

Overall, pupil and blink-based measures are the most commonly used. Especially the pupil diameter and PERCLOS. However, since PERCLOS is originally used for the measurement of fatigue and not cognitive load [17], the average blink duration is used here.

Table 1 Overview on existing studies

Source	Field	Task	Predominant type of thinking	Eye movement types
Benedetto et al. [18]	Driving simulators	Simulated lane change test (LCT) in a driving simulator	Fast thinking	Blinks pupil
Buettner [19]	HCI	Job interviews	Slow thinking	Pupil, fixation, saccade
Chen et al. [3]	HCI	Arithmetic tasks	Fast thinking	Blinks, pupil
Chen et al. [20]	HCI	Flight tasks with different difficulties	Fast thinking	Blinks, pupil, fixation, saccade
Chen et al. [21]	HCI	Search task in computer-based training application	Slow thinking	Blinks, pupil, fixation, saccade
Halverson et al. [17]	Flight simulators	Aircraft monitoring on screen	Fast thinking	Blinks, pupil, fixation, saccade
Pedrotti et al. [22]	Driving simulators	Different driving tasks	Fast thinking	Pupil
Petkar et al. [23]	Design	Stroop-tests	Fast thinking	Blinks, pupil
Zagermann et al. [24]	HCI	Stroop-tests	Fast thinking	Blinks, pupil, fixation, saccade
Zheng et al. [25]	Medicine/surgery	Two simulated cases of laparoscopy	Slow thinking	Blinks

Aims

As derived from the state of the art, there is already a large number of studies from different research areas that have identified a connection between the cognitive load and different eye parameters. Following the definition of Kahneman [6], the tasks used so far (see Table 1) must be considered mainly in the category of fast thinking. Kannengiesser and Gero [26] for instance point out that the design process tends to be seen as a very challenging process that takes place over a long period of time. Thus, there are also many phases of slow thinking in design.

Consequently, the area of slow thinking processes must also be examined more closely to extend the findings from the state of the art to the design processes.

Therefore, the aim of this paper is to identify suitable eye tracking parameters that can be used to determine the cognitive load in the phases of the design process where analytic thinking is predominant. This may enable an in situ investigation of design processes in the future. To achieve this aim, the following research question will be investigated:

How applicable are established eye parameters for capturing cognitive load in phases of the design process where slow thinking is predominant?

To better answer the research question, it will be examined using four different parameters derived from the state of the art. Based on the eye movement types, a link between pupil diameter, fixation duration, blink duration, and saccade rate to cognitive load is investigated.

To investigate the design process, typical activities of the design process are to be simulated. According to Nolte and McComb [27], these are concept generation, concept selection and physical modeling. Since the latter activity would be too extensive for the scope of this study, only the first two activities will be investigated here.

Materials and Methods

Participants

A total of 27 participants attended the study. Since engineering design students and design engineers differ in the way they analyze and process perceived information [28], participants from both groups were considered.

The group of students consisted of 13 male and 2 female participants. They were on average 24.1 years old (standard deviation: 2.4 years) and in their 10th semester (average: 9.1 semesters, standard deviation: 3 semesters).

The 12 participating design engineers consisted of 10 males and 2 females and were on average 33.2 years old (standard deviation: 7.2 years). The designers came from different companies and had between one and 20 years of professional experience (average: 7.6 years, standard deviation: 5.3 years). All participants had normal or corrected to normal vision.

A detailed overview of all participants is shown in Table 2.

Task

The participants were given a task from the field of design for manufacturing. The objective was to redesign a given fastening bracket using sheet metal forming process. In addition, the manufacturing effort was to be reduced as much as possible. The task consisted of two phases following the activities stated by Nolte and McComb [27]. In the first phase, the participants had to create variant concepts considering the new manufacturing process. For this purpose, they were provided with an initial assembly of a holding bracket. By changing the manufacturing process, the participants were asked to make the manufacturing of the assembly more cost-effective. For example, the number of parts could be reduced or welds could be replaced by bends. They were

Table 2 Participant demographics

	Type	Age	Gender	Semester	Work experience [in years]
P 01	Design engineer	34	Male		6
P 02	Design engineer	45	Male		20
P 03	Design engineer	30	Male		3.5
P 04	Student	27	Male	13	
P 05	Student	26	Male	7	
P 06	Student	26	Male		11
P 07	Design engineer	30	Male		4
P 08	Design engineer	49	Female		15
P 09	Student	21	Male	3	
P 10	Design engineer	26	Male		1
P 11	Student	20	Female	3	
P 12	Student	22	Male	10	
P 13	Student	26	Male	12	
P 14	Student	22	Female	9	
P 15	Student	29	Male	11	
P 16	Student	24	Male	7	
P 17	Student	22	Male	9	
P 18	Student	25	Male	11	
P 19	Student	24	Male	11	
P 20	Student	23	Male	9	
P 21	Student	25	Male	13	
P 22	Design engineer	29	Female		3
P 23	Design engineer	25	Male		2.5
P 24	Design engineer	26	Male		6
P 25	Design engineer	37	Male		7
P 26	Design engineer	33	Male		11
P 27	Design engineer	35	Male		9

asked to sketch several alternatives on paper. In addition to the new manufacturing process, a number of boundary conditions were specified, such as a constant material and an unchanged drilling pattern. In the second part of the task, created concepts were then to be evaluated first against each other and then in comparison with a selection of predefined concepts. For this purpose, the participants were asked to identify the various properties of the concepts such as the number of parts and the number of welds and bends. Subsequently, the various properties were to be weighed against each other in terms of their influence on manufacturing costs.

The participants evaluated the concepts in terms of manufacturing effort. The participants were given predefined criteria (number of parts, number of manufacturing steps, etc.) for evaluation.

Procedure and Data Collection

The study procedure was designed such that the participants took part in the study consecutively and alone. In preparation for the task, the eye tracking technology was set up and calibrated, and the recording was started. Tobii glasses 2 (sampling rate 100 Hz) were used to record the eye tracking data. The calibration was done using the related calibration card. Subsequently, the participants were instructed to read through the task description. For the completion of the first task, the participants were given a target time of 10 min. Task 1 was given to them on the computer, but the actual processing of the task then took place using pen and paper. Upon completion, the participants' cognitive load during conceptualization was assessed by a NASA-TLX questionnaire. The dimensions of Hart and Staveland [14] were used, with the exception of the physical demand. This was not considered, since the entire study took place at a desk and thus no physical demand was expected. The dimensions of mental and temporal demand, effort and frustration were assessed on a scale from low to high. Performance was surveyed ranging from good to poor. This procedure has already proven successful in previous studies (e.g. Zimmerer and Matthiesen [29]).

No time limit was set for the second part, the evaluation. This task took place entirely on the computer. After the participants had evaluated their concepts against each other and against the predefined concepts, the cognitive load for the concept evaluation was assessed using the NASA-TLX.

Data Analysis

First, the results from the NASA-TLX questionnaires were analyzed. Thereby, the variant without weighting factors (NASA Raw TLX) proposed by Hart [15] was used. Accordingly, the values of the individual dimensions were added and thus a cognitive load between 0 and 100 was determined for the first and second task part respectively.

The analysis of the eye tracking data was limited to the phases of task processing starting after the reading of the task description. Therefore the eye tracking data was first analyzed using the Tobii Pro Lab analysis software provided by Tobii. This involved event detection using the I-VT Fixation Filter developed by Tobii. Based on predefined parameters, fixations, saccades are detected in the raw data. The data is first smoothed by moving median filters. Subsequently, fixations and saccades are defined via a classifier. This classifier consists of a limit for the eye movement speed, which is set to 30°/s in this case. Fixations are then defined as the contiguous regions where the eye velocity remains below this limit. A more detailed explanation of the choice of the individual parameters in the filter settings is described by Olsen and Matos [30]. Situations in which the eyes could not be detected were classified as blinking.

The pupil diameter was evaluated separately from the other data since it was measured continuously over the evaluation frequency, while the other parameters always have a certain event length.

For the statistical analysis, the confidence interval was set to 95%. Because of the level of measurement available, Spearman's rank correlation test was used to determine correlations. For the identification of differences, the Mann Whitney U test was applied.

The SPSS 26 software from IBM was used for the analysis.

Results

Out of the 27 participants, 6 could not be considered for the evaluation due to errors in the recording of the data (P2, P8, P9, P15, P21, P22). Thus, 12 engineering design students and 9 design engineers were considered for the following analysis.

Table 3 combines all data from the NASA-TLX questionnaires and the mean values of the considered parameters over the total task duration.

The analysis of the NASA-TLX questionnaires shows that most participants ($n = 16$) reported a higher cognitive load in the second task, the concept evaluation, than in the concept generation. Only three participants rated the first task as more challenging. For two participants, both scores were equal.

There are also no differences between the engineering design students and the design engineers. Two engineering design students indicated a higher cognitive load for the first task. In the case of the design engineers, this applies to one participant and, in addition, there are two participants in this group who rated both tasks with exactly the same value.

In the next section, statistical correlations between the cognitive load and the considered parameters shown in Table 3 are examined in more detail. The results of the correlational analysis are summarized in Table 4.

As can be seen from the table, no significant correlations can be found between the cognitive load and any of the parameters considered. Although statistically no correlation can be detected, it is possible to read a trend from the correlation coefficient. This trend indicates the direction in which the parameters change with increasing cognitive load.

While the pupil diameter, blink duration, and saccade rate increase slightly with increasing cognitive load, fixation duration slightly decreases.

Since no significant correlations to the cognitive load could be found by the correlation analysis, the next step is to evaluate if there are any differences in the parameters between the two tasks concept generation and concept evaluation.

Table 3 Overview of the cognitive load and the mean values of all parameters per task (CL: cognitive load, PD: pupil diameter (mm), FD: fixation duration (ms), BD: blink duration, SR (ms): saccadic rate (1/s)). The higher value in the comparison between the tasks is highlighted in dark grey (white indicates equal value)

	Task 1					**Task 2**				
	CL	PD	FD	BD	SR	CL	PD	FD	BD	SR
P 01	16	3,49	290,39	108,55	2,48	21	3,20	228,49	81,13	3,08
P 03	36	4,08	207,67	73,61	3,13	38	3,41	135,19	66,36	5,28
P 04	23	3,16	419,45	64,28	2,31	42	2,82	313,83	76,46	2,59
P 05	65	3,73	213,73	141,51	3,82	69	3,36	197,37	274,03	2,75
P 06	87	3,43	242,75	73,58	3,80	88	2,92	217,22	75,42	3,82
P 07	33	3,09	281,07	95,98	3,27	53	2,95	246,12	60,49	3,35
P 10	42	3,42	324,68	97,96	2,51	39	3,04	193,13	50,83	4,20
P 11	50	4,66	303,64	99,51	2,62	49	4,03	234,90	121,14	2,92
P 12	47	3,72	331,04	58,15	2,26	48	3,40	242,32	54,31	2,90
P 13	49	3,33	394,73	99,98	2,53	58	2,91	264,21	117,00	3,22
P 14	41	3,83	203,65	62,37	3,78	57	3,58	156,90	64,96	4,85
P 16	40	2,91	234,66	106,71	2,83	45	2,58	170,59	110,38	3,75
P 17	41	3,84	222,26	63,65	2,58	62	3,54	223,95	68,65	3,36
P 18	28	3,53	193,74	70,59	2,73	80	3,16	164,75	71,53	3,76
P 19	39	4,87	412,93	72,09	2,11	64	4,19	341,89	88,64	2,68
P 20	59	3,55	367,69	153,23	2,15	52	3,36	230,29	3,78	3,01
P 23	36	4,67	366,02	1488,28	2,36	38	3,41	267,83	3,55	3,28
P 24	5	4,18	231,94	98,93	3,56	5	3,32	250,22	1,49	3,19
P 25	22	2,99	433,68	62,91	1,74	29	2,76	279,61	1,65	3,12
P 26	39	3,72	290,98	77,52	2,72	52	3,43	267,07	4,86	2,81
P 27	28	2,74	263,59	164,93	3,24	28	2,58	175,82	2,63	4,93

Table 4 Results of the correlation analysis between cognitive load and the parameters considered. Here, both tasks were considered

	Pupil diameter	Fixation duration	Blink duration	Saccade rate
Correlation coefficient	0.106	−0.156	0.184	0.173
p	0.502	0.324	0.244	0.274

The results of this analysis are shown in Table 5.

When looking at the results, it can be seen that there is a significant difference in all four parameters between the two tasks. The pupil diameter, as well as the fixation duration and the blink duration, are significantly larger during concept generation than during concept evaluation. According to Cohen [31], there is a large effect in each case.

Table 5 Results of the statistical analysis regarding differences between the tasks used and the parameters considered

	Pupil diameter (mm)	Fixation duration (ms)	Blink duration (ms)	Saccade rate (1/s)
Median task 1	3.55	290.39	95.98	2.62
Median task 2	3.32	230.29	66.36	3.22
p	0.01	0.007	0.024	0.003
U	117.5	114	131	338.5
Cohen's d	0.872	0.908	0.741	1.031

For the saccade rate, it is exactly the opposite. Here, the value is significantly larger for concept evaluation than for concept generation. Here, too, a large effect is observed (according to Cohen [31]).

Discussion

The aim of this paper was to identify suitable eye tracking parameters that can be used to determine the cognitive load in the phases of slow thinking during the design process. This should be the first step to enable an in situ investigation of the design process.

For this purpose, the research question was stated to what extent established eye parameters are applicable to capture cognitive load during the design process.

In order to answer the research question, four parameters were examined in more detail, which should show a correlation to cognitive load based on the current state of the art. For this purpose, the cognitive load was measured using the NASA-TLX questionnaire, which was developed by Hart and Staveland [14] and is a widely used and effective way to measure the cognitive load of participants [15]. Since different activities from the design process were used for the data collection, it was evaluated in a second step whether an influence of the tasks on the eye parameters can be observed.

The results of this study show that there is no significant correlation between the cognitive load of the participants and the eye parameters used. Although the correlation analysis yields a trend for each of the parameters considered, none of them is significant. One possible reason for this could be the lack of randomization of the tasks. However, since two different types of tasks were involved, the influence should be rather small. Nevertheless, it has to be considered for future investigations.

As mentioned in the literature review by Marquart et al. [4] an increasing cognitive load leads to enlarged pupil diameter and an increased fixation duration. Blink duration, in turn, decreases with increasing cognitive load [4]. Comparing this with the results from this study, it can be seen that only the trend in pupil diameter is in line with these findings. For the other parameters, the opposite can be observed. This may be due to the fact that the results by Marquart et al. [4] refer to driving simulators, which are not comparable to the design process, or that the eye parameters were more influenced by factors other than the cognitive load.

Therefore, the second step of the evaluation examined whether the task itself had an influence on the eye parameters. The results showed that for all parameters there was a significant difference between the tasks. This result may be explained by the fact that the two tasks induce a different gaze behavior.

While concept generation tends to evoke a serene gaze pattern with long fixations and fewer saccades, this is the other way around for concept evaluation. This could be due to the fact that the different concepts are considered in rotation during the evaluation.

The difference in pupil diameter can also be explained since the participants had to look on paper for the concept generation and not on a monitor as in the evaluation. The significant differences can be explained by the changes in brightness that occur during this process. According to Klingner [32], these are considerably stronger than the influence caused by changes in the cognitive load.

However, in the case of blink duration, unlike the three parameters before, no direct influence can be seen by the way the tasks were provided.

From the results, it can be concluded that it is reasonable to first limit the focus to one activity of the design process. Once the cognitive load can be reliably measured in this activity, further efforts should be made to transfer the findings to other activities.

Conclusion

This study aimed to verify findings from eye tracking research on cognitive load in the design process. However, the results from the state of the art cannot be verified in the activities of design engineers, since the occurring cognitive processes seem different from those investigated in the state of the art. Therefore, this study was conducted with tasks typical for the design process. For this purpose, four different parameters based on the eye movement types were derived from the state of the art and the relation to the cognitive load, which was assessed via a questionnaire, was examined in more detail.

In a first analysis of the results, the scores from the NASA questionnaire by Hart [15] are compared with the mean values of the four parameters. However, no significant correlations can be found here. Instead, a strong influence of the task on the eye parameters can be assumed. This is particularly evident in the pupil diameter. The pupil diameter is larger for all participants in task 1 than in task 2. Considering that task 1 was performed on paper and task 2 on a computer, this effect can be explained. While on the screen the pupil diameter becomes smaller due to the brightness of the monitor, the work on paper leads to an enlargement of the pupil diameter.

The only parameter considered here for which no direct relationship to the task was apparent is blink duration. In the more difficult task, the blink duration was slightly increased. This is supported by the state of the art, where blink-based parameters are often considered well-suited for measuring cognitive load [23, 25].

Since most of the parameters used were more clearly influenced by the tasks than by the cognitive load, new approaches need to be developed to be able to examine cognitive load even in activities such as those considered here. There are two approaches to this. First, it might be appropriate to consider the context of the task. For example, it might be effective to use different eye parameters for different types of tasks.

Second, it might be useful to consider several parameters in combination that are affected differently by the tasks.

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A Test of the Structural Alignment Model for Similarity Judgements of Design Concepts

Chris McTeague, Alex Duffy, Laura Hay, Tijana Vuletic, Gerard Campbell, and Madeleine Grealy

This paper presents a test of the Structural Alignment (SA) model of psychological similarity judgements on a sample of design students and recent graduates (n = 37) making similarity judgements of early-stage design concepts (n = 30) represented by sketches and text. A correlational, quasi-experiment was conducted to test five predictions derived from the SA model. It was found that similarity can be predicted as a function of the common and different features of a pair of design concepts, and similarity is positively associated with the number of commonalities, indicating that design concept similarity judgements are carried out via a process of comparison. However, one of the five hypotheses that was unique to the SA model was falsified, meaning the SA model was rejected and it was not possible to determine the nature of the comparison process.

Introduction

Similarity judgements are a central aspect of human cognition. Knowledge of how people make similarity judgements has aided in understanding a variety of cognitive processes, including learning, knowledge, problem-solving, prediction and categorization [1]. Likewise, similarity has been implicated in a variety of cognitive processes in engineering design. For example, similarity (or distance) is associated with changes in creative outcomes in combinational creativity [2], has been conjectured to be a component of novelty judgements [3], and has been implicated in product performance prediction [4]. Similarity also forms the basis of computational aids for engineering design that augment the designer's cognitive processing. Retrieval systems can provide designers with sources of inspiration, examples of past

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design cases, or targets for analogical transfer. Since the similarity of these stimuli is associated with outcomes like novelty in subsequent concept generation, a goal of these systems is to tailor the similarity of retrieved stimuli to maximize the designer's novelty, e.g., [5].

Despite the role of similarity in design cognition and computation, it is not clear how designers perceive similarity for the kinds of representations they use in the design process. Although domain-general models of similarity exist [1], it is not known whether they also represent the cognitive processes of designers during the design process. Design is a creative, goal-directed process in which the designers attempt to meet requirements, whilst dealing with contexts and constraints that are unique from project to project. During the design process, designers generate and reason about design concepts, which are representations of physical artefacts that do not yet exist that vary in abstractness and detail. Without models of similarity that are tailored to a design context, we are limited in the extent to which we can leverage knowledge about similarity as a foundation for understanding designer cognition and developing computational support tools.

The present research aimed to model the cognitive processes involved in designer similarity judgements of design concepts. This was done via a deductive research approach, where an existing, domain-general cognitive model was proposed as a candidate model for design concept similarity judgements and tested through experimentation. It was proposed that the Structural Alignment (SA) model would represent designer similarity judgements. This followed from prior research showing that design concept similarity judgements involved assessment of the common and different features of a pair of design concepts [6]. Five predictions were derived from the model and were subjected to falsification via a correlational quasi-experiment. The methods used were the same as those that had been used to develop the SA model previously [7, 8] with minor modifications. This short paper provides a brief overview of the SA model, the results of the five hypothesis tests and a discussion of whether the SA model is an appropriate representation of designers making similarity judgements of design concepts.

The Structural Alignment Model of Similarity Judgements

The SA model of similarity judgements is a featural model of similarity judgements. 'Featural' models are so named because they assume that a persons' perception of similarity is a function of a comparison process that operates on the common and different *features* of a pair of concepts (features being a generic term for the constituent elements of a concept). Featural models provide a plausible basis for understanding similarity judgements in design because engineered artefacts are created through the composition of parts and assemblies in new configurations to achieve novel functions and solve new problems. Since designers reason about the constituent features of design concepts, it follows that their similarity judgements of design concepts may be determined by the common and different features of a pair of design concepts.

The SA model assumes that concepts are represented in the mind as structured representations. These structured representations comprise four kinds of feature. They are entities, attributes (entity descriptors), functions (continuous quantitative values) and relations (links between two or more attributes, objects or other relations). Figure 1 shows structured representations comprising entities and relations for two groups of geometric shapes (attributes have been omitted for brevity). The reason for proposing the SA model as a candidate for design similarity is that it explicitly represents relations and higher-order relations (relations of relations). The relations represent causal links between entities, and causal knowledge is an important aspect of reasoning about design artefacts [9].

The Structural Alignment process operates by attempting to find the maximally structurally consistent match between two structured representations. A structurally consistent match satisfies the two constraints of *parallel connectivity* and *one-to-one* mapping [8] (shown by the dotted lines in Fig. 1. Parallel connectivity means that when matching relations are aligned, their arguments (the things bound to those relations) are also aligned. One-to-one mapping means that a representational element of one concept can have no more than one matching representational element in the other concept when they are aligned. The alignment process also seeks to achieve *systematic* mappings and prefers to align matching relations over entities and higher-order relations over lower-order relations.

The alignment process inherently enables the distinction between two kinds of differences: alignable differences (ADs) are those that are related to the common structure, and nonalignable differences (NDs) are independent of the common structure. In Fig. 1, the two groups of shapes are aligned by the common relation 'above' as this facilitates the most systematic mapping. Parallel connectivity means that the circles and triangles become alignable differences. The hexagon and the 'beside' relation are nonalignable differences, because there is no common relational structure in (b) that it aligns with.

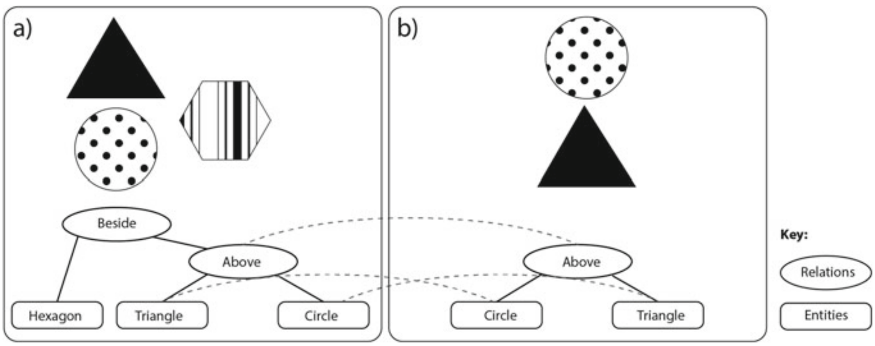

Fig. 1 Illustration of two aligned structured representations, adapted from [8]

As both commonalities and ADs are part of the common relational structure, ADs become more influential in the perception of similarity than NDs, and noticing the existence of commonalities leads to the noticing of ADs. The special nature of ADs leads to a series of predictions [8]. Like earlier comparison-based featural models (see e.g., [10]), similarity is a function of the common and different features of a pair of concepts, with commonalities influencing similarity more than differences (H1a). However, it should be ADs that exert this influence on similarity rather than nonalignable differences (H1b). As the alignment process maximizes the common relational structure, the number of commonalities *and* ADs should increase, meaning that relatively more similar concepts should have more commonalities (H2) and more ADs (H3). ADs should be easier to identify than NDs, making them more numerous than NDs (H4).

The Present Study

A test was conducted of the Structural Alignment model of similarity judgements for a sample of product design engineering students and graduates making judgements about pairs of design concepts. Five predictions were derived from the SA model (Table 1). The predictions concern the relationship between the outputs of similarity judgements (elicited via similarity ratings) and comparison (elicited via a commonality and difference listing task). Hypotheses H1a and H2 are common predictions of featural models of similarity judgements. Support for these would be taken as evidence that design concept similarity judgments are carried out via some kind of comparison process, but would not aid in determining the nature of that comparison process. If design concept similarity judgements occurred via a process of Structural Alignment, it was expected that all of the five predictions in Table 1 would be supported. Falsification of any single hypothesis would mean rejection of the SA model.

Table 1 Five hypotheses derived from the SA model

H#	Hypothesis
1a	Similarity should increase as a function of commonalities (positive regression coefficient) and decrease as a function of differences (negative coefficient). Commonalities should influence similarity more than differences
1b	This is an extension of H1a that is unique to the SA model. In addition to H1a, alignable differences should be more important in evaluating similarity comparisons than nonalignable differences
2	There should be a positive correlation between rated similarity and the number of listed commonalities
3	There should be a positive correlation between the number of commonalities and alignable differences
4	Alignable differences should be more numerous than nonalignable differences

Method

Design. A correlational, quasi-experimental design was used. Participants made similarity judgements about pairs of design concepts and then listed the commonalities *or* differences for the same concepts, but never both. Thus, two participants were needed for a full sample of commonalities and differences for each pair. The correlational design was recreated from [7, 8] with minor modifications to aid in testing the same hypotheses with continuous rather than binned variables. The design was not a true experiment because it lacked random allocation to multiple groups.

Participants. The 37 participants were undergraduate (final semester of 2nd year or above) or postgraduate students of Product Design Engineering (PDE), or recent (<2 years) graduates of a PDE degree, all from the University of Strathclyde or the University of Glasgow, Scotland.

Materials. 40 pairs of design concepts were used, 10 pairs from each of four design tasks, 1 design task used in a warmup and the other 3 used for the main study. Each stimulus comprised a written description of the design brief and two design concepts of varying relative similarity (Fig. 2). The design concepts were created in a concept generation experiment by different participants from the same population and were represented by sketches, annotations and written text. The pairs were created through three rounds of iterative testing and validation with human similarity ratings. Each participant saw pairs spanning a range of similarities in one of ten random orders.

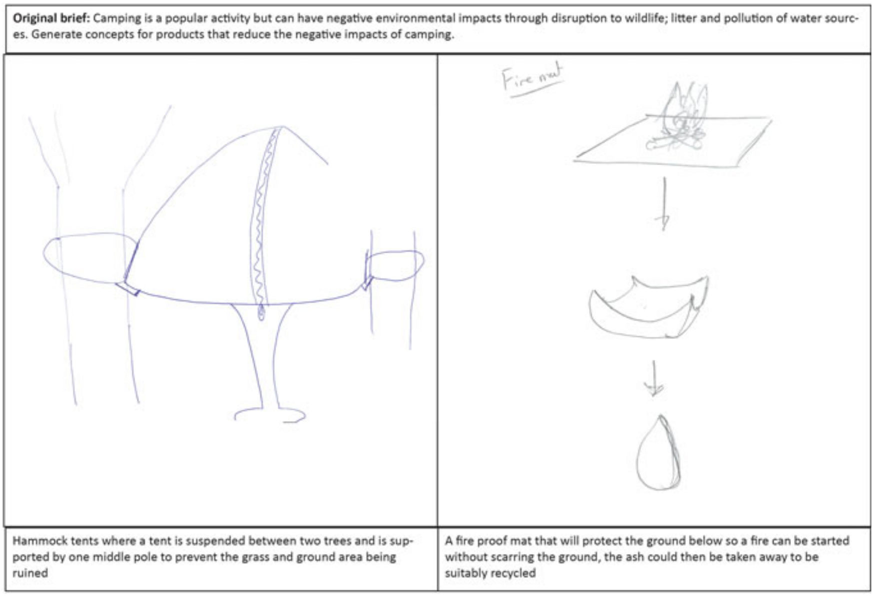

Fig. 2 An example of a pair of base concepts used as stimuli

Procedure. The study was carried out in three sequential parts: (1) warmup similarity rating exercise (10 stimuli), (2) main similarity ratings (30 stimuli), and (3) commonality or difference listing (the same 30 stimuli). In the warmup and main similarity rating task, participants rated the similarity of one pair at a time from 1 (not at all similar) to 9 (extremely similar), with 5 being ‘moderately similar’. After providing a rating the participant could move to the next page at their own pace but could not then move back to a previous pair. Once the participants had completed the ratings they were instructed to return to the start of the booklet to begin the commonality and difference listing task. They whether to list the commonalities or differences for each pair, and to list as many as they could by typing them into a response box until they felt they had run out. No time limit was placed on the task. Prior research had the same participants complete the listing task and then the similarity rating task [8]. The order of these tasks was reversed in the present study based on research showing that prior comparison processing (in a combination task) can influence subsequent similarity ratings [11].

Scoring. Differences were coded as ADs or NDs. The code definitions were based on an existing coding scheme [8] with additional design-specific examples and coding aids. Differences were coded based on the syntactic content of the participant's response. For example, corresponding to Fig. 1, an example of an AD was “*the mat protects from fire, the tent protects from compression damage*”, both products share the explicit common dimension of protection, but they differ in what they protect. An example of an ND was “*one is not fireproof. one is.*”, in this case, the participant has identified a feature of one concept (fireproof) and negated it for the other. A sample of 13.5% of the responses (n = 245) was coded two by two independent judges, achieving inter-rater reliability of Krippendorff's alpha = 0.797 on the second round of coding. This result was taken as sufficient for moving on to coding the full coding scheme. A final arbitration was conducted to resolve disagreements before the lead author coded the remaining responses.

Results

Descriptive statistics. Table 2 presents summary statistics for each variable across three design tasks after outliers have been removed. Sim(all) includes all similarity ratings, Sim(com) are only those ratings given for pairs that the participants listed commonalities for, Com is a count of the number of listed commonalities, Dif(tot) is total differences before coding and ADs and NDs were coded from the Dif(tot) sample.

Hypothesis 1a states that similarity should increase as a function of commonalities and decrease as a function of differences, and commonalities should influence similarity more than differences. A multiple regression analysis was conducted to determine whether changes in Com and Dif(tot) predict changes in the dependent variable Sim(all). The multiple regression model was significant, $R^2 = 0.770$, F(2,

Table 2 Values for all variables per design task and in total

DT		Sim(all)	Sim(com)	Sim(dif)	Com	Dif(tot)	AD	ND
1	M	4.81	4.84	4.83	3.28	3.31	2.25	1.01
	SD	*2.77*	*2.79*	*2.85*	*1.84*	*1.82*	*1.43*	*1.33*
	Sum	–	–	–	489	507	345	155
	n	340	149	153	149	153	153	153
2	M	4.82	4.75	4.92	3.28	3.34	1.83	1.49
	SD	*3.00*	*2.99*	*3.00*	*1.80*	*1.99*	*1.32*	*1.64*
	Sum	–	–	–	466	481	264	214
	n	343	142	144	142	144	144	144
3	M	4.21	4.25	4.16	3.52	3.97	2.70	1.29
	SD	*2.59*	*2.61*	*2.54*	*1.93*	*2.28*	*1.65*	*1.74*
	Sum	–	–	–	553	612	416	199
	n	346	157	154	157	154	154	154
Total	M	4.61	4.61	4.63	3.37	3.55	2.27	1.26
	SD	*2.80*	*2.80*	*2.81*	*1.86*	*2.06*	*1.51*	*1.59*
	Sum	–	–	–	1508	1600	1025	568
	n	1029	448	451	448	451	451	451

Note *DT* Design task, *M* Mean, *SD* Standard Deviation, *n* number of stimuli that were responded to, *Sum* total number of items listed

27) = 45.107, $p < 0.001$, with an adjusted R^2 of 0.753 (Table 3). Both commonalities (β = 0.1.598, $p < 0.001$) and total differences (β = −0.883, $p = 0.006$) were significant predictors of Sim(all), explaining 77% of the variance in rated similarity. That the unstandardized regression coefficient is greater for commonalities than differences indicates that commonalities count more towards similarity than differences count against similarity. These findings support H1a.

Hypothesis 1b states that alignable differences should be more important in the judgement of similarity than nonalignable differences. This is an extension of H1a that is specific to the SA model that considers two kinds of differences, ADs and NDs. Again, the multiple regression model was significant, $R^2 = 0.761$, F(3, 26) =

Table 3 Summary of multiple regression analysis for H1a

Variable	*B*	95% CI for B		SE_B	*Beta*	*Sig*
		LL	UL			
Intercept	2.398	−1.305	6.101	1.805		
Com	1.598	1.008	2.188	0.288	0.633	<0.001
Dif(tot)	−0.883	−1.488	−0.278	0.295	−0.341	0.006

Note *B* unstandardised regression coefficient; SE_B Standard error of the coefficient; *Beta* standardized coefficient; *CI* Confidence Interval; *LL* Lower limit; *UL* upper limit

Table 4 Summary of multiple regression analysis for H1b

Variable	B	95% CI for B		SE_B	Beta	Sig
		LL	UL			
Intercept	1.789	−1.964	5.542	1.826		
Com	1.722	1.112	2.332	0.297	0.682	0.000
AD	−1.036	−1.858	−0.213	0.400	−0.265	0.016
ND	−0.469	−1.218	0.280	0.364	−0.144	0.210

Note Variables as listed in Table 3

27.586, $p < 0.001$, adjusted $R^2 = 0.733$ summary in Table 4. Commonalities ($\beta = 1.722$, $p < 0.001$) and ADs ($\beta = -1.036$, $p = 0.016$) added statistically significantly to the variance in the similarity ratings. The regression coefficient for NDs was not significant ($\beta = -0.469$, $p = 0.210$). This finding supports H1b in that it shows that it is ADs, not NDs, that exert greater influence over similarity.

Hypothesis 2 states that there should be a positive correlation between similarity and the number of listed Coms. A Pearson's product-moment correlation showed that, as predicted, there was a statistically significant, strong positive correlation between mean rated similarity (Sim(com)) and the mean number of listed commonalities (Com), $r(28) = 0.827$, $p < 0.001$ (one-tailed), with 68.4% of the variance explained (Fig. 3a). This finding supports H2 and shows that on average, concepts with higher similarity ratings have more listed commonalities, and concepts with lower similarity ratings have fewer listed commonalities.

Hypothesis 3 states that concepts with many commonalities should also have many alignable differences. That is, there should be a positive correlation between the mean number of Com and the mean number of ADs. Contrary to expectations, there was a negative correlation that was not statistically significant between the number of listed commonalities and the number of listed alignable differences, $r(28) = -0.302$, $p = 0.052$ (1-tailed), with 9% of the variance explained (Fig. 3b). This finding falsifies H3.

Hypothesis 4 states that alignable differences should be more numerous than nonalignable differences. There were 451 responses to the listing task in which a participant listed at least one difference. ADs were more numerous than NDs in 282 cases, NDs were more numerous in 100 cases, and the same number of ADs and NDs were listed in 69 cases (Fig. 3c). Participants listed a statistically significantly greater number of AD's (Mdn = 2.0) than ND's (Mdn = 1.0), $W = 16{,}719$, $p < 0.001$, $z = -9.279$. These findings support H4 and are consistent with the SA model in that that alignable differences should be more salient than nonalignable differences and thus easier to list.

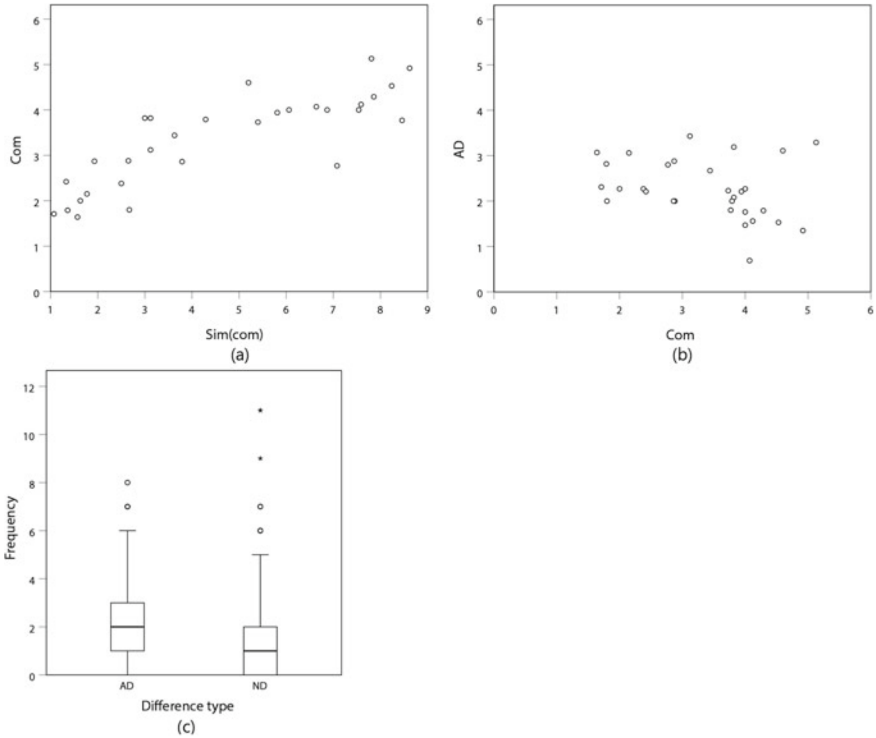

Fig. 3 Scatter plots for **a** Sim(com) and Com, **b** Com and AD, and boxplot for **c** frequency of ADs and NDs

Discussion

The results of the study provided support for four of the five hypotheses (Table 1), with one hypothesis being falsified. Two of the hypotheses (H1a and H2) were common predictions of comparison-based models of similarity judgements. As predicted, when designers make similarity judgements of design concepts, similarity can be predicted by the number of commonalities and differences listed for the pair of design concepts (with 77% of the variance explained), with commonalities contributing more to similarity than differences detract from it (H1a). Further, as the relative similarity of a pair of design concepts increases, so too does the number of commonalities that those concepts have (H2). These findings are consistent with previous findings of comparison-based models in non-design contexts [8, 10]. They provide evidence that similarity judgements of design concepts are carried out by a comparison process of some kind, where similarity is a function of commonalities and differences. In design, this finding is consistent with prior research in indicating that designer similarity judgements of design concepts operate over the common and different features of a pair of concepts [6].

The remainder of the predictions (H1b, H3 and H4) concerned the purported special nature of alignable differences over nonalignable differences in a SA model of similarity. Consistent with this view, it was found that it is alignable differences, not nonalignable differences, that are significant predictors of rated similarity (Com, ADs and NDs explained 73.3% of the variance in similarity) (H1b). Alignable differences were also found to be more numerous than nonalignable differences (H4). The hypothesis that was not supported (H3) is that there would be a positive correlation between the number of listed commonalities and ADs. Contrary to expectations, a non-significant negative correlation was found between Coms and ADs. The falsification of H3 means that the SA model cannot be accepted as a model of designer similarity judgements of design concepts. It does not conclusively falsify the SA model, as to do so would require the elimination of alternative explanations for H3 and the testing of additional auxiliary hypotheses.

The rejection of the SA model can be interpreted in two ways. The first is that the SA model is not an appropriate representation of designer similarity judgements of design concepts, and alternative models are required. Alternatively, the SA model *is* appropriate and the falsification of H3 was a Type II error caused by e.g., insufficient experimental power or measurement noise. In either interpretation, it may be possible that idiosyncratic characteristics of design concept similarity judgements mean that none of the existing domain-general cognitive models will apply to design contexts as-is. For example, the design brief may have introduced context effects or the relatively abstract and undetailed stimuli may prompt a focus on the purpose or function of the artefact. Such effects could require domain-specific models to explain. We intend to explore these possibilities in greater detail in future publications.

Conclusions

Five hypotheses were derived from the Structural Alignment model of similarity judgements and tested via a correlational quasi-experiment. The results indicate that when designers make similarity judgements of early-stage design concepts, they do so via a process of comparison. The evidence for this claim is that the similarity of a pair of design concepts can be predicted as a function of the commonalities and differences of that pair of concepts, and there is a positive association between similarity ratings and the number of commonalities of a pair (H1a and H2). Consistent with a Structural Alignment view of similarity, it was the contribution of alignable differences more so than nonalignable differences that influence similarity (H1b) and alignable differences are more numerous than nonalignable differences (H4). Contrary to expectations, however, there was no positive association between the number of commonalities and alignable differences (H3). The falsification of H3 means that the Structural Alignment model was rejected based on this data. The data do not support conclusive falsification of the SA model but it is not yet possible to determine the nature of the comparison process involved in design concept similarity judgements.

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Design Strategies that Work: How Engineers Use Sequential Decision-Making to Improve Design Performance in Concept Selection

Yakira Mirabito and Kosa Goucher-Lambert

Despite increased efforts to improve the quality of early-stage concepts, research has found that engineers often do not select the best designs available. Unnecessary time and money are spent when lower-performing concepts are selected and pursued within engineering design. This research studies the design strategies engineers utilize in completing a multi-objective concept selection task and their influence on design performance over task duration. Fifty-seven participants explored a design space containing 21 alternatives and gathered additional information about a subset of these alternatives through limited testing before submitting a final decision. Performance was measured via a quantified success rate, an experimental value developed in this work. Strategies such as isolating design parameters and prioritizing parameters improved design performance. In conclusion, there are clear strategies that engineers and designers benefit from using to guide their decision process. Future work will consider how these strategies are utilized within traditional concept selection methods.

Introduction

Concept selection is a critical phase in the engineering design process that significantly impacts later stages such as testing, development, and final deliverables [1]. After a problem is defined, engineers brainstorm possible solutions, usually via words and sketches. Then engineers must compare concepts and decide which concept(s) to select to advance to later stages in the design process. While the selected concept may not become the final design, features or functions of the concept may appear in the final solution [2].

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The design research community seeks to increase innovation and creativity in the design process through early-stage design by assisting engineers and designers in improving their innovative and creative potential in concept generation [3, 4]. Despite these increased initiatives resulting in more innovative or creative ideas, research has identified that engineers do not always select the best designs available, instead opting for more feasible solutions [5–8]. This tension serves as the motivation behind this research, which investigates the concept selection dynamics behind the sequential decisions made in this phase to understand how designers select less optimal concepts.

How designers select a concept can be formal using decision matrices or mechanical design principles [9–11] or informal without using such tools relying on intuition or a gut feeling [12]. A designer's final concept assessment could be captured in Pugh matrices as scores or weighting, but this tool/method does not capture the order of assessment attributes or the influence of exploration of prior designs on future design considerations. The order of assessment provides rich design data used to extract design strategies. Concept selection is a dynamic process composed of a series of sequential decisions influencing one another [13–15]. This research investigates the strategies designers use in the concept selection process and how they influence design outcomes (i.e., quantifiable design performance). The primary research question is, what concept selection strategies positively influence design outcomes?

Background

The motivation behind this research and relevant literature are discussed further in the following three sections. Selecting design concepts highlights why this research focuses on this stage in the engineering design process. Concept selection as a series of sequential decisions introduces a process approach in which nuances in design behavior can emerge for this study. Design strategies that influence design performance feature both positive and negative impacts known decision-making strategies have on design outcomes.

Selecting Design Concepts

Evaluating a concept is a crucial stage that converges on fewer concepts than initially generated [1]. Uncertainties associated with each design add to the difficulty of this stage. Designers usually must consider multiple design criteria, often criteria that contradict one another. Due to this stage's importance in engineering design, many methods and tools are available to assist decision-makers. Tools include but are not limited to decision matrices, analytic hierarchy processes, uncertainty models, economic models, optimization concepts, and heuristics [16]. Decision matrices vary in their effectiveness [10, 17]. A Pugh decision matrix lists the concepts to be evaluated, then the design team (individually or as a whole) rates the concepts on a series of qualities the team deems most important [9, 12]. Although the tool focuses on objectivity, literature has identified cases where team members have selected criteria to rate that would help confirm and support their preferred concepts [18]. Multi-attribute decision-making methods result in different outcomes [19]. Therefore, this research is not concerned with why designers select the method or approach but instead focuses on designers' observable actions throughout the concept selection process.

Concept Selection Is a Series of Sequential Decisions

Engineering design is an interactive and cyclic process composed of divergent and convergent stages [16, 20]. Concept selection should not be viewed as a single final decision but rather a process in which design alternatives are considered before the ultimate decision is made. Concept selection can be decomposed into multiple subsections of information gathering, evaluating the designs, weighing the evidence, and deciding between alternatives. Selecting a concept is generally convergent behavior; however, exploration and consideration of design alternatives align with divergent behaviors [20]. Taking a process approach in concept selection enables nuances in a design strategy to emerge that prior design research has not yet considered.

A design strategy consists of a string of design actions. This paper defines design actions as observable and quantifiable steps such as viewing a design, testing a design, or submitting a design. Participants can learn sequences based on the information provided or design actions possible, and this learning may or may not be conscious [21]. Due to the parameter tradeoffs and ability to test designs in this research study, optimization techniques [22–24] and interdependencies (coupled decisions) [25] on viewing and testing prior designs are explored. The use of design strategies in parameter tradeoff problems seeks to minimize or maximize a function. In this study, maximizing design performance means selecting a design with a high success rate.

Moreover, the design research community seeks to capture sequential decision behavior from human designers to transfer to computational agents. Research from McComb et al. identified decision sequences as beneficial to designers via Markov chains [14] which aligns with prior sequence learning work [21]. Another paper from McComb et al. mined process heuristics via Hidden Markov models that differed by design performance [15]. The first paper identifies that participants used operation sequences but did not go into the types of operational sequences and how they relate to engineering principles [14]. The second paper further identifies differences among designers based on performance; however, hidden states in this model lack an understanding of what those states are and why they result in specific design actions [15]. Similar work from Raina et al. focused on extracting design heuristics and transferring them to computational agents [26–28]. While successful in creating

Table 1 Concept selection strategies of interest and descriptions of the design behavior rooted in preliminary work [29]

Strategy	Explanation
Isolating variables	Adjusting one variable at a time while holding all other parameters constant such as single parameter tuning. Multiparameter tuning does not fall into isolating variables [22, 29]
Prioritizing variables	Focusing on a given variable throughout a portion of the decision-making process is measured by the number of sequential steps per one variable [22, 29]
Shifting between variables	Transitioning focus from one parameter to another is measured by the number of transitions [22, 29]

designs of similar performance or better, the agent takes design actions that will likely improve the design, but the rationale or motivation behind those actions remains unclear.

The purpose behind the three strategies of interest, listed in Table 1, is to generalize the findings beyond this specific design task. The complex nature of engineering design decisions often means the results and discussions in design research are unique to the type of design challenge. By taking a process approach focusing on systematic strategies, we highlight the design behavior that comes naturally to designers and its impact on design performance over task duration. These intuitive strategies, if present in this task without the explicit instruction to use a design method, should also appear in design processes where concept selection methods and tools are used. The strategies defined in this study are inspired by the literature on optimization as a concept selection method [16, 22, 23] and early observations from [29]. In previous observations, participants mentioned identifying the parameters that can be tuned (*isolating variables*) and focusing on one parameter at a time (*prioritizing variables*). The term *shifting between variables* refers to the shift in focus from one parameter to another. Such transitions within a process are similar to Atman et al. [30], but instead of engineers switching through engineering design phases, micro phases in concept selection focus on how engineers engage with the tunable variables.

Design Strategies that Influence Design Performance

Not only does this research identify and describe design strategies within concept selection, but it aims to determine the impact such strategies have on design performance. Prior work showed that designers' navigation through the design space and testing procedures impacted design performance [29]. Confirmation bias, ownership bias, or anchoring/design fixation are known biases influencing engineering design [18, 31, 32]. By moving beyond a single action, insight regarding how designers approach design problems and engage in the concept selection process could help uncover how biases unfold into design actions. The key to comparing design strategies relies on comparing design performance for a design task. Evaluation methods might use human raters to evaluate designs [3, 4] or use strength-to-weight ratio calculations. Objective measures based on experimental data are used in this study, not just for the final design submitted, but this measure assessed a participant's real-time performance over task duration.

Once the impact of design strategies on design outcomes is known, there are two common approaches to incorporating them into design practice. One might identify beneficial strategies, then teach those strategies to other designers—learn from what others do well. Alternatively, the research could identify pitfalls to avoid and bring these common issues to the attention of others—learn from others' mistakes. With the development of computational tools to assist in the design process, agents also need to learn how to design. Agents may learn human preferences or design approaches from traditional engineering principles; however, there is merit in understanding how designers design without structured methods or tools [26, 27]. Often such approaches use datasets from human designers to extract design strategies and biases that naturally occur. By understanding the influence design strategies have on the solution space and consequentially design performance, nudges can be used, for example, to help a designer pursue a particular strategy that causes them to increase their search space when a high degree of design fixation is detected.

Methods

This study identifies strategies used in the concept-selection process and their influence on design performance. Data from a human subject study carried out by the authors of this paper was analyzed to explore these patterns for insights into decision-making behavior [29]. The study asked participants to submit a design for a gripper surface for a dishwashing robot.

Concept Selection Task

Participants were instructed to submit one design to move forward to production, the next step in the fictional robotics team's design process. They were tasked with designing a gripper surface for a robotic arm, as shown in Fig. 1. The dishwashing robot uses a grasper in a wet and slippery environment due to dish soap. A design's success was determined by the robot's success rate in grasping a range of dishware. The designer has 21 alternatives to select among which are combinations of seven surface geometries and three material hardness options. After clicking on a design, as noted in Fig. 2, a screen displayed its datasheet where participants could test that design which revealed the testing result. The success rate is based on empirical friction data scaled proportionally between zero and 100%. Each participant had

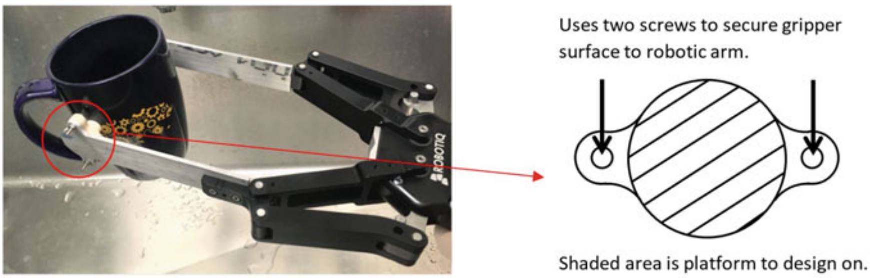

Fig. 1 Diagram of the design challenge to show participants the gripper surface and its interaction mechanism with the grasper on the dishwashing robot

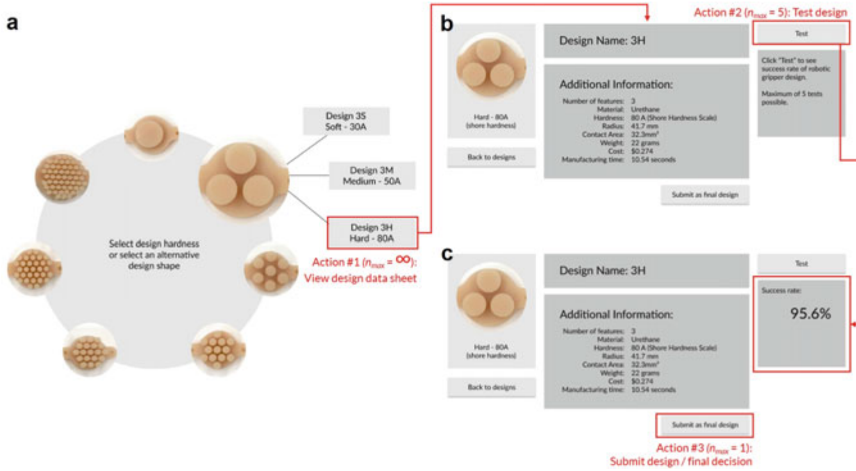

Fig. 2 The design actions of interest are represented as actions 1–3, and n_{max} indicates the number of times said action could occur. **a** Each of the seven geometries (shown as images) branched out to include a soft, medium, and hard version. Clicking one of the branched-out designs opened a datasheet **b** for that design. A test displayed a design's success rate (**c**)

ten minutes to complete the task with the option to test up to five designs to see corresponding success rates (design performance). No specific concept selection method or tool was provided.

Participants

A total of 68 participants were recruited for the design study using a call for participation at the University of California, Berkeley. Participants were compensated $10 for their participation for 30 min. A bonus of up to $20 was offered contingent on task performance. Participants were screened and required to be 18 years or older with engineering or design experience to participate in the research study. Experience ranged from completing a single design class upwards to over ten years as an engineer in industry (0–4 years, 34, 5–9 years, 21, and 10+ years, 2). Participant demographics included undergraduate, graduate, and working professionals with engineering and science backgrounds. Data from 57 participants (30 men, 26 women, and one non-binary person) was used for data analysis. Data from 11 participants were removed due to a lack of following instructions and equipment errors.

Research Design

The experiment took approximately 30-min and consisted of two parts: the design task and a post-task survey. For the scope of this research, only the design task is of interest, and thus information regarding the post-task survey is not mentioned but can be found in [29]. Colleagues provided the 21 gripper surface designs (seven geometries and three material hardness options) and experimental data based on a slippery environment [33]. Those friction values, not shown to participants, were then translated into success rates between 0 and 100%. A five-test limit was set to mimic real-life constraints in the design process, where a limited number of designs can be tested due to time or financial constraints. Preliminary experiments found that few participants converged on a "good" design with less than five tests.

As shown in Fig. 2, participants interacted with an interface for the design task portion, which displayed the consent form, task instructions, and possible design options. The interface collected the time and number of tests but left it to the participant to monitor due to interface constraints. However, this decision to self-monitor was aligned with what engineers and designers experience outside of controlled studies, where they are expected to meet deadlines and stay within budget. Although the robotic gripper design could have been optimized using a computer program, this predefined solution space removed researcher subjectivity in classifying a participant's design actions and performance that alternative experimental setups may have introduced (e.g., having participants sketch their designs followed by researchers rating designs using rubrics).

Data Analysis

Design actions defined in this study were steps traveled within the solution space, and objective methods such as the success rate were used to evaluate a design's performance [18]. Data was collected from the Figma website using Maze.co, a clickstream collection platform. Each screen a participant visited was recorded, and each participant's duration, screenId, and sequential path were exported. Participant groupings were determined using design performance measured by the design's success rate.

Decision strategies of isolating, prioritizing, and shifting parameters were coded using the sequential path per participant. Isolating parameters means using single parameter design actions. An increase, decrease, or hold was determined for each parameter, hardness, and geometry. A single parameter move means one parameter was held constant while the other moved. The percentage of single parameter moves quantifies the isolating variables strategy, as measured using the number of single parameter moves over the sum of single and multiparameter moves. Prioritizing parameters highlights a participant's focus on a given variable throughout the task duration. Percent prioritization was computed as the number of sequential steps where one variable is the focus over the number of single parameter design actions. Shifting between parameters identifies the number of transitions where a participant's focus shifts from one parameter to another. Each transition count was coded when a multiparameter move occurred or when the parameter held constant changed within single parameter moves. The percentage of transitions was computed using the total number of transitions over the total number of design actions per participant.

Results

The strategies of interest utilized by participants in the design task include (1) isolating variables, (2) prioritizing variables, and (3) shifting between variables. These strategies were extracted from 2451 total design actions where participants took as few as 20 and upwards of 162 design actions (M = 44) and viewed between four and 18 unique concepts (M = 7). First, the relationship between these strategies and design performance is presented, followed by the differences between strategy usage among high and low-performing designers.

Isolating Parameters and Prioritizing Parameters Improved Design Performance

Isolating variables or single parameter tuning are the most identifiable and likely to improve design outcomes. Single parameter tuning means adjusting one variable at a time while holding the other parameter constant (e.g., changing geometry while holding material hardness constant). Spearman's rank correlation tests were carried out between the percent of single parameter moves and the success rate achieved. The percentage of single parameter moves was coded as the number of single parameter classifications over the sum of single and multiparameter classifications. The results show a moderate correlation, as shown in Fig. 3, which is statistically significant ($r_s = 0.32, p < 0.05$). Therefore, participants who engaged in a higher number of single

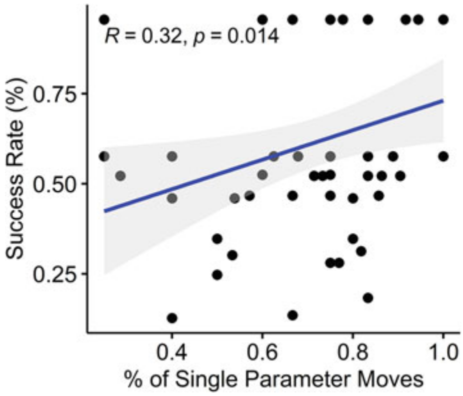

Fig. 3 The percentage of single parameter moves and corresponding success rate percentage. Each participant is represented by one data point. The shaded region represents a 95% confidence interval for the regression line

parameter moves were more likely to have improved performance. When participants did not use single parameter moves, they made multiparameter design actions which means they adjusted both parameters simultaneously. By completing multiparameter moves, participants jumped around the design space and could not understand the influence each variable had on design performance when conducting tests.

Prioritizing variables was a second design strategy shown to result in improved outcomes. Prioritizing variables means focusing on a given variable throughout a portion of the decision-making process as measured by the number of sequential steps per one variable. Moreover, single parameter design actions or isolating variables need to occur for one variable to be held constant. Spearman's rank correlation tests were carried out between the percent of variable prioritization and the success rate achieved. Percent prioritization is the sum of moves that were single parameter and held constant between a series of sequential steps over the total number of design actions. A participant with high prioritization carried out primarily single parameter moves and, of those moves, held hardness constant while adjusting geometry. The results show a moderate correlation, as shown in Fig. 4, which is statistically significant ($r_s = 0.44$, $p < 0.01$).

Shifting between variables means a participant's focus shifted from one parameter to another as measured by the number of transitions. Thus, a transition was coded as any time a multiparameter move occurred or when the parameter held constant changed within single parameter moves. The percentage of transitions is the number of transitions over the total number of design actions. Spearman's rank correlation tests were carried out between the percent of transitions and the success rate achieved. Fewer transitions indicate increased focus on a given parameter. A lower percentage is expected for participants engaged in single parameter moves and prioritized one variable for a longer duration. A higher percentage of transitions is expected for participants who only engaged in multiparameter moves or who changed the parameter of focus multiple times throughout the task duration (i.e., a participant who engaged in single parameter moves but only held a parameter constant for a brief number of steps and instead kept changing the tuning parameter). The results

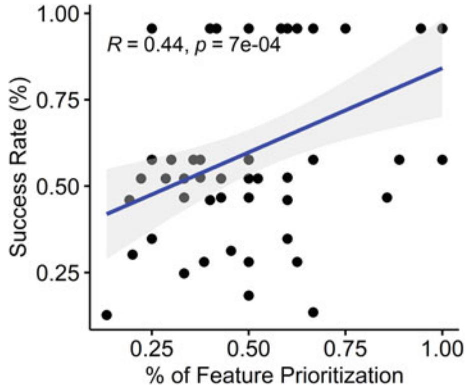

Fig. 4 The percentage of max feature prioritization and corresponding success rate percentage. Each participant is represented by one data point. The shaded region represents a 95% confidence interval for the regression line

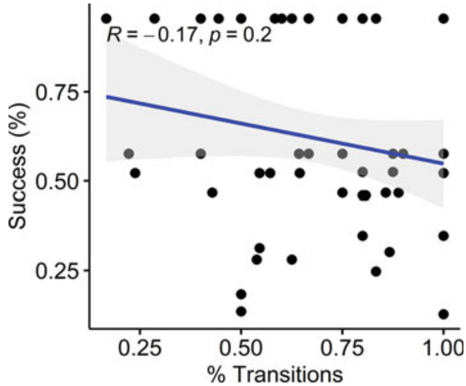

Fig. 5 The percentage of transitions and corresponding success rate percentage. Each participant is represented by one data point. The shaded region represents a 95% confidence interval for the regression line

show a very weak negative correlation, as shown in Fig. 5, which is not statistically significant ($r_s = -0.17, p = 0.20$).

High and Low Performing Designers Differed in Their Design Strategies

Participant groupings were determined using design outcomes measured by the design's success rate. Participants in the high-performing category ($n = 19$) achieved the best possible design (96% success rate). The average-performing category achieved success rates above 50%, excluding the optimal design ($n = 20$), while those in the low-performing category achieved success rates under 50% ($n = 18$).

Figure 6 shows the mean usage for the three strategies (isolating, prioritizing, and shifting) for high and low-performing designers, as indicated in light and dark blue, respectively. The y-axis represents the number of design actions categorized as a given design strategy over total design actions as a percentage. Design actions

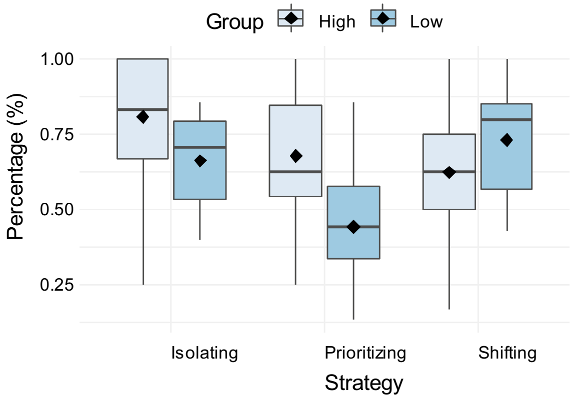

Fig. 6 Three strategies of interest and their corresponding mean percentage as indicated by the diamond shape (% of parameter isolation, % of parameter prioritization, and % of parameter transitions) split by high and low-performing designers

were categorized as isolating variables when only one variable was adjusted while holding the other parameter constant as measured by the number of single parameter moves. Design actions were characterized as prioritizing variables when a participant focused on a given variable throughout a portion of the decision-making process as measured by the maximum number of sequential steps per variable. Design actions were labeled as shifting between variables when the focus transitioned from one parameter to another as measured by the number of transitions.

For isolating variables, there was a 15% statistical difference across usage for high and low performers ($M_{high} = 81\%$ and $M_{low} = 66\%$; Mann–Whitney $U = 92.5$, $n_1 = 19$, $n_2 = 18$, $p < 0.05$ two-tailed). Expanding beyond the ability to isolate variables, to feature prioritization there was a 23% statistical difference across usage between the groups ($M_{high} = 68\%$ and $M_{low} = 44\%$; Mann–Whitney $U = 72.5$, $n_1 = 19$, $n_2 = 18$, $p < 0.05$ two-tailed). Lastly, regarding the frequency of transitioning between variables, high performers had −11% difference in usage than low performers ($M_{high} = 62\%$ and $M_{low} = 73\%$) which was not statistically significant (Mann–Whitney $U = 118$, $n_1 = 19$, $n_2 = 18$, $p = 0.11$ two-tailed). High performing participants had an increased usage in isolating and prioritizing parameters. No conclusion can be drawn regarding the shifting between variables strategy.

Since high and low performers differed in their ability to isolate design parameters over task duration, an additional analysis was carried out using Markov models to predict the probability of strategy used when considering the most recent design action. A first-order Markov model from the behavioral data was utilized to identify transition probabilities of moving from one state to another. The transition probabilities help explain the behavior observed and the likelihood of a specific sequence of decisions would occur. The three-state Markov approach is a simplified version of the initial 21 states explored (e.g., one for each design). With a 21-state model, entire path sequences could be generated for t timesteps, and their corresponding success rate could be computed. The three-state Markov model aims to generalize design actions beyond the specific robotic gripper surface design task via single parameter (SP), multiparameter (MP), and testing (TEST) design actions.

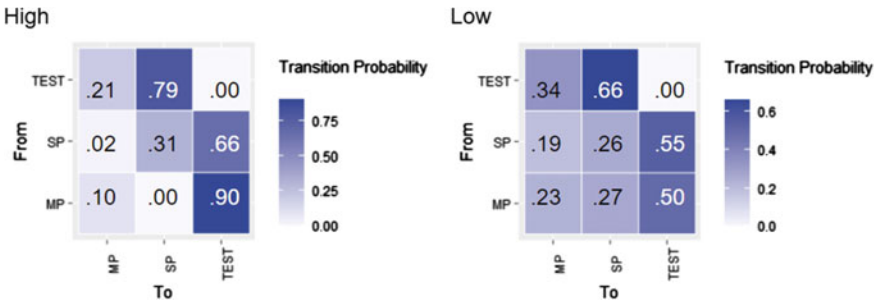

Fig. 7 Transition probabilities of a first-order Markov model split by design performance

Figure 7 demonstrates that high performers focus more heavily on single parameter moves (i.e., isolating design parameters). In the few instances that high performers use multiparameter design actions, they do so primarily before (0.90) and after (0.21) a test action. Based on the behavioral data, when high performers conduct a multiparameter move, they have a 0.10 chance of conducting another multiparameter move, a zero chance of conducting a single parameter move, or a 0.90 chance of running a test. Alternatively, low-performing participants engage more with both single and multiparameter design actions. The transition probabilities to and from a non-test state are within a range of 0.19 and 0.27, as noted in Fig. 7. Across both group groups, they each have a higher probability of moving into a single parameter state after conducting a test and a higher probability of conducting a test when in a single or multiparameter state.

Discussion

Three design strategies (isolating, prioritizing, and shifting between parameters) were investigated within concept selection, and their influence on design performance was determined. Fifty-seven participants were tasked with selecting the best gripper surface design for a dishwashing robot. Design performance for each of the predefined set of 21 concepts was based on experimental data. To answer the main research question, the findings show that the two strategies (isolating and prioritizing parameters) positively influenced design outcomes, while shifting between parameters did not significantly influence outcomes. These distinctions in design behavior reveal the nuances and complexity of an individual designer's approach and are discussed below.

Case Study: Strategy Usage for a High-Performing Participant

Figure 8 displays the three strategies of interest by visualizing the two tunable parameters and corresponding success rates for a high-performing participant over the task duration. In this design challenge, participants needed to recognize that geometry and hardness were the two tunable parameters and adjust them accordingly to find the optimal design. Initially, the participant switched between designs randomly, alternating quickly between parameter one (geometry), both parameters, and parameter two (hardness), indicating the participant had not yet figured out which parameters to isolate. After the first test was conducted, the participant focused on tuning geometry (prioritization) for most of the remaining time and only varied hardness three times (shifting). Once the shift occurred, this was the point in which a participant isolated variables and switched to prioritizing variables. Taken together, in Fig. 8a, the participant starts at the middle range for geometry and incrementally increases geometry while holding hardness constant, as shown in Fig. 8b. Visualizing design behavior over task duration indicates that high-performing participants employed a high percentage of single parameter moves and engaged in a high degree of prioritization of parameters. In a scenario where a participant had a low single parameter usage percentage, their moves for both parameters would vary at every step with fluctuating y-values.

Implications of Key Results

Performing a high percentage of single parameter moves did not guarantee success. Instead, the findings suggest that using single parameter moves and making incremental adjustments to one parameter for multiple steps did increase the likelihood of success. Across the 57 participants, all utilized single parameter moves. However, the data shows that only seven participants used single parameter moves exclusively, and the lowest percentage of single parameter usage was 25%. Of the participants engaged in high single parameter move usage, their success rates were not all in the highest performing category. The participant who utilized single parameter moves almost entirely yet performed poorly could be explained by the large leaps between designs they took or lack of order in testing. For example, a participant who used single parameter moves but adjusted one parameter in large leaps rather than incremental changes, or a participant who changed which parameter they held constant (e.g., switching from parameter one to the other while holding the opposite parameter constant). The strategies participants used resemble techniques commonly used in algorithms for optimization problems, such as agent search strategies or methods to maximize objectives [16, 22, 34]. Thus, improving design outcomes relied on a combination of systematic strategies rather than random walk approaches.

Humans are naturally uneasy with uncertainty and desire order [35, 36]. These patterns of sequential design actions emerged, regardless of whether such patterns

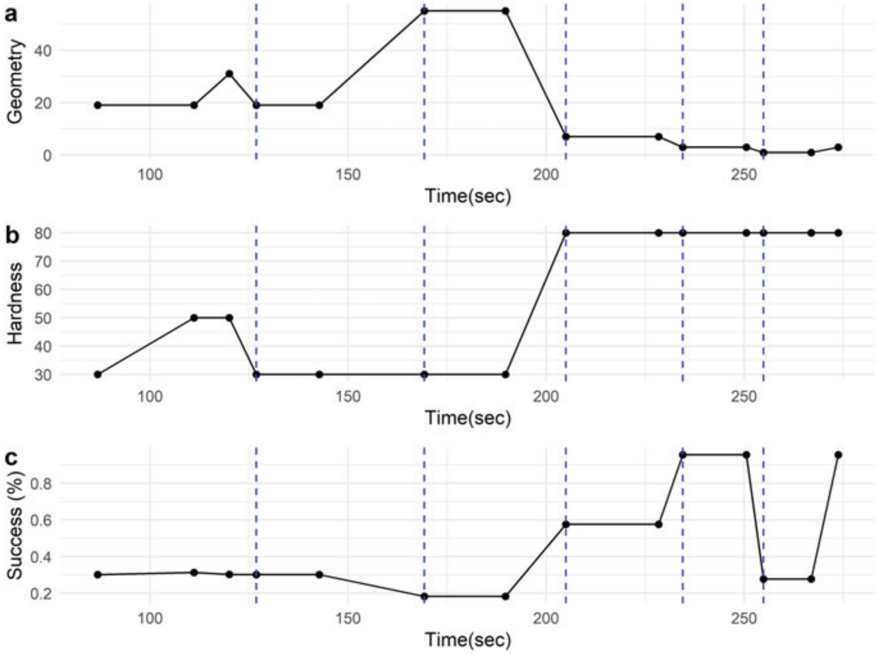

Fig. 8 Design parameter tuning over task duration for a high-performing participant. The five dashed blue vertical lines represent the moment the participant conducted a test, enabling the success rate to become known for that design. **a** Parameter 1—Geometry over task duration. **b** Parameter 2—Hardness over task duration. **c** The success rate as a percentage over the task duration. The success rate is known to the researcher for each design explored. A participant can learn the success rate only after conducting a test for a maximum of five designs

were conscious [21]. Participants' usage for design strategies could be explained by the brain's intrinsic desire to reduce cognitive load whenever possible (i.e., use heuristics or biases). Cognitive load means the mental effort needed to learn new information [37]. Research suggests that improved design performance might be caused by a decreased cognitive load [38, 39]. Kahneman's systems one and two could help explain the differences observed in the speed of decision making and the degree of mental effort used by participants [40]. Fast and strategic actions might be associated with system one for a participant who has increased design expertise or a participant who is simply guessing throughout the task [41]. In contrast, participants who took longer between decisions might be utilizing system two, which requires more effort due to their unfamiliarity with the problem type and time limit imposed.

The cognitive load of single parameter moves should be smaller than multiparameter moves since the information for the next design explored shares a parameter with the previous design. Multiparameter moves do not share either geometry or hardness. Participants then integrated the information received and established relationships between design actions and knowledge (e.g., identifying which design parameters were relevant, determining the relationship between each parameter and success rate). Engaging in the design strategies studied, the cognitive effort required was likely decreased, thus making key relationships easier to identify and integrate into the design process.

Contrary to what one might expect, participants did not mention traditional concept selection methods or tools such as weighting or ranking of designs via decision matrices in their open-end responses regarding their decision process [9, 16, 42, 43]. All participants stated they had completed a design course, and most have participated in design project-based teams in a course or industry that likely included standardized decision processes. Research from López-Mesa and Bylund that studied concept selection method usage inside a company identified that five of the 22 interviewees used none or one method in their concept selection process; The lack of use was explained by the roles of the engineers working in late-stage design and an engineer who is known to be 'against' methods [12]. Neither of these explanations appeared in the participants' open-ended responses in this study. Perhaps the results reveal the underlying building blocks (e.g., design strategies) designers use within standard concept selection methods. The varying percentage of design strategies used may help explain why standard concept selection methods have varying outcomes in design performance.

The task duration, problem type, or presentation of concepts for the robotic gripper task may have limited participants' concept selection methods and tools. Ten minutes was used based on research that found designers spend a relatively short time deciding between concepts (between three and eight minutes) [30]. An extended timeframe might have led participants to use commonly taught concept selection methods or develop more complex design strategies. The presentation of designs may have also influenced the strategies designers used, which might have differed from physical prototypes, excel spreadsheets, or an interactive prototype that could have parameters altered via a sliding tool. Note that future work could extract additional strategies using methods (i.e., varying the levels of analysis concerning time and transitions between design activities/stages) from Atman et al. that explored the nuances between novice and expert designers' engagement with different aspects of the design process [30, 44].

Incorporating Design Strategies of Interest into Practice

There is a need to assist human designers and computational design agents in the concept selection phase [26, 27]. Human designers could benefit from understanding what they do well and not so well. Depending on the purpose of a computational agent, one might want to mimic human design behavior for modeling, alternatively outperform human designers, or build a collaborative computational tool that collaborates with human designers. Regardless of the application, understanding human design behavior is necessary to integrate design strategies into practice.

The two strategies of isolating and prioritizing parameters could be integrated into computational models to describe, explain, or predict design behavior. The

Markov models generated in the results section could be transferred for computational modeling of design behavior, as previous research has shown possible [14, 15, 27]. Fictional design data could be generated with a transition matrix of state-state probabilities, enabling comparisons between computational agents and human designers. Future analyses in this application might consider the speed or rate of exploration as another measure in systematic strategies. Alternatively, the two strategies of interest could be integrated into engineering education.

Figure 8 shows the designs a participant explored over time as split by parameter with corresponding success rates. Visualizing design behavior for evaluation or assessment could be one use case; however, visualizing a designer's learnings or providing real-time design feedback might be more beneficial. This visualization could show a student's or employee's decisions in solving a design challenge. Students and practicing engineers could see the sequence of decisions they performed at a high level and pinpoint when they were and were not systematic in the design process. Not systematic, meaning design strategies of interest are not captured. One should note that not using one of the strategies of interest does not mean no strategies were used but more likely that they are using strategies not captured in this research design. Future work might explore the use of design behavior dashboards to highlight efficient and less efficient portions and explore how this tool impacts design outcomes and designer experience.

Conclusion

Engineers routinely select lower-rated concepts despite higher-rated alternatives within the solution space. Prior research has studied the influence of specific concept selection methods and tools that influence final decisions; however, the focus of this research investigated the concept selection phase as a series of sequential decisions in which strategies for exploring and evaluating designs emerge. Not only do the findings identify strategies participants used in the robotic gripper design task but also how strategies in isolating and prioritizing design parameters positively influenced design outcomes. High-performing designers were found to engage more with isolating and prioritizing design parameters than low-performing designers. While a select number of strategies were highlighted in this study, there are likely additional decisions strategies worth studying, such as degrees of transitions and time spent on design parameters. Isolating and prioritizing design components are likely used within other concept selection methods and tools such as Pugh matrices, where designers need to assess multiple concepts. How an engineer explores and evaluates design alternatives will provide further insight into how engineers select lower-performing designs despite using standardized selection methods. Design researchers should evaluate how these design strategies show up within standard concept selection methods, not just which strategies or methods designers use, but work to understand their influence on design outcomes.

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Knowledge Transfer in Designing as a Situated Activity: A Case Study of Spatial Design Using Lego Blocks

Yuval Kahlon and Haruyuki Fujii

Existing frameworks for situated design enable to model design activity while considering how agents internally see and understand the external world. Therefore, they are important for developing human-level intelligence in computational design systems. One major aspect in developing situated design agents is that of agent-environment interaction. While the contribution of such interaction to structuring design processes is acknowledged by practitioners and researchers alike, we lack evidence concerning the manners in which it unfolds in practice. Addressing this issue, we gather empirical data regarding agent-environment interaction in design, with emphasis on knowledge transfer (KT)—a cognitive process by which an individual applies knowledge from one situation in another. Six participants collaborated and competed in modeling a real-world building using Lego blocks. Examining KT during the activity sheds some light on the role of concrete circumstances in shaping design processes, thus offering insights towards developing situated design agents.

Introduction

Frameworks for situated design agents, which have been proposed by various researches [1–3], can be seen as a bold attempt to implement human-level intelligence in computational design systems. As these draw on the situated approach to cognition [4], such frameworks emphasize agent-environment interaction as key for intelligent action.

An essential characteristic of human design processes is the way in which designers draw on their interaction with the world in developing their design ideas. As an example, consider Fig. 1. The authors were requested to develop an algorithm for

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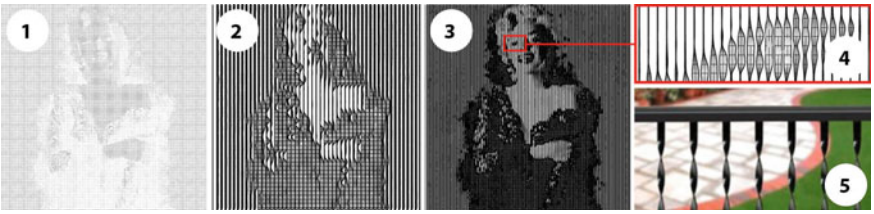

Fig. 1 Knowledge transfer as a result of agent-environment interaction; (1) before transfer; (2–3) results after transfer, in two level of granularity; (4) enlarged segment of 3; (5) twisting rods as a source of inspiration

generating posters from photos. The initial attempt of mapping between alpha values to dots/voids seemed quite conventional and thus unsatisfactory (1). Following this, while walking outside, a fence with twisting rods was noticed by one of the authors (5). Since such rods enable to generate interesting variations between full and void, they inspired the next design solution, which was implemented by remapping the alpha values of photos onto 3D rods (2,3). In this episode, strolling and visually interacting with the environment played an important role in designing.

The above episode not only demonstrates the effects of interaction on designing, but also provides an example for how designers benefit from focusing on one thing (source), extracting an insight from it (knowledge) and applying it to another thing (target). This ability to engage in knowledge transfer (KT, see next sub-section) is extremely important for designers, both as a strategy of drawing inspiration, and as a concrete means to avoid starting from scratch whenever a new situation arises.

This paper explores the manners in which interaction with the environment facilitates KT in designing, via a two-phased spatial design task. In the first phase, participants worked in small groups to represent an existing building using Lego bricks. In the second phase, they were asked to create individual designs, on the basis of insights from the group activity. We examined the ways in which participants utilized knowledge from the former phase to improve their designs in the latter phase, as a form of KT driven by agent-environment interaction. Our observations serve as a source for drawing insights regarding the enhancement of situated design agents, which are grounded in empirical data from design activity.

Knowledge Transfer in Design

The term KT, which has become strongly associated with organizational theory, is somewhat ambiguous in the literature [5]. Therefore, we open this sub-section by stressing that, in this study, KT refers to a cognitive process occurring on the individual level (as opposed to an inter-subjective level, organizational level etc.). According to Nokes [6], KT has been studied in cognitive science from multiple perspectives, such as: analogical transfer, knowledge compilation, constraint violation and more. Among these, design researches commonly focus on the role of analogy in conjuring design solutions, whether as a vehicle for creativity at the individual level [7–9], or even in design teams[10, 11]. Constraint violation is also associated with these issues. Grace and Maher, for example, tied the violation of expectations with the novelty of artifacts [12] (expectations frame one's perspective and can thus can be seen as imposing constraints on the design space).

Existing work regarding KT focuses mainly on analyzing mappings between situations and/or design products, and less on the contribution of concrete circumstances to facilitating KT. However, since such circumstances are important for explaining human design processes [13], we have devised this study from the perspective of situatedness in design (as explained in the next sub-section). To facilitate further discussion, we provide a definition for KT which is specific for our purposes, from cognitive science.

First, Clancy suggests that knowledge primarily consists of two types of information: how the world appears, and how to behave [14]. In this study, the former includes the state of the artifact, design materials and more. The latter includes designers' thoughts regarding how to make progress in designing by: (1) identifying aspects in which the artifact can be improved as to reach a more desirable state, and (2) finding practical ways to do so. Notice that cognitive science generally regards knowledge as information captured within mental representations [15], however we include information stored in some form of external representation as well (e.g. notes). Second, with respect to KT, Singley and Anderson provide us with a starting point: "how knowledge acquired in one situation applies… to another" [16] (p. 1). Based on the above, we consider an episode X as KT if: (1) knowledge K from one situation S1 is employed in a situation S2 to modify an artifact A1 into a more desirable artifact A2, and (2) when K is employed, it is necessary to adapt/modify it into K', to enable its implementation in S2.

Agent-Environment Interaction and Memory in Situated Design Agents

Situated Cognition emphasizes that thinking and action can only be understood by looking beyond agents as world-independent entities and examining coupled agent-environment systems [4]. Such systems can be described as dynamical systems, in which each side perturbs the other, as they interact [17]. One reason for interaction being an important aspect of real-world designing is that it plays a role in biasing our perceptions with respect to design representations, such that our expectations determine (to some extent) their interpretation [18]. Another is that, as we interact with the environment, we discover new possibilities for thinking and action [19, 20].

Derived from the above is the following basic characteristic of design processes—both internal (agent) and external (environment) factors shape the course of design. Thus artifacts are produced from the dynamics between the two [21].

On the basis of theories which view intelligent action as a form of situated coordination [22] and memory construction [23], Gero has put forward the observation that design is fundamentally situated [13]. Design is situated in the sense that designers are forever embedded in contexts which shape the way they view the world, and therefore their decisions and actions. A fascinating example is the famous "duck-rabbit" figure, attributed to Jastrow [24], which tends to be interpreted as a rabbit when approaching Easter [25]. Such motivational expectancy is a clear demonstration of the ways our circumstances shape our dispositions and thus our view of the world.

Since modeling designing requires considering its situated nature, situated design agents have been proposed, with the intention of simulating human-like design capabilities [1, 26]. One of the main components of such agents is their constructive memory—a dynamic memory system which consist not only of storage and retrieval, but also of reconstruction of past events based on current happenings. According to Kannengiesser and Gero, memories are constructed based on: (1) the specific demands of the situation, and (2) the original experience to which they can be traced to [3]. In other words, memories are tightly linked with the design situation, both during formation and during recall, which essentially involves their reconstruction [21].

Cases of KT may thus be described as follows: an agent Q constructs some knowledge K as a memory M in a situation S1 and by interacting with an environment E. Later, Q is found at a situation S2 in which M is deemed useful, and thus (considering the difference between S1 and S2) reconstructs it as M' to apply it to S2. This study sheds some light on how such complex processes unfold in practice, towards the enhancement of situated design agents.

Aim, Objectives and Significance

Our research aims to inspire the development of artificial design agents. In this study, our efforts focus on the description of important phenomena concerning KT which shape the course of design. Our main objectives are: (1) collect evidence for KT events in human design activity; (2) relate these events with agent-environment interaction and memory construction, to stimulate the development of situated design agents.

By suggesting ways to enrich current frameworks for modeling design from a situated perspective, our work furthers the efforts of striving towards autonomous artificial agents for designing. These are valuable both from the perspective of artificial intelligence and from the viewpoint of cognitive science, for obtaining a deeper understanding of human cognition via simulation and reflection on their performance.

Method

In accordance with our objectives we: (1) devised, executed, and documented a design task in which various forms of KT could be observed; (2) identified events of KT and described them in a sequential manner; (3) related these events with agent-environment interaction and memory construction; (4) drew conclusions for inspiring the development of situated design agents.

Task Overview

A task involving group designing as well as individual designing was devised (see "Execution and Documentation") such that the two sub-tasks (group/individual work) were similar, but not identical. This provided participants for possibilities for KT between the sub-tasks while necessitating certain adaptation in the process.

The core of the activity was to design an abstract expression for an architectural building in Gunma (Japan) using Lego blocks. Participants were provided with a set of monochrome Lego blocks (white, gray, transparent). The requirements were to design a model that is: (1) an ekphrastic expression of the original building [27], i.e. expresses it in a different medium; (2) is as small as possible. The choice to employ Lego blocks for constructing physical models, along with the demand to minimize their size, posed a challenging task—since it is impossible to reproduce the original in detail, participants needed to find original ways of representing (or re-presenting) certain aspects of the source, thus stimulating creative expression. Further, using the same medium across the different phases of the task facilitated KT among non-professionals, as they continuously worked in the same "design world" [28] spanned by the limited possibilities that Lego blocks entail.

Finally, note that while participants were asked to transfer *some* knowledge, they were not told *what* should be transferred nor *how* to adapt it to the new situation. As this investigation focuses largely on the latter, explicitly instructing participants to engage in KT did not hinder the collection of reliable empirical data.

Execution and Documentation

Six participants, all holding a bachelor's in architecture (at minimum) were recruited for the task. All participants have joined a preliminary activity of three meetings, in which they were asked to model an existing building of their choice using Lego. In the preliminary activity, the participants have experienced designing using Lego, and had a chance to practice documenting their ideas, as well as conveying them to others via discussion.

Phase 1: Team Design Task (TDT)

The six participants divided themselves into two teams of three via discussion, while considering their preference regarding working with certain peers. The activity was conducted in a lab environment. Audio and video data were recorded using a video camera (top). Sketches were kept and numbered immediately after completing the design session. The activity consisted of three 100 min sessions, while each session was structured in the form of five 20 min mini-sessions of designing (15 min) and documenting the design process (5 min).

This phase resulted in: (1) one physical model per team, and (2) one individual document set per subject. The latter included a description of the design and decision-making process (step by step, from the first meeting to the last), as well as pictures which show the different states of the model.

Phase 2: Comparison and Critique

This phase was designed to enable participants to think critically about their team's design by meaningfully engaging with the other team's result. Participants were requested to: (1) read the documentation made by others and examine their model; (2) write an individual report comparing his/her team's result with their other team's result. The main guidelines in this phase were to mention both strong and weak points of the models, and to comment both on the product and the process. Following this, a one-hour discussion with all participants was held and video-recorded, as an opportunity to share their comments and deepen their understanding of others' designs.

Phase 3: Individual Design Task (IDT)

Each participant was requested to utilize his/her insights from the process thus far for designing a new and improved model, within a two-week period. The design process of this model was documented by each participant using photos and sketches. Participants were asked to document and report the number of hours invested in producing the final model.

Phase 4: Final Evaluation and Retrospective Interviews

A panel of three experts was recruited to evaluate the models, all holding a Ph.D. in a related discipline, and at least 5 years of experience in teaching architecture at a major academic institute. An event including all participants was organized in which the individual models were set for display and examination by the judges. Each model was evaluated twice by each judge, based on first impression and following an explanation given by the participant. Evaluation consisted of grading on a rising scale of 1–10 and free commentary. The main criteria for evaluating the models were: (1) realism, i.e. the extent to which the model invokes the feeling of real architecture; (2) resemblance to the original, specifically; (3) originality; (4) size.

Following the presentation, all participants were interviewed individually by the investigators. The goal of the interviews was to clarify how each participant devised the final model and in what sense has he/she implemented the insights from the group design phase in his/her design. During the interview, the team models and the interviewee's individual model were placed side by side on a desk in front of the interviewee, to facilitate communication and enable easy reference to the results. Interviews were recorded using a video camera. A whiteboard was prepared for sketching, to enable the interviewee to easily communicate his/her thoughts. The result was documented using one still image.

Results

Design results from the TDT and IDT are shown below in Figs. 2 and 3. Based on these, we present important episodes of KT in designing. Notice that, while there were six participants in total, one participant chose not to join the individual design activity, which resulted in five individual models.

We begin by focusing on what knowledge was transferred overall, noting the key-features which were extracted from the original building and translated into the different Lego models across the whole task ("Feature Selection" sub-section). The rest of this section then provides a detailed account of events in which KT was observed, as participants tried to employ insights from TDT in IDT.

Feature Selection

When creating the Lego models, some aspects of the original building were focused on and deliberately expressed, while others were excluded/ignored/forgotten. Table

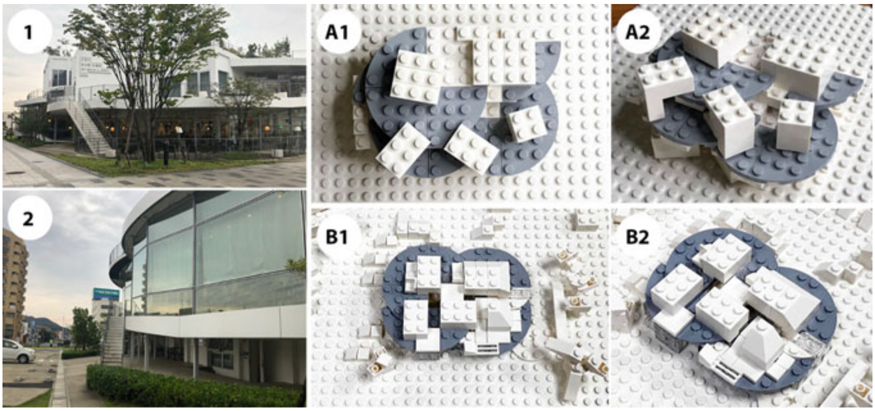

Fig. 2 Left: Original building of Art Museum & Library Ota, Japan: (1) main entrance at eye-level; (2) back entrance, characteristic rounded slabs; photos by Alisa Hiramatsu, with permission. Right: TDT results; team A (A1–A2), team B (B1–B2)

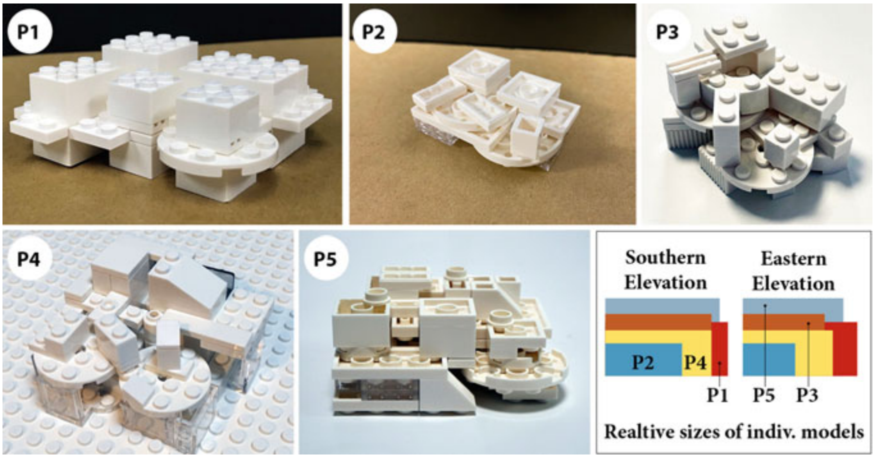

Fig. 3 Results from IDT, as photographed by the participants (P = Participant)

1 enumerates various key-features of the original and their inclusion/exclusion in the different models, generally classified into categories of structure-related and function-related features [29].

By examining Table 1 we can make several important observations regarding the participants' focus during the activity. First, all participants seem to have perceived the museum as the concrete mass of the main structure and placed little emphasis (or none) on the exterior space around it. For example, the grassy area at the foot of the building (e8), which is clearly visible, was not represented in any of the models. In fact, planation in general was largely ignored (e6,m3,m4), except for a single case discussed later. Similarly, the large openings (e2) in the white concrete volumes (e1) are absent from all models. Contrary to these, several aspects seem to have been perceived as central to the building's identity, which is reflected in their inclusion in all models. Prominent among these are the box-like concrete masses (e1) and the slabs which extend into balconies, and are thus visible (e3). Further, a comparison on a group level also yields interesting insights, the most striking of these is the difference in representation of functional vs. structural aspects. It seems that none of the main functional aspects of the building (f1-f5) were neither expressed by group A in TDT, nor later by any of the group's members in IDT. In a similar manner, aspects of material were also less attended to, while other structural aspects such as form and spatial relations were generally included in the designs.

With respect to KT between the two activities, several observations can be made: (1) not all knowledge from group model is transferred to the individual model, as can be seen in the case of sr2, which was expressed by group A in TDT but not by P1 in IDT; (2) some knowledge was transferred in an intra-group manner in the sense that an individual reused knowledge from TDT in IDT, such as fo1 which was carried from TDT to IDT by members in group B; (3) some knowledge was transferred in an inter-group manner in the sense that an individual adopted knowledge constructed

Table 1 Key features of original building and their inclusion across models

					IDT by original group				
			TDT		A			B	
F/S	ID	Building feature	A	B	P1	P2	P3	P4	P5
F	f1	Enter the space	N	Y	N	N	N	Y	Y
	f2	Move through the space	N	Y	N	N	N	Y	Y
	f3	Display and view art	N	N	N	N	N	N	N
	f4	Read books etc	N	Y	N	N	N	Y	N
	f5	Park bicycles	N	Y	N	N	N	Y	N
	f6	Rest (in café etc.)	N	Y	N	N	N	Y	Y
S	e1	Concrete volumes	Y	Y	Y	Y	Y	Y	Y
	e2	Glazed openings in e1	N	N	N	N	N	N	N
	e3	Flat concrete slabs	Y	Y	Y	Y	Y	Y	Y
	e4	Sloped exterior slabs	N	N	N	N	N	Y	Y
	e5	Exterior staircases	N	N	N	N	N	N	N
	e6	Roof gardens	N	N	N	N	N	N	Y
	e7	Curtain wall	N	Y	N	Y	N	Y	Y
	e8	Grass on ext. ground	N	N	N	N	N	N	N
	e9	Other env. elements	N	Y	N	N	N	N	N
	m1	Concrete (white)	Y	Y	Y	Y	Y	Y	Y
	m2	Glass (transparent)	N	Y	N	Y	N	Y	Y
	m3	Trees (mixed)	N	N	N	N	N	N	N
	m4	Grass (green)	N	N	N	N	N	N	N
	fo1	Not all e1 are boxes	N	Y	N	N	Y	Y	Y
	fo2	e1 top contour visible	N	N	N	Y*	N	N	Y
	fo3	e3 visible from outside	Y	Y	Y	Y	Y	Y	Y
	fo4	e3 on multiple levels	Y	Y	N	Y	Y	Y	Y
	fo5	e3 have spacing	Y	N	N	N	Y	Y	Y
	fo6	e3 curved and straight	Y	N	Y	Y	Y	Y	Y
	sr1	e1 rise from SE-NW	Y	Y	N	Y	Y	Y	Y
	sr2	e1 are not orthogonal	Y	N	N	Y	Y	Y	N
	sr3	e1 vary in height	Y	Y	Y	Y	Y	Y	Y

e physical element; *m* material; *fo* form; *sr* spatial relations.; *f* function; *Y* transferred; *N* not transferred; * transferred accidentally

by the other group during TDT and reused it in IDT, e.g. fo5 which was carried over from group A to two participants from group B.

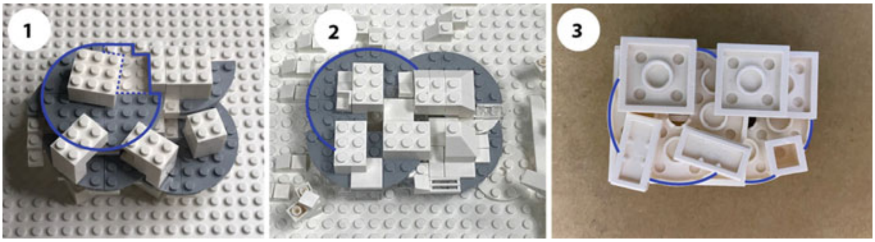

Fig. 4 KT between activities: (1) participant's team slabs, "not organized", two colors; (2) other team, "organized", one color; (3) individual result, single-colored

Example for Knowledge Transfer During the Activity

Our task was devised to first let participants design in teams, and then engage in individual designing. This enabled to observe the effects of the former phase on the construction of memories that facilitated KT in the latter.

As a simple example, consider the following episode: P2 reported that, having seen the other's team's model, he noticed that the building's large horizontal slabs were expressed using a single color (gray), in contrast with his teams' model which had two colors (gray and white; this was due to the limited number of blocks available, as well as their decision to express the real curvature of the slabs, which does not adhere to a perfect circle). He further described the other team's result as being "more organized", especially with respect to the slabs. The simplicity of P2's final design, which was highly praised by the judges, owes much to his choice to reduce the visual complexity, via using a single color for the whole model (Fig. 4).

What knowledge was transferred in the above episode? Taking P2 as the agent and the models & other participants as his environment, we can recount the series of events as follows: P2 created (1) by collaborating with his peers. Having seen (2) he decided that it is preferrable over (1), in the sense of being "more organized". P2 then related the number of colors with visual "organization" (or simplicity), which he embodied in his design (3), eventually propagating it to other parts of the model (i.e. beyond the slabs).

Verbal and Visual Forms of Knowledge Transfer

One way in which knowledge was transferred between the activities is in the form of explicit linguistic descriptions. Consider P1 who described her model as consisting of "boxes and limbs" (referring to the large box-like volumes and slabs in the original building, accordingly). She explained that this view of the building was developed during TDT using a diagram found online. In this sense, the original building was "summarized" as a linguistic expression, that later served as a basis for her design in IDT (Fig. 5).

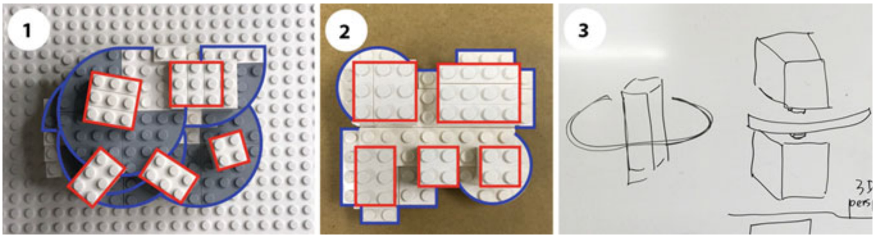

Fig. 5 Carrying over the notion of "boxes (red) and limbs (blue)" from TDT to IDT: (1) P1's team model; (2) P1's model; (3) P1's conceptual sketch

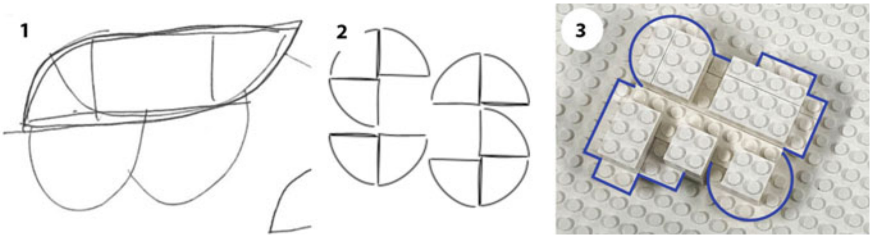

Fig. 6 Embracing design ideas from another team: (1) "limbs" sketch by P1's team—"not simple"; (2) "limbs" sketch by other team—"simple"; (3) P1's individual result

Notice, however, that while the linguistic description used for both models was identical (i.e. "boxes and limbs"), it was embodied differently in each case. This is evident from the orientation of the boxes, for example, which are not orthogonal in the team model (1) but are in the individual one (2). Another difference concerns the "limbs"—as the participant explained, she thought her team's expression of boxes was "simple" (and thus desirable) so she maintained it in her design. However, the "limbs" in her group's model were "not simple", which lead her to adopt the other team's idea about their construction (Fig. 6).

Another form of KT, which has a stronger visual component, is seen in the case of P4. The participant explained that he "copied" the slabs that were "not so circular" from the other group's design. Figure 7 shows the design produced by his team (1) in comparison to the sketch and model by the other team (2–3), as well as his final design (4). His individual model embodies the idea of incorporating both round and non-round elements when constructing the slabs, albeit in a different form. This case is somewhat different from the one reported above, since the participant did not explicitly form a linguistic description to guide his design in IDT. Rather he implemented the insights from the other group's design, while drawing directly on the visual expression they created.

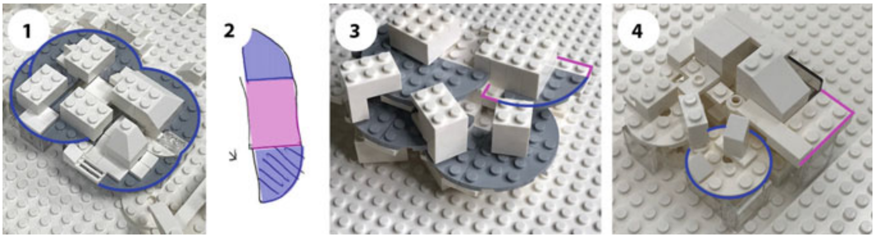

Fig. 7 Embracing a visual design idea and implementing it in a loose manner in the case of P4. (1) own team model; (2) sketch for slabs by other team incorporating round and non-rounded forms; (3) other team's model; (4) P4's design result

Selection and Adaptation in KT Across Participants

As the reader may have noticed, in most of the above cases knowledge was not transferred "as is". Due to differences between TDT and IDT (working together vs. individually, using a different set of parts etc.), some adaptation was required to fit past knowledge to the demands of new situations. For example, when P2 chose to embrace the idea of single-colored slabs and implement it in his design, he chose to use blocks of a different color (white, refer to Fig. 4). In this case, the general property of color uniformity was selected and transferred, but the specific color was not. One reason for this was the limited number of non-white blocks in IDT. As a more complex example, we expand on the case of P1 (Fig. 8; initially introduced in Fig. 6).

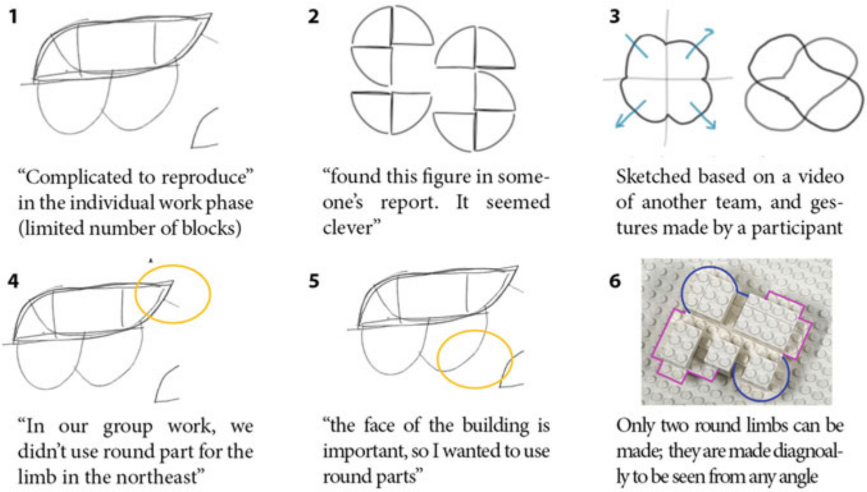

Fig. 8 Transference and adaptation by P1 in accordance with the design situation

P1's group produced slabs ('limbs') which incorporated both straight and round elements. Since she viewed her team's model as "complicated to reproduce" at IDT (1) she wondered what other options are available. Looking through the reports written by others, she found a different expression for the slabs and thought it was "clever" (2). In a further investigation, she observed the video data of the other team, and saw one of the participants making a hand gesture to explain this idea. Based on her understanding of these, she drew the sketch in (3), as a simplified representation of their strategy. Taking into consideration two additional things—that in TDT her group did not use a round part in the northeastern side (4) and that the southeastern side is "the face of the building" (5), she decided to use the limited number of round parts available to form two slabs: one on the southeastern side, and another in the opposite corner. As explained by P1, this also enabled the round elements to be seen from any angle, as an added value (6).

While the above included some form of selectivity in terms of the knowledge transferred, a clear-cut example is found in P3's case, presented hereafter. The participant reported that she initially wished to "balance structure and size". The retrospective interview helped to clarify that by 'structure' she referred to general relationships between blocks (topology) and by 'size' to the visual aspect of proportion. Despite her intention to balance these, she judged her final design as successful in communicating the former much more than the latter. This is reflected in Fig. 9, which shows success in preserving a general hierarchy in sizes (see the boxes in 2, 3) alongside an undesirable, strong deviation from the original in terms of proportion (4, 5). To explain such (somewhat unintended) selectivity, the participant suggested that her focus on topology might have resulted from her habit of working with parametric design tools, which make matters of size negligible (as they may always be adjusted once the parametric model is constructed).

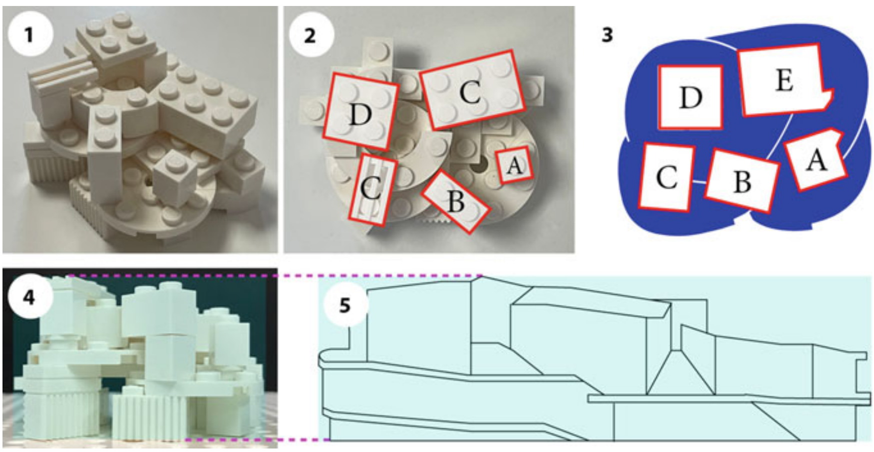

Fig. 9 P3's model vs. original: (1) bird's eye view; (2) top view; (3) schematic top view of original; (4) southern façade; (5) schematic southern façade of original

Thus far we have focused on KT within the boundaries of the activity. However, cases in which knowledge extraneous to the activity was explicitly utilized were observed as well. A somewhat extreme case of such KT is demonstrated in Fig. 10. P5 reported that, as he was organizing his room, he stumbled upon an architecture textbook which he had previously read. Flipping through its pages, he noticed another real-world building which seemed very similar to his group's model. Dissatisfied with this similarity, he resolved to make his individual model unique, by deliberately distinguishing it from the building in the photo. One way in which he managed to achieve this was by examining the building's composition in terms of roof heights. He noticed that the gradual rise which characterizes the original (4) was absent in his group's model, and thus invested efforts to consider it in his design in IDT (5).

Finally, contrary to the above, relevant (and thus potentially valuable) knowledge possessed by participants was not always utilized in the activity. P4 reported that, having studied about the museum in the past, he had prior knowledge of the circulation in the building, which he greatly admired as being "complex but rational". He explained that he chose not to make use of this knowledge in TDT, since it seemed too difficult to communicate with the team, considering the limited time available for designing.

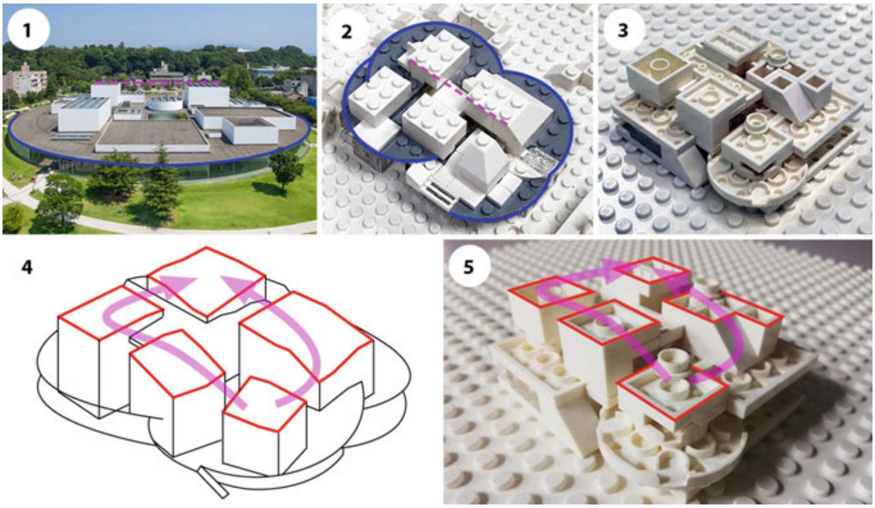

Fig. 10 Serendipitous KT: (1) 21st Century Museum of Contemporary Art, Kanazawa, Japan; Source: Kanazawa—http://open-imagedata.city.kanazawa.ishikawa.jp/; (2) P5's group model; (3) P5's model; (4) rise in roof heights in the original, from southeast; (5) expression of 4 in P5's design

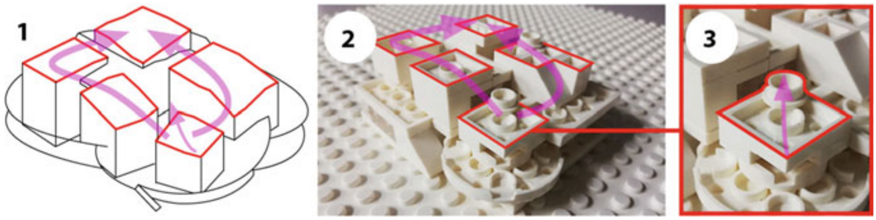

Fig. 11 Gradual rise in roof in two aspects: (1) original, from southeast; (2) global expression of rise in roof heights by P5; (3) local single-roof expression by P5

A Closer Look at KT and Memory Construction from Interactions

Examining a single case at an even higher resolution exposes the interrelations between interaction, KT and the construction of memories. In Fig. 10 we saw how P5 had found a way to express important aspects of the original in his model, by including the gradual rise in roof heights from southeast to northwest. A close examination of this episode during the retrospective interview had revealed the complexity of such events, and their relation to agent-environment interaction. First, note that the gradual rise in roof heights (previously discussed) occurs on two levels (Fig. 11) and that P5 was able to incorporate both into his design. Further, P5 was the only participant to include the roof gardens in his model (Table 1, e5), as well as the only one to acknowledge the existence of rooftop trees. In Fig. 12 we trace the expression of trees to its source, and relate it with the double-expression of the gradual rise in roof heights, which is characteristic of the original building.

As the participant explained in his interview, trees were expressed in his design using "UFO-shaped" round Lego blocks (1). Interestingly, he further pointed out that these blocks not only represent the trees, but also the gradual rise in heights (2) discussed above. When requested to reflect on the source of this decision, he remembered that he originally developed this specific expression of a tree in a previous activity (3) in which he designed a Lego model for the famous Salk Institute in San Diego, planned by Louis Kahn. At that time, he noticed that the top view of such blocks is similar to the common visual representation of trees in architectural plans (4). Even more striking is the fact that the model from the previous activity eventually did not include tree elements at all (5). Nonetheless, the knowledge was retained and transferred into the design of the museum, almost a month later.

Discussion

Acquiring, transferring, and adapting design knowledge enabled our participants to make progress in their design processes, and improve their models. P2, for example,

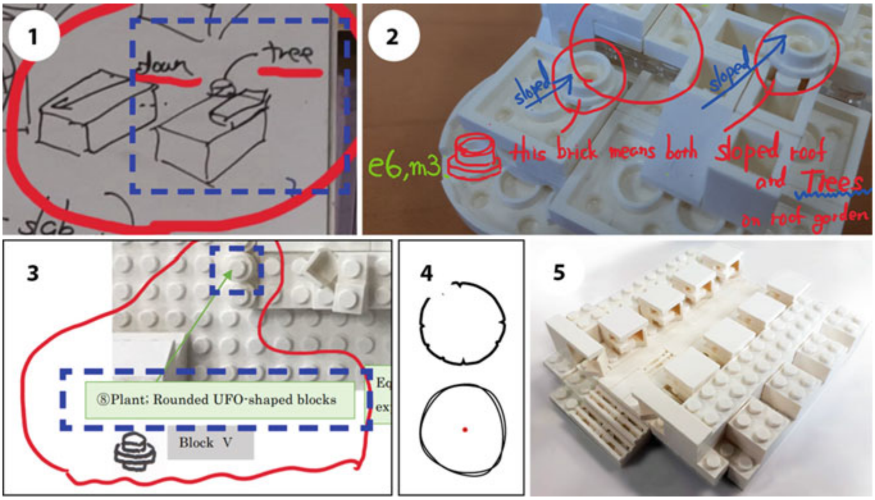

Fig. 12 Tracing effects of KT to a past event beyond the activity: (1) sketch by P5 during retrospective interview; (2) photo of P5's final model accompanied by his comments regarding a "tree block"; (3) P5's report from a prior activity; (4) typical tree representations in architectural planning; (5) result from prior activity, which did not include the "tree block"

managed to greatly reduce the complexity of his design (eventually producing the smallest model) by drawing on the other team's strategy of constructing the building's slabs (Fig. 4). Taking an opposite approach, P4 was able to sophisticate his model, by drawing on the visual material created by others, and their strategy of combining round with non-round slabs (Fig. 7). It is fair to say, that, regardless of their personal perspective and abilities, all participant benefitted from the acquisition of knowledge at TDT and its employment in IDT. What important human abilities played a role in KT in the above cases, which may be important for situated design agents?

First, to transfer any knowledge gained from TDT to a new situation in IDT, that knowledge must be stored in the memory in a manner which enables recall and reconstruction as the situation demands. Therefore an important question is the following—why was some knowledge retained from the first activity, while other parts were neglected or forgotten? Such selectivity is essential from a computational perspective since search is costly and should be optimized. This is especially true in the case of situated design agents, which are expected to run many "parallel" processes in real-time. We suggest that one reason for retaining a piece of knowledge is the fact that it was found valuable in a past situation from the designer's perspective, thus delaying the decay of the memory. In the case of P5, for example, the "tree block" idea was constructed in a different activity, in which it was found to be helpful for some time (until it was removed from the model for other reasons). Following this, it was retained for almost a month before its reconstruction and transference to our task. Therefore, in addition to the ability to form concepts from interactions (as proposed in [30]), situated agents need to be capable of classifying such concepts as applicable for KT, after attempting to implement them in a design situation. One difficulty with implementing such selectivity in a constructive memory, however, is that it seems to be affected by interactions beyond design activity itself. This is clearly reflected in the case of P3, who tended to focus on topological aspects of the design due to her past interactions with digital design tools, which shaped her dispositions towards what features were perceived as more/less important.

Further, P1's case of KT regarding the spatial layout of the slabs is enlightening as well (Fig. 8). In this case, the participant interacted with the knowledge constructed by the other group, in several steps: (1) examining their sketch, (2) watching a video recording, (3) making a sketch from recording, (4) considering additional requirements, (5) adapting the idea to the design situation. At the first stage, the spatial layout produced by the other group was seen as "clever" and thus as a candidate for transfer. At the second stage it was closely examined, to deepen her understanding of their design intention. The insights gained from both stages were integrated in another sketch, which retained some parts of the source and excluded others. Finally this sketch was combined with other relevant requirements. This account shows that KT is not a single cognitive event of mapping a source to a target, but rather a process which depends on the agent's external resources and the manners in which they are interacted with over time. This is reminiscent of Neisser's account of perception as time-extended process [31], in which dense series of transactions occur between agents and their environments even in the course of performing a seemingly simple task. Therefore, the memory system of situated agents is expected to distinguish knowledge about the design from the representations which embody it, such that existing external resources may be consulted and new ones may be constructed, as a means for facilitating processes of KT.

What other abilities were instrumental in our participants' performance? P5's capacity to design a single element which simultaneously fulfilled two roles (Figs. 11 and 12) depended on his ability to: (1) hold domain-specific knowledge from architectural drafting regarding visual representations of trees; (2) retrieve and project it onto the Lego blocks to construct the "tree block" concept; (3) recall this when creating a tree-like element at a much later activity; (4) hold in memory the current expectation to express rise in roof height in two aspects; (5) at the same time, hold the past expectation for re-creating the southeastern roof's slope; (6) notice the emergence of a design solution which is unexpected, namely that the tree block elegantly fulfills both expectations. The above account imply that even goals which are not attended should nevertheless stay active in the memory while engaging in various task, such that if a solution arises unexpectedly, it can be detected and embraced. From the perspective of AI, this can be seen as a sophisticated form of multi-objective constraint-satisfaction, where objectives are retrieved/suppressed according to the demands of the situation, to reduce computational (cognitive) load and focus on current matters. Considering the limitations on human working memory [32], it may be useful to study how goals are chunked for easy recall while one handles a seemingly unrelated matter.

Conclusion

KT in design was explored using a spatial design task. By examining the ways in which knowledge was transferred and adapted to fit the demands of the situation, several conclusions for the development of situated design agents were drawn. Mainly, we suggested that the constructive memory of situated agents possess specific mechanism for: (1) associating constructed memories with attempts to utilize them in the past and their results, to support selectivity and reflect the purposefulness of design knowledge; (2) holding multiple goals at different degrees of activation, such that they can be triggered when relevant; (3) chunking goals so that they are readily available for retrieval in real-time, such that latent ones may be fetched instantaneously. Closely observing and modeling the above may support the realization of situated design agents that can perform in a human-like manner.

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Shape Grammars and Design Knowledge

Back to the Drawing Board: Shape Calculations in Shape Machine

Athanassios Economou and Tzu-Chieh Kurt Hong

Abstract Three computer implementations of one of the earliest and most iconic shape grammars are given to showcase different ways to use shape rules in Shape Machine. These three modes of working with shape rules—manual, automatic and conditional—are used interchangeably to produce three skeuomorphic variations of the original checkerboard lattice grammar in different design domains—3D prints, origami and kerfing—and showcase the versatility and applicability of the shape rules for the specification of diverse artifacts for different scales, materials and functions. Some initial remarks on the extension of the shape grammar formalism to include programming constructs including states, loops, jumps, and conditionals are discussed.

Introduction

The machine-based specification of drawn shape rules has been the subject of a marginal but intense inquiry in the fields of shape grammars and more broadly, in computational design and computer aided design [1–10]. The challenges for the implementation of a shape grammar interpreter that is able to compute the shape rewrite productions envisioned by the shape grammar formalism are formidable [11–14]. Direct specification of shape rules by drawing rather than scripting, support of shape embedding (visual search) under all linear transformations, including isometric, similar, affine, and projective ones, resolution of indeterminate cases of shape embedding into workable workflows, extension of the formalism for a generous class of geometrical shapes including curves of all kinds and their boundary conditions, support of b-rep representations in two- and three-dimensions, integration with design workflows, all seemingly pose an impossible set of challenges to take on in a

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systematic and credible way [15–17]. The lack of effort is not to blame. In fact, more than seventy applications have claimed to have solved some aspect of the complex web of operations that are required to do to perform shape rewrite calculations, and more than twenty claim a general applicability to a wider set of design problems [18]. And yet, a general solution to the shape rewrite for all sorts of shapes, transformations, geometric dimensions, boundary conditions, and parametric representations is yet to be identified. Still, the situation is not grave as it seems. Recently, Shape Machine, a general shape grammar interpreter claims it has successfully resolved the challenges underlying shape embedding in the algebra U_{12} for straight lines and arcs and labeled straight lines and arcs in the algebra V_{12} [10]. The application effectively reworks the geometrical representations underlying the CAD representations of lines and arcs introducing a reworking of the dual representation of the maximal elements and their underlying hyperplanes [19]. The extension to apollonian conics, Bezier and NURBS is currently under way to determine the extension of the shape embedding to other shape types in CAD geometry and their ability to be searchable and replaceable in a shape production. And yet, as important is the extension of the underlying technology to allow for more shapes and operations, equally important is the exploration of the integration of this formalism in design workflows to demonstrate its value of design and to justify the efforts needed to extend the project [20]. The successful implementation of shape searches and replacements for shapes consisting of straight lines and arcs in the algebra U_{12} and labeled straight lines and arcs in the algebra V_{12}—should be able to offer substantive examples of how this formalism can help designers do better what they already do with other means (pencil, drafting, precision modeling, parametric modeling) and more importantly, do things that they would not be able to do without.

Any collection of existing artifacts or design briefs for new workflows or new artifacts would do. Here, the emphasis is given in the reworking of some fundamental work in the shape grammar formalism to demonstrate the original claims in the literature of a purely visual composition of shapes made up of lines, and open up the possibilities that emerge in such creative reworking. Several efforts have been made over the years on this front and produced interesting and valuable results and yet, all of them, were limited because their underlying technology did not allow them to generalize their calculations for any type of shape made up of lines or arcs [21–23].

The shape grammar selected to demonstrate the automated implementation of shape embedding and shape replacement in Shape Machine is one of the earliest shape grammars in the field, Stiny's checkerboard grammar for a Chinese lattice design filling a 18th c. window frame at Chengtu, Szechwan [24]. Interestingly, Stiny's work focuses on the specification of parametric shape grammars that capture the conventionalization of ice formation in the making of traditional Chinese grill design (and there are many to admire), and yet, the simplicity of the very first checkerboard grammar and the possibilities it offered for the formal description and generation of a wide class of arresting designs that involve modularity, repetition, symmetry, proportion, planar growth, periodicity, and other fundamental principles of design, has made it one of the most popular shape grammars to rework [25, 26].

The work here revisits the checkerboard ice-ray lattice grammar, implements it in a Shape Machine enabled CAD system (Rhinoceros) by drawing shapes (and not scripting shapes), shows how the shape rules can be executed in a step-by-step fashion or combined in sums and/or with conditionals to produce programming instructions to a computer, shows how these shape rules and the resulted designs can be changed ad hoc at any time during the production, and concludes with three design workflows in different design domains, namely, 3d printing, origami and kerf modeling. A brief discussion comparing the three modes of working with shape rules in Shape Machine is given in the end.

Back to the Drawing Board

The 18th c. checkerboard lattice design at Chengtu, Szechwan, published in Daniel Dye's A Grammar of Chinese lattice [27], an influential catalogue of Chinese ornamental and grilled window designs ranging from the 10th c. to the 19th c, is one of earliest examples of designs that are formally captured by the shape grammar formalism [24]. The longevity of the appeal of this early shape grammar is easy to explain. It was a simple example that could work both ways: show the shape formalism at work using the simplest possible means, that is, having more than one shape rule but not too many; insist on the absence of counters or other formal devices to produce the gridiron framework; and generate a visually interesting design that was part of a significant cultural collection. The details are worth repeating, even if some of the terminology has changed and significantly expanded over the years since its original publication. The original design, along with the shape grammar, that is, the initial shape and a set of shape rules are shown in Fig. 1. Note that the design is shown in a smaller gridiron frame (5 $\times$ 4 grid) as opposed to the original (6 $\times$ 7 grid) published in Dye's and Stiny's works respectively, to allow for the comparative calculations and illustrations following in this work. The initial shape is marked with triangular labels on its sides to specify a boustrophedon generation, that is, a bidirectional production unfolded from left-to-right and left-to-right in alternate lines. All shape rules have the form $u \rightarrow v$, that is, a shape u is rewritten as a shape v. The shape u is on the left-hand-side of the rule (LHS) and the shape v on the right-hand side of the rule (RHS). The shape rules 1–4 are comprised by labeled shapes consisting of shapes made of lines and points and specify the production of the checkerboard design in a boustrophedon manner, that is, a bidirectional production unfolded from left-to-right and left-to-right in alternate lines. Shape rule 5 specifies the deletion of the pair of the labelled points denoted by a circle and triangle. Shape rule 6 specifies the substitution of a labeled square with a spatial motif. Note that this definition of labeled shapes is slightly different from the original set up of the shape grammar formalism that used markers rather than labelled points to guide the shape generation process [28] and different too from later accounts that used an extended definition of shapes in the algebras U_{ij} for $i \leq j$ and $j \leq 3$, and labelled shapes in the algebras V_{ij} for $i \leq j$ and $j \leq 3$ to classify basic elements of shapes and their parts [29].

The formal description of the checkerboard ice-ray lattice in Fig. 1a in terms of the shape grammar in Fig. 1b–c is straightforward. A shape computation is a sequence of shapes in which each shape, except for the first shape, is generated from the previous shape by shape rules. A shape rule $u \rightarrow v$ is applied to a shape W, when there is a geometric transformation f that embeds the shape $f(u)$ in W. The resulting computation identifies the instance of the shape $f(u)$ as a part of the shape W and replaces it with the corresponding instance of the shape $f(v)$ to generate a new shape $W' = W - f(u) + f(v)$. In this case, the shape rules 1–6 are applied to the initial shape consisting of six lines denoting the frame of the window and a square

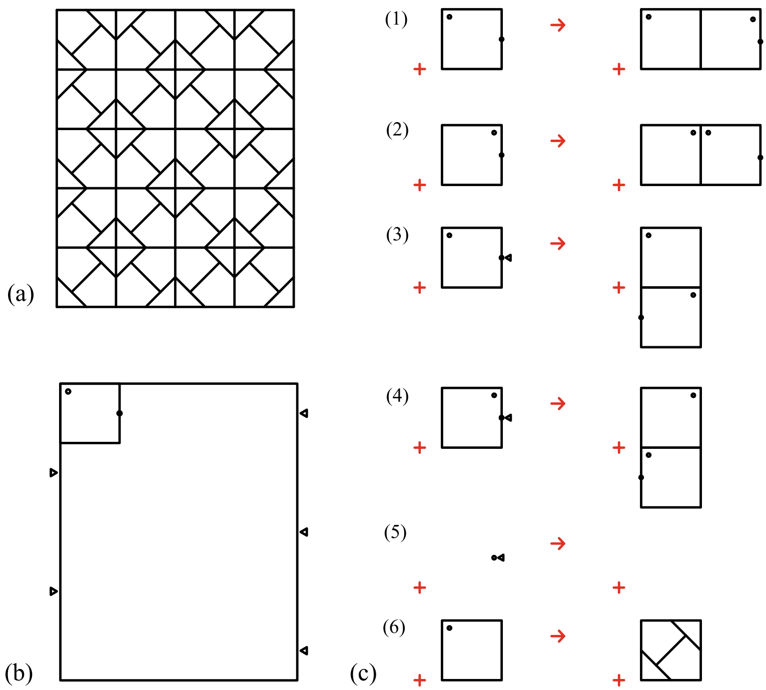

Fig. 1 A generative description of a checkerboard ice-ray lattice design. **a** Lattice design; **b** Initial shape; **c** Shape rules

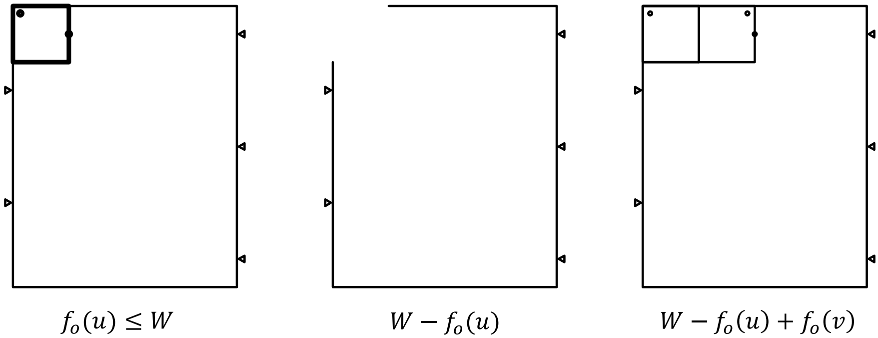

Fig. 2 A shape computation. **a** Embedding of the shape $f(u)$ in W for f an isometry; **b** Subtraction of the instance of the shape $f(u)$ from W; **c** Addition of the instance of the shape $f(v)$ to the corresponding instance of the shape $W - f(u)$

at its upper left corner to gradually fill in the complete frame with labeled squares to produce a checkerboard pattern. More abstractly, the six rules are cast in two rule schemata that capture diverse compositional procedures [30, 31]: shape rules 1–4 are instances of the rule schema $x \rightarrow x + t(x)$ for x a square and t a translation of the square; shape rule 5 is an instance of the schema $x \rightarrow y$ for x labelled triangles and circles denoting labels and y the empty labelled shape, and shape rule 6 is an instance of the schema $x \rightarrow div(x)$, for x a square module and $div(x)$ an division of the shape x in terms of an inscribed H-motif. Note that the alterative series of labeled squares is specified by the alternating array of labeled points specifying the application of the shape rules. The application of the shape rule 1 of the checkerboard ice-ray lattice grammar is shown in Fig. 2.

The calculation is easy to say and show, and yet remarkably hard to implement in a computer for *any* two shapes made up of lines. The very same design actions described above involving shape embedding, subtracting, adding, and fusing, are reworked below in Shape Machine to demonstrate a completely mechanical implementation of the shape grammar. The reworking and implementation of the checkerboard grammar evoke several of the possible user control scenarios for the development and application of a shape grammar, including manual, semi-automatic and fully automatic roles in the process outlined in [32], as well as possible extensions to programming constructs [33]—and bring more detail too. The design of the shape grammar and its production are briefly outlined below. All shape rules are digitally drawn rather than scripted in some way. The design of the shape rules can be done in two ways: each shape rule may be drawn from scratch or it may be selected from a design at any state of its completion and appropriately edited. In either case, each shape rule is an active drawing (model) that may be tested at any moment during the design workflow to test its correct instantiation and its formative power over the making of the design. The test is straightforward: the designer selects the shape rule $u \rightarrow v$ and the design W to which the shape rule will apply and specifies the transformation f under which the shape rule may apply. If indeed there is a transformation f that embeds the shape u in the design, then the embedding of the shape $f(u)$ and its corresponding replacement by the shape $f(w)$ are highlighted in the Shape Machine and the designer chooses to apply it or not. The application supports both a serial and parallel application of a shape rule in a production: in the first case of serial calculation, the Shape Machine executes the shape rule for one the found instances of embedding a shape $f_i(u)$ in W and generates the design $W' = W - f(u) + f(v)$. In the second case of parallel calculation, the Shape Machine executes the shape rule for the sum of the found instances of embedding a shape $f_i(u)$ in W and generates the design $W = W - \sum f_j(u) + \sum f_j(u)$.

Manual Production

The production of the checkerboard ice-ray can be generated following a serial or a parallel execution of shape rules. In the serial computation, the production is done in 40 steps. The boustrophedon insertion of the pairs of labeled squares within the frame requires 20 steps and the substitution of these squares by the terminal motifs requires 20 additional steps. In the parallel computation the production is done in 21 steps as the substitution of the sum of the 20 labeled squares of the frame by the terminal motifs can be done in one step. In a manual execution of the application of each shape rule, the serial mechanical production requires 40 discrete selections of the pairs of a shape rule and the evolving design and 21 discrete selections for the parallel production. The complete serial production of the checkerboard ice-ray pattern is shown in Fig. 3.

Automated Production

The very same production of the checkerboard ice-ray can be generated in Shape Machine in an automated way by ordering all the shape rules in a continuous calculation, the one shape rule firing after the other. The complete sequence of shape rules may comprise distinct sets of shape rules that produce symmetrical parts [34]. The encoding of the ordering of the shape rules in Shape Machine is done in its DrawScript module, a drawing/scripting environment that allows the users to freely order shape rules, specify the transformations they apply under, the number of loops each of them applies before the next one in the sequence, and the mode of application of each rule in the sequence, that is, the serial or parallel execution of each shape rule. The encoding of the checkerboard ice-ray grammar in the DrawScript module of Shape Machine begins to reveal its visual and computational power once the RHS of the terminal sixth rule is substituted by other motifs. Simple copies of

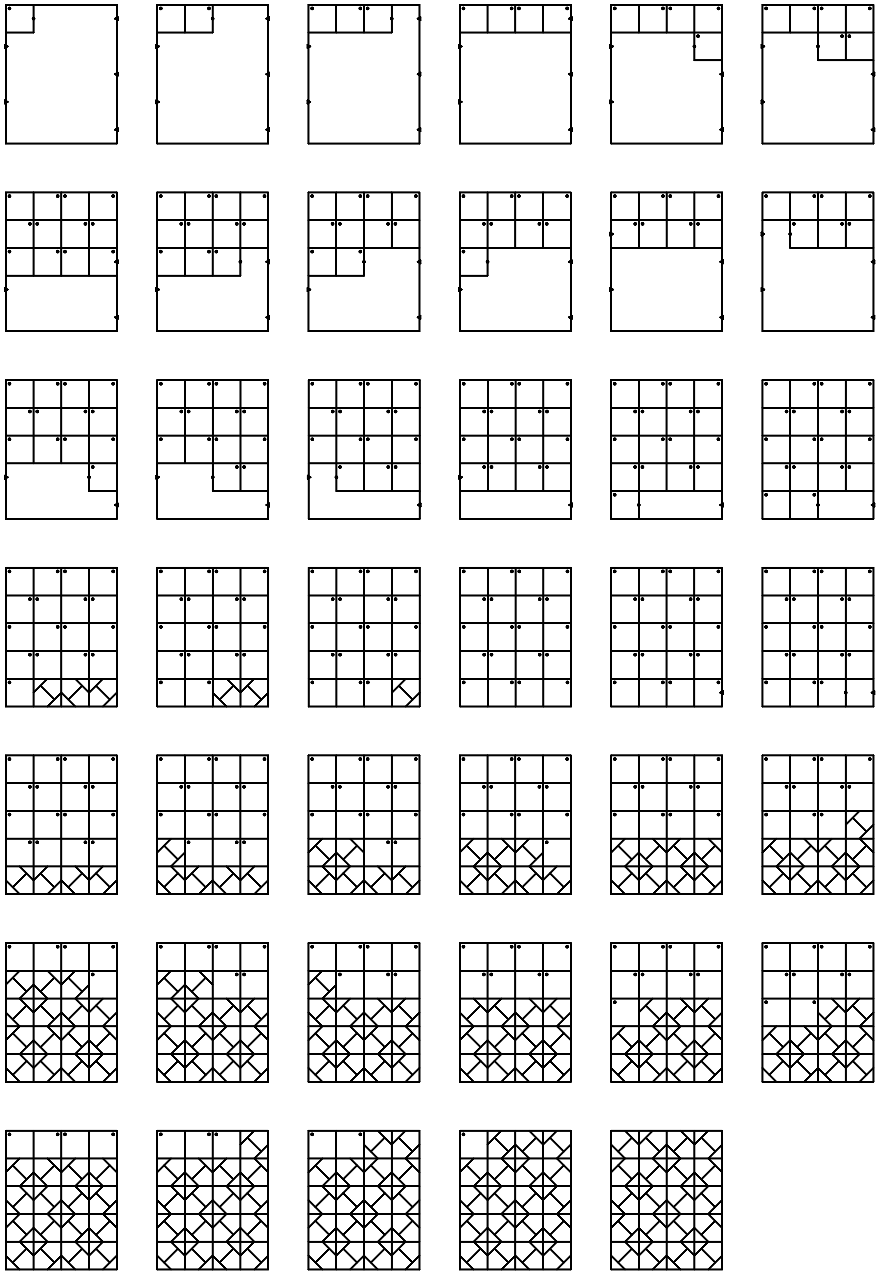

Fig. 3 The complete production of the checkerboard ice-ray lattice design in the shape machine

the initial sequence of the 21 productions along with different terminal productions reveal when executed widely diverse and unanticipated designs. A very small list of designs produced by the modified checkerboard ice-ray grammar in DrawScript is shown in Fig. 4.

Conditional Production

Significantly, the very same production of the checkerboard ice-ray can be generated in Shape Machine by using even more sophisticated programming tools including jumps and conditionals [19]. The encoding of the ordering of sets of shape rules in Shape Machine is done in its DrawScript+ module, a drawing/scripting environment that allows the users to freely order sets of shape rules and specify their relation to one another based on programming specifications: Jumps allow the seamless ordering of sets of shape rules; conditionals allow the firing of shape rules based on whether a Boolean condition has been met, e.g. upon the possibility that a shape is matched (if true) or its reverse (if false). Combined these two operations create a formidable programming interface to provide precision and expressiveness in shape computation. Significantly, every shape rule in each rule set can be freely edited to determine the transformation it applies under, the number of loops it will execute before the next one in the sequence, and its mode of serial or parallel application for each embedding. The specific details of the design of the programming interface of DrawScript+ are deliberately left aside as this is currently work in progress. A sample of four sets of shape rules in DrawScript+ that can generate the checkerboard ice-ray lattice design in Fig. 1 is shown in Fig. 5. Note that there are alternative ways of specifying the same shape production in the Shape Machine.

Skeuomorphic Variations

The checkerboard ice-ray lattice design variations in the section above were given to illustrate the increasing power and expressiveness of Shape Machine to bring to life the visual calculations that characterize the shape grammar formalism. The next series of design vignettes aim to show how this computational framework can be rewardingly utilized when it is tested in real design problems. Clearly, the constant remodeling from scratch of a given set of instructions (shape grammar) to achieve a new design goal is not a solution. The increasing complexity and sophistication on the computational framework of Shape Machine and its support of drawn instructions in Drawscript+ is impressive but none would matter if the complete shape computation would not support the seamless calculations that the shape grammar formalism has always been adamant about—and the opportunities that abide when one looks at a

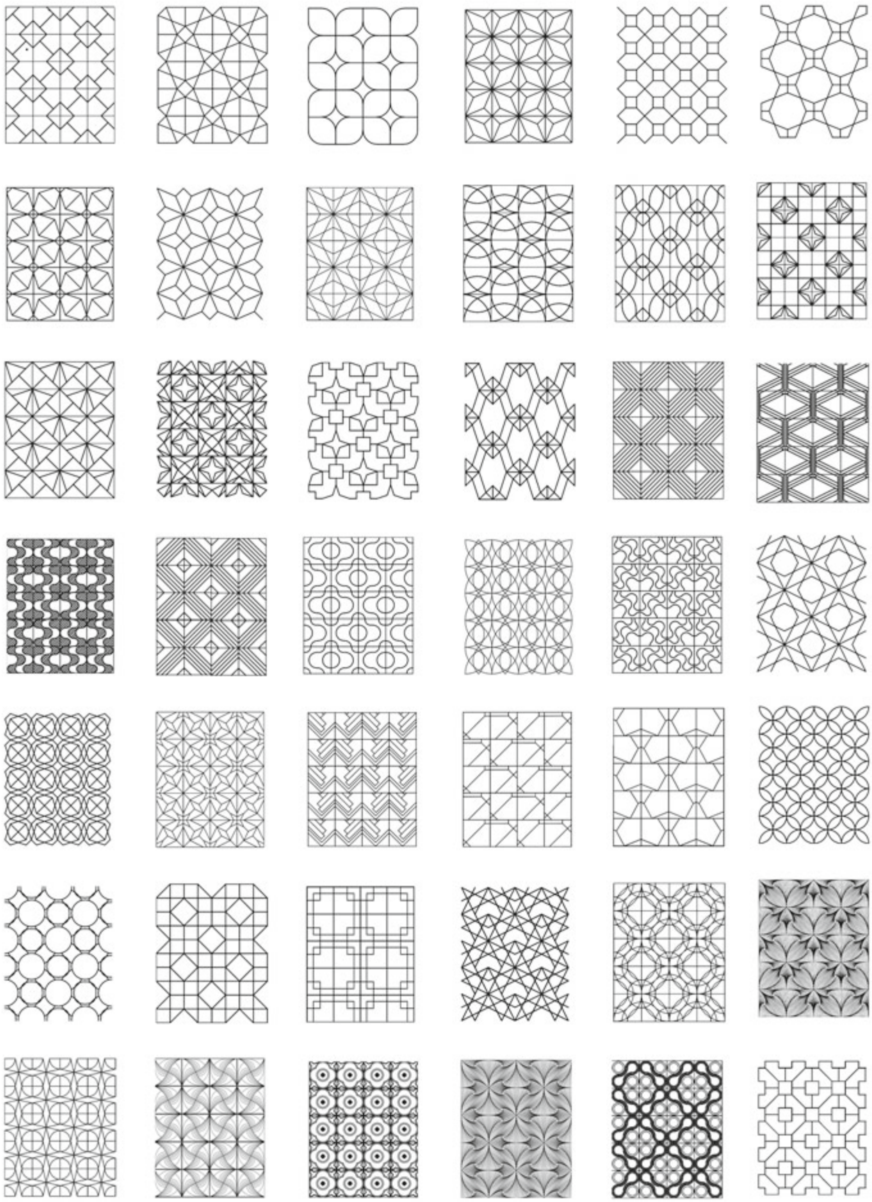

Fig. 4 Ornamental designs based on the checkerboard ice-ray lattice algorithm mechanically executed in Shape Machine

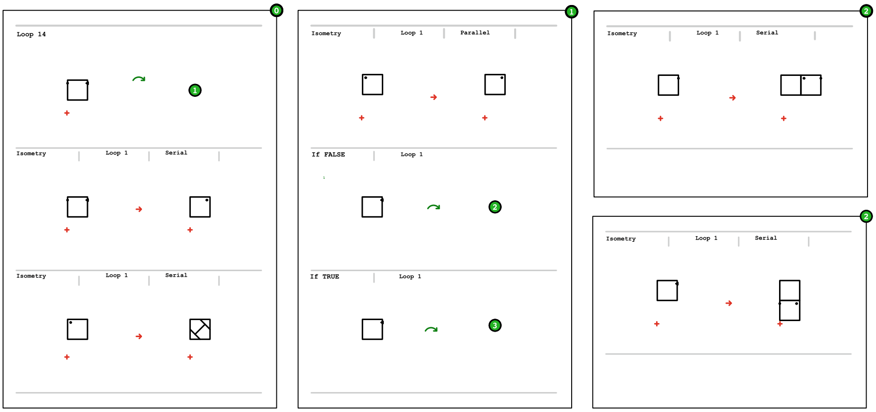

Fig. 5 A set of four sets of shape rules in DrawScript+ to generate the checkerboard ice-ray lattice design of Fig. 1

design problem. No matter how many programming constructs, complex operations and UX enhancements are introduced, if the shapes are not searchable and replaceable to accommodate the emergent possibilities the designers see—the edifice is useless. And after all, the instructions for the construction of a checkerboard Chinese ice-ray lattice design are as relevant to checkerboard Chinese ice-ray lattice designs as are to a host of widely different design artifacts. The following three case studies are shown to illustrate the seamless translation of a given set of shape rules in three different domains in making—3D printing, origami, and kerfing—using the very same premises of the shape code of the Chinese checkerboard lattice to achieve the designers' diverse material intuitions. The series is called skeuomorphic variations to foreground the analogy of the process with the art historic postulation of a seamless migration of spatial motifs (here drawn code) among diverse artifacts, scales, materials and functions [35].

3D Prints

The translation of the abstract diagrammatic models of the ice-ray lattices into some physical form is not as straightforward as it seems. The checkerboard lattice grammar represents the bars of the ice-ray lattices with single straight lines rather than with pairs of lines denoting their physical edges. The solution of rewriting the shape rules to account for the emergent bars between the squares [30], might work in the short term, but it brings more problems in the long run. Better, the translation should occur by using the current state of the design rather than reworking the whole computation from scratch. Indeed, a single shape rule suffices to capture the offset of all the single line axes of the bars to produce the width of the bars, and five more shape rules suffice to capture the resolution of the joints between the bars themselves and to the frame. All shape rules are introduced seamlessly without any prior definition of their parts, here, the emergent maximal lengths of the bars and the five different types of joints, namely, the Ψ, Y, T, Γ, and X shape joints, and all under different transformations from the original grammar too.

The first shape rule applies under an affine transformation, that is, a transformation that retains parallelism but varies dimensions and angles [36]. Significantly, this shape rule opens up a new way of thinking about shape rules and transformations under which they apply in a shape calculation as it bridges the visual immediacy of shape rules applied under Euclidean transformations that retain the shape while varying its position, handedness and scale, with the more abstract impact of shape rules applied under affine transformations that retain partial information of the shape, that is, parallelism and cross ratio, while varying its overall shape. Still, the application of this shape rule is not easy; in fact, this shape rule is an indeterminate rule, that is, there is an infinite number of ways it can be embedded in the design [18, 30]. Here, Shape Machine resolves the indeterminate matching of the shape rule by allowing the users to determine the embedding by specifying the maximum stretch of the line in the LHS of the shape rule to match the length of each line in the design and the substitution of each such instance with the corresponding affine congruent pair of lines in the RHS of the shape rule. Note that the width of the bar remains constant for the complete stretching of the pair of lines. No matter what is the original length of the axis of the bar the final bar will have the required width.

The next four shape rules clean up the emergent and/or incomplete intersections between the offset lines of the bars one another and to the frame of the window. Note that these shape rules are applied here under similar transformations, that is, transformations that retain shape but not size. The complete shape grammar to produce an ice-ray model that can be used as a profile for a 3D-printing requires the initial six rules plus the six new rules above. The six new shape rules required for the translation of the diagrammatic model to a 2D profile that can be plotted and printed to produce a physical model are shown in Fig. 6.

Origami

Non-representational origami, e.g. origami tessellation, has a rich history in various fields including art, design, architecture, computational geometry and mathematics [37–39]. Classic origami tessellations, such as the Miura-ori, the Resch pattern, and so forth, routinely appear in several pattern books showcasing focused studies in the architecture of form [40, 41]. Here, the modular ice-ray grammar produced in Shape Machine is used to provide an alternative method for constructing origami designs without requiring the complex modeling methods and the steep learning curve associated with the understanding of the appropriate tools and methodologies

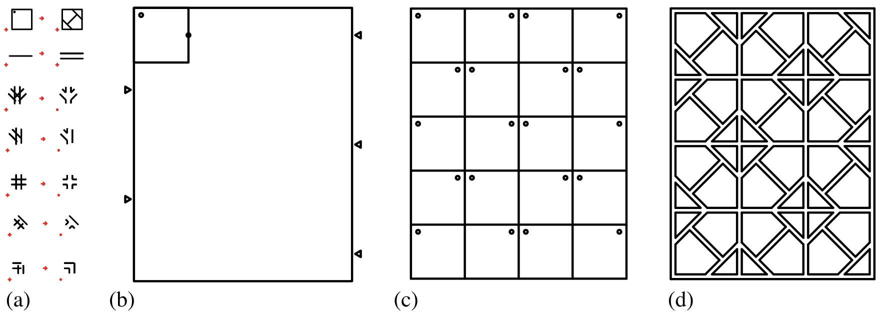

Fig. 6 The six material rules and the derivation of the profile of the checkerboard ice-ray lattice for 3D printing

to model and analyze origami design. Clearly, modeling in Shape Machine cannot guarantee the rigidity or flat foldability of a surface, but the patterns generated in the Shape Machine can be readily exported and tested in origami software and imported back again in the shape machine for a new design cycle of generation and evaluation [42].

Here, the checkerboard ice-ray grammar is reworked to produce a regular lattice design to comply within the conventions of origami design. The arc origami pattern can be generated by a straight forward variation of the original ice-ray lattice grammar featuring a different labeling scheme of the basic structural shape rules for the generation of the underlying square lattice and a different terminating shape rule. In this new grammar, the labeling of the square reduces its symmetry to 1. This reduction of symmetry is achieved here by the simple translation of the label in any other portion of the shape of the square such that it will not overlap to any of the eight elements (geometrical loci) of the symmetry group of the square [43]. The key rule that captures the structure of the arc pattern is the shape rule (6). The shape in the RHS of the rule consists of a set of solid and dotted lines simulating the characteristic features of mountains and valleys of an origami construction. Note that the shape rules of the grammar (1)–(5) apply as before in the schema $x \rightarrow x + T(x)$ while the shape rule (6) apply in the schema $x \rightarrow \sum T(x)$ to the complete set of available labeled squares in the lattice (Fig. 7).

Kerfs

Kerf structures are flexible surfaces generated by a subtractive manufacturing approach from stiff planar materials [44]. Applications of kurfing or relief cutting can be found in several domains, mostly architectural design, acoustical design, wall paneling, furniture design, and boat construction [45, 46]. This manufacturing approach changes the rigidity of flat panels by subtracting material and weakening the integrity of the panel while improve its flexibility and ultimately, its bendability. The

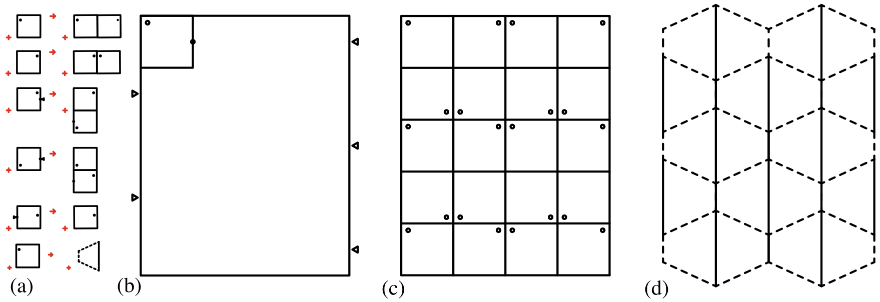

Fig. 7 An arc origami tessellation. **a** Shape rules; **b** Initial shape; **c** Symmetry configuration; **d** Final design

method is mostly used for making flat surfaces to single curvature surfaces as well as for double curvature surfaces, typically achieved by algorithmic constructions of 2D meander interlocking patterns [47]. Here, the modular ice-ray grammar produced in Shape Machine is used to provide an alternative method for constructing double curvature kerf surfaces without requiring the complex modeling methods required to obtain meander motifs. As in the case of the origami generation, modeling by subtraction in Shape Machine cannot guarantee the bendability of a surface, but the patterns generated in the Shape Machine can be readily exported and tested in Finite Element Analysis (FEA) for modeling the flexible surfaces under bending forces and imported back again in the Shape Machine for a new design cycle of generation and evaluation.

Here, the original ice-ray grammar is reworked to produce a regular lattice design to comply within the conventions of kerf design. As in the case of the additive manufacturing, the initial five shape rules for the addition of the lattice squares remain identical with the original ice-ray grammar. The new rules in the grammar are the two shape rules in Fig. 8a that use the motif of the meandering pattern complying with the condition of bendability of kerf design. The first additional shape uses a meander cutting motif with a pair of two interlocking turns and the second additional shape rule removes the emergent grid of squares and to produce a kerf design which can be bendable in two directions. Note that the meander motif that is used here is but a single sample of the meander shape grammar given by Knight (1980); any other insertion of 2D meander patterns would create 2D bendable surfaces. As in the case of the 3d print checkerboard grammar, the shape rules (1)–(5) apply as before in the schema $x \rightarrow x + T(x)$ while the two new shape rules apply in two rule schemata respectively: the first in the schema $x \rightarrow \sum T(x)$ to substitute all labeled squares with copies of the meander motif and the second in the schema $x \rightarrow \sum T(x - prt(x) + y)$ to delineate the sets of the continuous meandering lines of the kerf design.

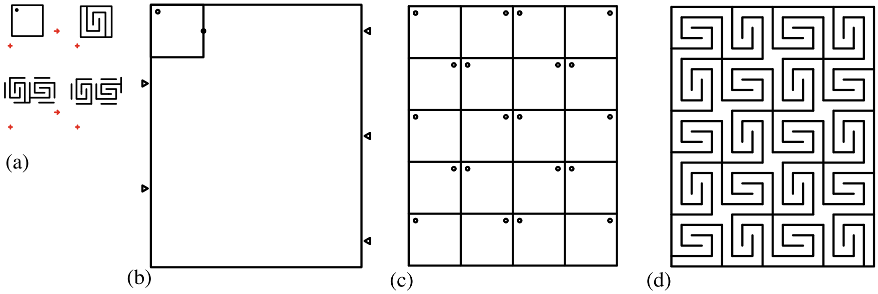

Fig. 8 A kerf design. **a** Shape rules; **b** Initial shape; **c** Symmetry configuration; **d** Final design

Discussion

The work here presented a systematic series of formal constructions produced by the mechanical implementation of one of the earliest and enduring shape grammars that specifies the generation of a checkerboard Chinese lattice window. The goal was to show that the seamless visual calculations that the shape grammar formalism has been advocating since the early seventies has indeed been accomplished in Shape Machine, and that in doing so, several possibilities, hitherto unseen, have begun to emerge. Two aspects have been paramount in this inquiry: (a) the engineering of the infrastructure of Shape Machine to handle the shape embedding relation for a generous class of shapes, in fact, any shape consisting of lines and arcs in the plane in the algebras U_{12} and V_{12}—the latter modeled in layers in CAD systems—, and for a generous class of transformations that the embedding is applied under—in fact, the complete *Erlangen* program including Euclidean, affine, and projective transformations, and for any determinate and indeterminate embeddings; and (b) the design of the interface of the Shape Machine to allow novice or experienced designers to work seamlessly with shapes and geometric modeling tasks without scripting windows or other rule windows of sorts and appreciate the seamlessness of working with shape rules in regular design workflows. It is certainly rewarding to see new shape rules or old pencil shape rules seamlessly applying in their digitally drawn versions and realize the insights and richness that this kind of automation can offer in design workflows. And as every designer knows, in the midst of doing so, it is equally rewarding to discover unforeseen directions and applications to move forwards—a true insight machine in work. The three so-called skeuomorphic variations of the original checkerboard lattice grammar were executed in different design domains than the one the grammar was grounded in—3D prints, origami and kerfs—to showcase that the shape rules themselves can provide the seeds in the specification of diverse artifacts, scales, materials and functions. And at the same time, the very same checkerboard shape rules can vanish too—no need to look at these designs as variations upon checkboard frames—and give space to new shape rules that have no structural relations to them.

The production of the Chinese checkerboard lattice design showcased three distinct modes in working with Shape Machine: a manual, an automated, and a programming environment, all offering diverse ways to interact with the generation of a design. The first relies on the manual selection (drawing) of an identity rule or a shape replacement rule to inspect what it does for the design; the second orders the production in a unique sequence that provides a formal specification of a design; and the last opens up the formalism to programming constructs including states, loops, jumps and conditionals.

The expressiveness of each mode is quite distinct. The first mode privileges a workflow akin to the typical workflow in every day design practice: a shape may be jotted down next to the model or marked up with a lasso tool within the model itself. This shape can be then searched within the drawing to show how it relates to other parts of the design and if desired so, it can be copied to the rule template within the canvas of the file to specify the design action—or alternatively, be modified within the design itself to have an immediate feedback on the design action. The second mode uses sets of shape rules along with metadata characterizing the type of transformation that every shape rule applies, the serial or parallel application of the shape rule, and so on, to put into action individual shape rules into a continuous string of instructions (DrawScript). The execution of the series of the shape rules produces a complete specification of a design in a step-by-step action simulating the shape grammar productions that have characterized the field. The third mode of working uses primary modes of logical processing including states, loops, jumps and conditionals and traverses new uncharted grounds in the expressive reach of the formalism. The possibilities that this expansion suggests are within reach. A simple shape calculation based on two nested loops is shown in Fig. 9. In this production for each square that is added in the design, a flag motif is rotated within to create a whirling series that changes in its totality for each iteration of the shape rule. The result of the shape calculation can be surprising even for the seasoned designer. A new union of two trajectories is coming together—the recursive modeling techniques taking full advantage of the computing power; and the fusion of shapes in seamless redescriptions, the everyday working paradigm of the designing process.

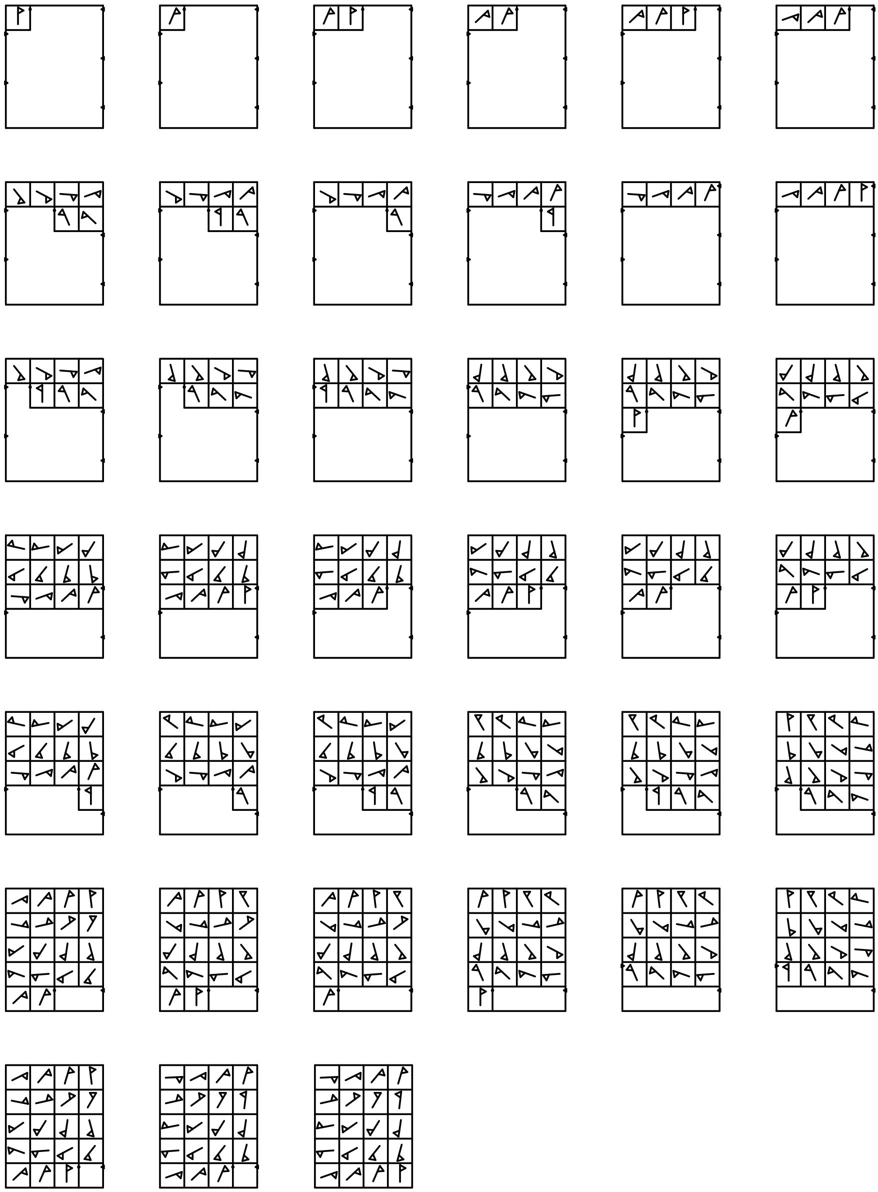

Fig. 9 A production in DrawScript featuring two nested loops of shape rules

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Notes on Shape Valued Functions

Djordje Krstic

This paper is an omnibus dealing with mathematics of shape grammars. It consists of four independent notes on shape valued functions. The first note frames rule schemas as shape valued functions, while the second continues with schemas that connect shapes in different algebras. The third note places the rule application procedure in the context of shape valued functions, while the fourth places shape valued functions in the context of Boolean functions.

Introduction

Design-producing, rule-quidded calculations with shapes have a 50-year long history starting with the introduction of shape grammars by Stiny and Gips [1]. Numerous papers, a good number of dissertations, and a couple of monographs have been advancing the field since.

This paper is in the area of mathematics of shape grammars which has a relatively small footprint in the field. The paper is in an omnibus format consisting of four independent notes connected by the fact that each makes use of shape valued functions.

The first note attempts to frame powerful (and popular) rule schemas as shape valued functions. It does so with limited success.

The second provides a formal framework for more difficult rule schemas which use operators that connect shapes in different algebras.

The third note is a brief attempt at placing the rule application procedure in the context of shape valued functions.

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The fourth and last note is more theoretical than the previous ones. It compares the standard Boolean functions to shape valued functions that belong to more general Boolean algebras. This note is more geared to the mathematically inclined readers and the those interested in shape grammars could skip it without any loss.

Shape valued functions are defined in the framework of algebras of shapes [2, 3], which provide the framework for all calculations with shapes. We will make use of the two-sorted versions of the algebras [4, 5] which have Boolean and group parts to deal with both structure and symmetry of shapes, respectively.

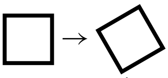
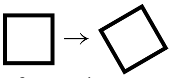
The Boolean part has set U_{ij} of shapes built of geometric elements of dimension i and occupying a finite chunk of space of dimension j. Shapes, together with Boolean operations, form a relatively complemented distributive lattice with the least element, but without the greatest one. Such a structure, due to its Boolean properties, is known as *Generalized Boolean Algebra* (GBA) [6].

The group part has set T_{ij} of similarity transformations that can act on shapes from the Boolean part. It is closed under group operations and forms a group which facilitates calculating with transformations.

Boolean and group parts are connected via the operation of group action where a transformation acts on a shape to create the transformed shape.

The two parts are combined in a two-sorted algebra $\boldsymbol{U_{ij}}$ with carrier $\{U_{ij}, T_{ij}\}$ having elements of two different sorts—shapes and transformations—and the signature with Boolean and group operations as well as the group action.

Note 1: On Rule Schemas and Shape Valued Functions

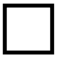
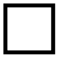
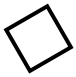
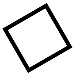
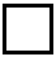
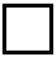
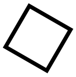
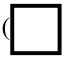
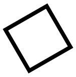
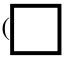
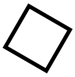
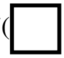
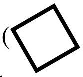
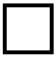
The (replacement) rules of a shape grammar are of the form $\boldsymbol{a} \to \boldsymbol{b}$, where $\boldsymbol{a}$ and $\boldsymbol{b}$ are shapes. For example, rule  rotates the square appearing before the arrow by replacing it with the one appearing after it. Although, shapes $\boldsymbol{a}$ and $\boldsymbol{b}$ could be arbitrary ones it is more often the case that one is in some way related to another. For example, the rule above has $\boldsymbol{b}$ which is a transformed (rotated) version of $\boldsymbol{a}$. Such relations are captured by rule schemas[1] where rules are defined using symbols as place holders for shapes and transformations. An instance of the rule is produced by plugging shapes and transformations into a schema. Rule  can be generalized in schema $\boldsymbol{x} \to \boldsymbol{t}(\boldsymbol{x})$, where $\boldsymbol{t}$ is an arbitrary transformation.

Because the righthand side of schema $\boldsymbol{x} \to \boldsymbol{t}(\boldsymbol{x})$ is a function of its lefthand side, the schema may be seen as equivalent to the function $f_t(\boldsymbol{x}) = \boldsymbol{t}(\boldsymbol{x})$. This is a shape valued function defined in an algebra of shapes $\boldsymbol{U_{ij}}$, or f_t: $U_{ij} \to U_{ij}$. The inverse of the schema is $\boldsymbol{t}(\boldsymbol{x}) \to \boldsymbol{x}$ [7]. By extending the notion of the equivalence of rules [5, 9] to rule schemas we may transform both sides of $\boldsymbol{t}(\boldsymbol{x}) \to \boldsymbol{x}$ in the same way

[1] Rule schemas are used by Stiny very early on. However, he gave a more systematic approach to this topic in [8] and [7].

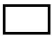
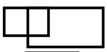
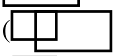
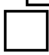
via $\boldsymbol{t}^{-1}$ to get an equivalent schema $\boldsymbol{x} \to \boldsymbol{t}^{-1}(\boldsymbol{x})$. The latter schema lends itself to function $f_t^{-1}(\boldsymbol{x}) = \boldsymbol{t}^{-1}(\boldsymbol{x})$, which is the inverse of f_t.

To see how these schemas work we need to initialize them by replacing the variables and constants with shapes and transformations.

For example, variable $\boldsymbol{x} =$  and constant $\boldsymbol{t} = rot_{30°}$ (a 30° rotation). Schemas $\boldsymbol{x} \to \boldsymbol{t}(\boldsymbol{x})$, $\boldsymbol{t}(\boldsymbol{x}) \to \boldsymbol{x}$, and $\boldsymbol{x} \to \boldsymbol{t}^{-1}(\boldsymbol{x})$ are transformed into rules  $\to$ ,  $\to$  and  $\to$ , respectively. The functions are evaluated, f_t () = , f_t^{-1} () =  and the inverse is checked for undoing of what ft did, f_t^{-1} (f()) = f_t^{-1} () = .

We have started with a rule schema, turned it into an equivalent function, then did the same with the inverse schema only to find out that the two functions were related in the same way the rule schemas were—one was the inverse of the other. The symmetry may imply that schemas and functions are the same except that one uses the language of shape grammars and the other of mathematics. However, this is not what transpires. In spite of the symmetry, schemas and functions are not the same. Stiny [7] notes that inverse schema $\boldsymbol{x} \to \boldsymbol{t}^{-1}(\boldsymbol{x})$ is superfluous because $\boldsymbol{t}^{-1}$ is also a transformation so that both schemas—the original and the inverse—are replacing $\boldsymbol{x}$ with its transformed version. In contrast, $f_t(\boldsymbol{x}) = \boldsymbol{t}(\boldsymbol{x})$ and its inverse $f_t^{-1}(\boldsymbol{x}) = \boldsymbol{t}^{-1}(\boldsymbol{x})$ are two distinct functions. Schema $\boldsymbol{x} \to \boldsymbol{t}(\boldsymbol{x})$ uses only the group part of a $\boldsymbol{U_{ij}}$ algebra namely, the transformations. The latter are reversible which accounts for the availability of the inverse function and the symmetry above. In contrast, when shapes are combined in the Boolean fashion, they "fuse without divisions—once shapes go together, they disappear in the result" [ibid., p. 16].

For example, schema $\boldsymbol{x} \to \boldsymbol{x} + \boldsymbol{a}$ is equivalent to the function $f_a(\boldsymbol{x}) = \boldsymbol{x} + \boldsymbol{a}$, while inverse schema $\boldsymbol{x} + \boldsymbol{a} \to \boldsymbol{x}$ does not amount to a function because we cannot tell which parts of $\boldsymbol{x}$ fused with $\boldsymbol{a}$. We may try $g(\boldsymbol{x}) = \boldsymbol{x} - \boldsymbol{a}$, which works for numbers. Yet, with shapes we get inequality $g(f_a(\boldsymbol{x})) \le \boldsymbol{x}$ in place of the (desired) identity. It becomes identity for $\boldsymbol{x}$ disjoint from $\boldsymbol{a}$ in which case g is the inverse of f_a. Let $A = \left\{\boldsymbol{y} \in U_{ij} | \boldsymbol{y} \cdot \boldsymbol{a} = 0\right\}$ be the set of all shapes disjoint from $\boldsymbol{a}$ and let the domain of f_a be restricted to A. The restriction is defined as $f_a|_A : A \to U_{ij}$ and $f_a|_A(\boldsymbol{x}) = f_a(\boldsymbol{x})$ whenever $\boldsymbol{x} \in A$. Set $A' = \left\{ f_a|_A(\boldsymbol{x}) | \boldsymbol{x} \in A\right\}$ is the range of $f_a|_A$ and the restriction $g|_{A'}$ of g to A' is the inverse of $f_a|_A$, or $f_a|_{A^{-1}}(\boldsymbol{x}) = g|_{A'}(\boldsymbol{x}) = \boldsymbol{x} - \boldsymbol{a}$.

Again, we plug in shapes to see how this works. Let  be shape $\boldsymbol{a}$,  shape $\boldsymbol{x}$, and  their sum, which is equal to $f_a(\boldsymbol{x})$. The result of f_a^{-1}() is shape  which is clearly not $\boldsymbol{x}$ but its proper part. If $\boldsymbol{x}$ is shape  instead, so that $f_a|_A(\square) = \square\,\square$, then $f_a|_A^{-1}\big(f_a|_A(\square)\big) = f_a|_A^{-1}(\square\,\square) = \square$ and we got $\boldsymbol{x}$ back.

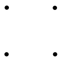
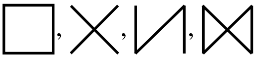
From the designer's point of view such a restriction to disjoint shapes is not very interesting. It is harder to have a fresh look, or see in the new way the result of a calculation when its arguments are there in the plain view. Calculating with such shapes is like calculating with symbols.

A very handy rule schema often used in shape grammars is $\boldsymbol{x} \rightarrow \boldsymbol{x} + \boldsymbol{t}(\boldsymbol{x})$. It is a combination (a sum) of the redundant rule schema $\boldsymbol{x} \rightarrow \boldsymbol{x}$ and the already discussed $\boldsymbol{x} \rightarrow \boldsymbol{t}(\boldsymbol{x})$ one. Both $\boldsymbol{x} \rightarrow \boldsymbol{x}$ and $\boldsymbol{x} \rightarrow \boldsymbol{t}(\boldsymbol{x})$ have respective equivalent functions $h(\boldsymbol{x}) = \boldsymbol{x}$ and $f_t(\boldsymbol{x}) = \boldsymbol{t}(\boldsymbol{x})$ with inverses $h^{-1} = h$ and $f_t^{-1}(\boldsymbol{x}) = \boldsymbol{t}^{-1}(\boldsymbol{x})$ which are equivalent to the inverse schemas $\boldsymbol{x} \rightarrow \boldsymbol{x}$ and $\boldsymbol{x} \rightarrow \boldsymbol{t}^{-1}(\boldsymbol{x})$, respectively. All these nice symmetries amount to very little when the two schemas are summed. Sum $\boldsymbol{x} \rightarrow \boldsymbol{x} + \boldsymbol{t}(\boldsymbol{x})$ has the equivalent function $f_g(\boldsymbol{x}) = \boldsymbol{x} + \boldsymbol{t}(\boldsymbol{x})$ with no inverse.

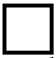
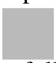
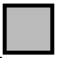
So far, we examined three different schemas. The first one has both the function equivalent to it and another function equivalent to its inverse. The second one has the first function, but not the second function unless we calculate with disjoint shapes only. Finally, the third one has just the function equivalent to it. We will now look into a schema which does not lend itself to a function.

Schema $\boldsymbol{x} \rightarrow prt(\boldsymbol{x})$, which describes a rule that picks a part of a shape, has no function to describe it. There is nothing in the schema to point to the specific part of $\boldsymbol{x}$ to be picked which would be needed for a function to work. Stiny points to two related schemas $\boldsymbol{x} \rightarrow \boldsymbol{x}$ and $\boldsymbol{x} \rightarrow$ which are more specific about picking the parts of $\boldsymbol{x}$ [ibid.]. The former picks the biggest part of $\boldsymbol{x}$, $\boldsymbol{x}$ itself, while the latter picks the smallest part, the empty shape. Schema $\boldsymbol{x} \rightarrow prt(\boldsymbol{x})$ leads to expression $r(\boldsymbol{x}) = prt(\boldsymbol{x})$ which defines a relation rather than function. It pairs $\boldsymbol{x}$ with infinitely many shapes, which are its parts, starting with $\boldsymbol{x}$ itself and ending with the empty shape. Stiny defines the inverse schema as $\boldsymbol{x} \rightarrow prt^{-1}(\boldsymbol{x})$ meaning "$\boldsymbol{x}$ goes to a shape with $\boldsymbol{x}$ as a part" [ibid.]. Like with $r(\boldsymbol{x})$, expression $r^{-1}(\boldsymbol{x}) = prt^{-1}(\boldsymbol{x})$ defines a relation which pairs $\boldsymbol{x}$ with all of the shapes that have $\boldsymbol{x}$ as a part. All the functions describing schemas that we developed so far were rule generating functions. Such is a function from U_{ij} to U_{ij} which maps a shape representing the lefthand side of a rule to the shape representing its righthand side. We have seen that for schema $\boldsymbol{x} \rightarrow prt(\boldsymbol{x})$ and its inverse such functions do not exist, however, it is not all lost. We can still define functions that describe the schema and its inverse, but the functions will not be the rule generating ones. The functions are f_p and its inverse $f_p{}^{-1}$ which map shapes from U_{ij} to the set of all subsets of U_{ij}, or f_p, $f_p^{-1} : U_{ij} \rightarrow \wp\big(U_{ij}\big)$. They are defined as $f_p(\boldsymbol{x}) = \mathbf{I}(\boldsymbol{x})$ and $f_p^{-1}(\boldsymbol{x}) = \mathbf{F}(\boldsymbol{x})$, where $\mathbf{I}(\boldsymbol{x})$ and $\mathbf{F}(\boldsymbol{x})$ are the principal ideal and principal filter generated by $\boldsymbol{x}$, respectively. The latter are defined as $\mathbf{I}(\boldsymbol{x}) = \big\{\boldsymbol{y} \in U_{ij} | \boldsymbol{y} \leq \boldsymbol{x}\big\}$, or the set of all parts of $\boldsymbol{x}$, and $\mathbf{F}(\boldsymbol{x}) = \big\{\boldsymbol{y} \in U_{ij} | \boldsymbol{y} \geq \boldsymbol{x}\big\}$, or the set of all shapes with $\boldsymbol{x}$ as a part.

It seems that we exhausted all types of schemas with respect to how they relate to, or can be described by shape valued functions. However, we will take a look at yet another schema, namely the one that takes a shape to its boundary, or $\boldsymbol{x} \rightarrow b(\boldsymbol{x})$. The function describing it is $f_b(\boldsymbol{x}) = b(\boldsymbol{x})$ which works because shapes always have boundaries and the latter are unique. The only exception are shapes made of points as points have no boundaries. The function maps such shapes to the empty shape. For the inverse schema Stiny uses similar notation like in the ptr/ptr^{-1} case, that is, $\boldsymbol{x} \rightarrow b^{-1}(\boldsymbol{x})$ meaning "$\boldsymbol{x}$ goes to a shape with the boundary $\boldsymbol{x}$" [ibid.]. There are two problems with trying to find a function describing the inverse schema. First, not all shapes are boundaries of shapes, and second, a shape is not always determined by its boundary. The first one narrows the domain of the potential function, but the second one does away with it—as there can be more than one shape having the same boundary.

For example, four-point shape  is the boundary of   and more.

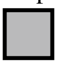
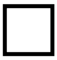
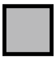
We can, as we did before, introduce a non-rule-generating function describing the inverse schema $g_b\colon U_{ij} \rightarrow \wp\left(U_{i+1j}\right)$ defined by $g_b(\boldsymbol{x}) = b^{-1}(\boldsymbol{x}) = \left\{\boldsymbol{y} \in U_{i+1j} | b(\boldsymbol{y}) = \boldsymbol{x}\right\}$. The latter set is in many cases a singleton rendering g_b a rule-generating inverse.

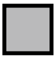
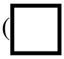
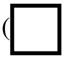
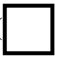
There is more than meets the eye to schemas $\boldsymbol{x} \rightarrow b(\boldsymbol{x})$ and related $\boldsymbol{x} \rightarrow \boldsymbol{x}+b(\boldsymbol{x})$. Hiding behind their intuitive appeal and simplicity of drawing the outline in place of a 2D patch,  $\rightarrow$ , or on top of it,  $\rightarrow$ , are technical issues related to the nature of the boundary operator. The following note deals with that.

Note 2: On Functions Containing $b(x)$

Note that a shape is made of geometric elements that are one dimension higher than the elements of its boundary which renders the boundary operator as a mapping from one algebra of shapes to another, or b: $U_{i+1j} \rightarrow U_{ij}$. Consequently, such an operator cannot be defined in a single algebra unlike Boolean and group operations of standard algebras of shapes.

Unlike the other schemas where symbol + is the Boolean sum from an algebra of shapes, in $\boldsymbol{x} \rightarrow \boldsymbol{x}+b(\boldsymbol{x})$ it has to be something else, as $\boldsymbol{x}$ and $b(\boldsymbol{x})$ belong to different algebras. But what? If we try to work this schema with pencil, paper and possibly some coffee stains on it, the answer is easy. Just pick a stain and trace its outline. With that we combined a planar shape (the stain) with a linear one (the outline).

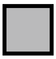
A shape produced by a rule adhering to schema $\boldsymbol{x} \rightarrow \boldsymbol{x} + b(\boldsymbol{x})$ is a compound shape. It is composed of a shape belonging to algebra $\boldsymbol{U}_{i+1i}$ and its boundary belonging to $\boldsymbol{U}_{ij}$, like shape  having one shape  from $\boldsymbol{U}_{22}$, and another shape  from $\boldsymbol{U}_{12}$. Shape  has to be defined in a combination of the two algebras, and + in the schema actually refers to some kind of sum or a combination of algebras of shapes. There are several ways of defining such a combination.

A standard algebraic combination is the direct product of component algebras which have the same signatures. Direct product $\boldsymbol{U_{12}} \times \boldsymbol{U_{22}}$ is an algebra of shapes with the Boolean part having Cartesian product $U_{12} \times U_{22}$ as carrier and Boolean operations which are done componentwise. Likewise, its group part has $T_{12} \times T_{22}$ as carrier and the group operations that are done componentwise [4, 5]. Compound shapes are represented by ordered pairs $(\boldsymbol{x}, \boldsymbol{y})$, where $\boldsymbol{x} \in U_{12}$ and $\boldsymbol{y} \in U_{22}$. For example, shape  is in direct product algebra $\boldsymbol{U_{12}} \times \boldsymbol{U_{22}}$ represented by ordered pair (, ) and its components are extracted via projection operators pr_{12}(, ) =  and pr_{22}(, ) = .

Another combination of algebras is their subdirect product which is a subalgebra of a direct product enumerating all elements of the component algebras, but not all their combinations. The sum of algebras of shapes [4, 5] is a subdirect product which enumerates all shapes of the component algebras as well as all their combinations, but allows only combinations of equal transformations. Sum preserves the integrity of compound shapes in calculations by requiring all components of compound shapes to be transformed in the same way.

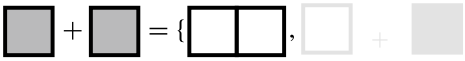
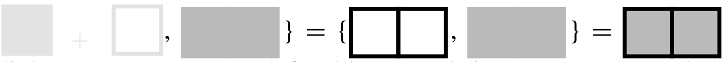
Note that the components of a direct product algebra of shapes are defined in spaces of the same dimension, but with each component enjoying its own space. It is as if the components of shapes are defined on different layers of a CAD system. They can freely move on each layer without affecting the shapes on the other layers. In contrast, all the components of a shape defined in a sum of algebras of shapes move in the same way creating the impression that they occupy the same space. This renders the sums of algebras of shapes a better choice for calculations involving the boundary operator. However, it is not clear how the operator will fit into their compartmentalized algebraic structure.

There are also algebras where shapes are paired with their boundaries allowing for parallel calculations with both [10, 11]. Although boundaries are central to these algebras, the boundary operator has no place there as pairings were done ahead of calculations and not as their consequence.

Yet another algebra, the extended algebra of shapes [4] comes to mind. It is a multi-sorted algebra with carrier $\{U_{33}, T_{33}, U_{23}, T_{23}, \ldots U_{03}, T_{03}\}$ containing all shapes that could be defined in a 3D space, as well as the matching transformations paired with Boolean, group, and group action operations such that each pair $\{U_{i3}, T_{i3}\}$ with related operations reassembles the standard two-sorted algebra of shapes. This algebra seems like the right choice because it contains all kinds of shapes defined in 3D spaces so that boundary operators $b_1\colon U_{33} \to U_{23}$, $b_2\colon U_{23} \to U_{13}$, and $b_3\colon U_{13} \to U_{03}$ could be defined. Unfortunately, this algebra cannot calculate with compound shapes so that rule described by schema $\boldsymbol{x} \to \boldsymbol{x} + b(\boldsymbol{x})$ like  $\to$  cannot be processed within its framework.

The only algebra which could work in this context is a commutative sum of algebras of shapes [5]. The standard sum of algebras of shapes is not commutative because it is a subalgebra of direct product algebra which is not commutative. Commutative sum is developed to model pencil on paper drawing, where we get the same result regardless of the order in which we drew points, lines, and shaded regions.

Commutative sum algebra is a two-sorted algebra with the Boolean and group parts. However, it differs from all of the composite algebras mentioned above which are related in one way or another to the direct product. Without the loss of generality, we will consider the commutative sum of $\boldsymbol{U_{12}}$ and $\boldsymbol{U_{22}}$ algebras. The carrier of the Boolean part of $U_{\mathbf{12}} + U_{\mathbf{22}}$ is denoted by $U_{12} + U_{22}$ and defined as $U_{12} + U_{22} = \{\{\boldsymbol{x}, \boldsymbol{y}\} | \boldsymbol{x} \in U_{12}, \boldsymbol{y} \in U_{22}\}$. It consists of two-element sets or (unordered) pairs in place of the ordered pairs of $U_{12} \times U_{22}$. Boolean operations cannot be done componentwise as there are no components, but elements instead. The other possibility is to define the operations by combining the elements of their arguments exhaustively.

Let two sets $\{\boldsymbol{x_{12}}, \boldsymbol{x_{22}}\}$ and $\{\boldsymbol{y_{12}}, \boldsymbol{y_{22}}\}$, where $\boldsymbol{x_{12}}, \boldsymbol{y_{12}} \in U_{\mathbf{12}}$ and $\boldsymbol{x_{22}}, \boldsymbol{y_{22}} \in U_{\mathbf{22}}$ belong to $U_{12} + U_{22}$. Their Boolean sum, when defined exhaustively, is $\{\boldsymbol{x_{12}}, \boldsymbol{x_{22}}\} + \{\boldsymbol{y_{12}}, \boldsymbol{y_{22}}\} = \{\boldsymbol{x_{12}} + \boldsymbol{y_{12}}, x_{12} + y_{22}, x_{22} + y_{12}, \boldsymbol{x_{22}} + \boldsymbol{y_{22}}\}$. However, the elements of the sum appearing in the gray typeface are not defined as their arguments belong to different algebras, thus, $\{\boldsymbol{x_{12}}, \boldsymbol{x_{22}}\} + \{\boldsymbol{y_{12}}, \boldsymbol{y_{22}}\} = \{\boldsymbol{x_{12}} + \boldsymbol{y_{12}}, \boldsymbol{x_{22}} + \boldsymbol{y_{22}}\}$. The result of the Boolean sum operation is a pair with one element in U_{12} and the other in U_{22}, so that the sum is an element of $U_{12} + U_{22}$ and $U_{12} + U_{22}$ is closed under the Boolean sum. The calculations above are redone with actual shapes in place of symbols:  . Note that the light-gray sums are not defined because their argument shapes belong to different algebras.

Operations of shape product and difference are defined in the same way.

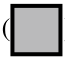
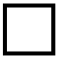
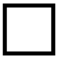
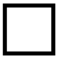
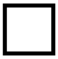
There is the treatment of the empty shape that may not be intuitive but is important for the algebra to work. Empty shape 0—which is defined as the empty set of geometric elements—is seen here in the context of an algebra it belongs to, that is, as the smallest element of that algebra. Consequently, $0 \in U_{12}$ is different than $0 \in U_{22}$ and will be denoted by 0_{12} and 0_{22}, respectively. This is necessary to make sure that the results of calculations are not singletons (but pairs).

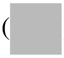
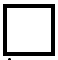
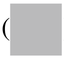
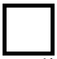
The group part has carrier T_2 which is a set of pairs of transformations with one element in T_{12} and the other in T_{22}. The group operations are also defined exhaustively.

For example, group composition $\{\boldsymbol{t}_{12}, \boldsymbol{t}_{22}\} \circ \{\boldsymbol{g}_{12}, \boldsymbol{g}_{22}\} = \{\boldsymbol{t}_{12} \circ \boldsymbol{g}_{12}, t_{12} \circ g_{22}, t_{22} \circ g_{12}, \boldsymbol{t}_{22} \circ \boldsymbol{g}_{22}\} = \{\boldsymbol{t}_{12} \circ \boldsymbol{g}_{12}, \boldsymbol{t}_{22} \circ \boldsymbol{g}_{22}\}$, where $\boldsymbol{t}_{12}, \boldsymbol{g}_{12} \in T_{12}$ and $\boldsymbol{t}_{22}, \boldsymbol{g}_{22} \in T_{22}$.

The elements of a pair are extracted via operators that play the role the projection operators play in direct product algebras. For lack of a better name, we will call them projections and denote by pr_{12} and pr_{22}. These are defined as $pr_{12}(\boldsymbol{a}) = \cup(\{0_{12}\} + \boldsymbol{a})$ and $pr_{22}(\boldsymbol{a}) = \cup(\{0_{22}\} + \boldsymbol{a})$, where $\boldsymbol{a} \in \boldsymbol{U_{12}} + \boldsymbol{U_{22}}$ and pr_{12} extracts the element belonging to $\boldsymbol{U_{12}}$ while pr_{22} extracts the element belonging to $\boldsymbol{U_{22}}$.

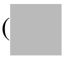
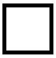
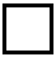
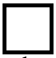
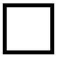
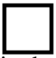
For example, let $\{\boldsymbol{x_{12}}, \boldsymbol{x_{22}}\} \in \boldsymbol{U_{12}} + \boldsymbol{U_{22}}$, where $\boldsymbol{x_{12}} \in U_{12}$ and $\boldsymbol{x_{22}} \in U_{22}$, then $pr_{12}(\{\boldsymbol{x_{12}}, \boldsymbol{x_{22}}\}) = \cup(\{0_{12}\} + \{\boldsymbol{x_{12}}, \boldsymbol{x_{22}}\}) = \cup(\{0_{12} + \boldsymbol{x_{12}}, 0_{12} + x_{22}\}) =$

$\cup(\{\boldsymbol{x}_{12}\}) = \boldsymbol{x}_{12}$,, or with actual shapes in place of the symbols: $pr_{12}($$) =$ $\cup(\{0_{12}\}+ \{$, $\}) = \cup(\{0_{12}+$ , $0_{12} +$ $\}) = \cup(\{$$\}) =$ .

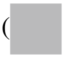
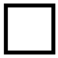
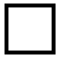
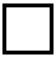
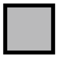
Unlike $\boldsymbol{U}_{12} \times \boldsymbol{U}_{22}$, algebra $\boldsymbol{U}_{12} + \boldsymbol{U}_{22}$ is not compartmentalized so that a boundary operator can be added. Boundary operator b has two-sorted domain $\{U_{12}, U_{22}\}$ and is defined as $b(\boldsymbol{x}) = b_{22}(\boldsymbol{x})$ if $\boldsymbol{x} \in U_{22}$, and $b(\boldsymbol{x}) = b_{12}(\boldsymbol{x})$ if $\boldsymbol{x} \in U_{12}$, where b_{22} is the standard boundary operator that turns a planar shape into its linear boundary and b_{12} is a constant function $b_{12}(\boldsymbol{x}) = 0_{22}$. To see how it works let $\boldsymbol{a} = \{\boldsymbol{x}_{12}, \boldsymbol{x}_{22}\} \in \boldsymbol{U}_{12} + \boldsymbol{U}_{22}$, where $\boldsymbol{x}_{12} \in U_{12}$ and $\boldsymbol{x}_{22} \in U_{22}$, then $b(\boldsymbol{a}) = b\{\boldsymbol{x}_{12}, \boldsymbol{x}_{22}\} = \{b(\boldsymbol{x}_{12}), b(\boldsymbol{x}_{22})\} = \{b_{12}(\boldsymbol{x}_{12}), b_{22}(\boldsymbol{x}_{22})\} = \{0_{22}, \boldsymbol{y}_{12}\}$, where $\boldsymbol{y}_{12}$ is the boundary of $\boldsymbol{x}_{22}$. Boundary operator is pretty neat one. It first takes the planar shape from a pair and turns it into its linear boundary, which leaves behind a pair of linear shapes. Such a pair does not belong to the algebra so the operator takes the other linear shape and turns it into the planar empty shape, thus keeping the books in order. With shapes it looks as follows: $b($$) = \{b_{12}($$), b_{22}($$)\}$ $= \{0_{22},$ $\}$. Note that the boundary operator erased the original linear shape (a line). This may look strange, but the operator is not foolproof. If a boundary of a planar shape is what is needed then it is better to use just a planar shape and nothing else, like for example: $b($$) = \{b_{12}(0_{12}), b_{22}\ ($$)\} = \{0_{22},$ $\}$.

The technical machinery that provides the framework for schemas like $\boldsymbol{x} \to b(\boldsymbol{x})$ and $\boldsymbol{x} \to \boldsymbol{x} + b(\boldsymbol{x})$ is now ready. Any schema that requires hopping between the different algebras of shapes could be realized in the framework of commutative sum of algebras of shapes. Commutativity prevents the algebra from being compartmentalized, which allows for all of the component algebras to be defined in the same space, and enables operators that connect different algebras.

We can now try schema $\boldsymbol{x} \to b(\boldsymbol{x})$ which becomes the compound shape valued function $f_b(\boldsymbol{x}) = b(\boldsymbol{x})$ defined in a commutative sum algebra.

Let shape  be the value of variable $\boldsymbol{x}$, which in its compound shape form is $\{0_{12},$ $\}$, then $f_b(\{0_{12},$ $\}) = b(\{0_{12},$ $\}) = \{b_{12}(0_{12}), b_{22}($$)\}$ $= \{0_{22},$ $\}$ or . Going back, with $\boldsymbol{x} \to b^{-1}(\boldsymbol{x})$, we may try inverse $b^{-1}(\boldsymbol{x}) = b_{12}^{-1}(\boldsymbol{x}) = \{\boldsymbol{y} \in U_{22} | b(\boldsymbol{y}) = \boldsymbol{x}\}$ if $\boldsymbol{x} \in U_{12}$ and $b^{-1}(\boldsymbol{x}) = b_{22}^{-1}(\boldsymbol{x}) = 0_{12}$ if $\boldsymbol{x} \in U_{22}$. Note that if $\boldsymbol{x} \in U_{12}$ is not a boundary of a shape then $b_{12}^{-1}(\boldsymbol{x}) = \{\} = 0_{22}$. The inverse operator leads to a non-rule-generating inverse function $f_b^{-1}(\boldsymbol{x}) = b^{-1}(\boldsymbol{x})$, which for $\boldsymbol{x} =$  yields $f_b{}^{-1}(\{0_{22},$ $\}) = b^{-1}(\{0_{22},$ $\}) = \{\{0_{12},$ $\}\}$ or $\{$$\}$. Note that in this particular case the result, that is the set of all shapes with $\boldsymbol{x}$ as the boundary, is a singleton which renders $f_b{}^{-1}$ as a rule-generating function. We may also restrict $f_b{}^{-1}$ to just shapes that are boundaries of shapes to avoid getting $\{0_{12}, 0_{22}\}$ as a result. This way $f_b^{-1}\big|_B(\boldsymbol{x}) = b^{-1}(\boldsymbol{x})$, where $B = \{\boldsymbol{y} | \boldsymbol{z} = b(\boldsymbol{y}), \boldsymbol{z} \in U_{12} + U_{22}\}$.

Schema $\boldsymbol{x} \rightarrow \boldsymbol{x} + b(\boldsymbol{x})$, becomes function $f_{xb}(\boldsymbol{x}) = \boldsymbol{x} + b(\boldsymbol{x})$ defined in a commutative sum algebra. Note that $+$ in the schema above does not stand for some kind of sum of algebras. It has regained its usual meaning of a Boolean sum of (compound) shapes.

For $\boldsymbol{x}$ valued as above we have $f_{xb}(\{0_{12},$  $\}) = \{0_{12},$  $\} + b(\{0_{12},$  $\})$ $= \{0_{12},$  $\} + \{b_{12}(0_{12}), b_{22}($  $)\} = \{0_{12},$  $\} + \{0_{22},$  $\} = \{0_{12} +$ , $0_{22} +$  $\} = \{$ ,  $\}$ or .

The inverse schema is $\boldsymbol{x} + b(\boldsymbol{x}) \rightarrow \boldsymbol{x}$ becomes $f_b^{-1}(\boldsymbol{x}) = b^{-1}(\boldsymbol{x})$, the same function that we had for $b(\boldsymbol{x}) \rightarrow \boldsymbol{x}$ schema. However, this time the function has to be restricted to the range of f_{xb} which consists of shape/boundary pairs, or $f_b^{-1}\big|_{B'}(\boldsymbol{x}) = b^{-1}(\boldsymbol{x})$, where $B' = \{\boldsymbol{y} = f_{xb}(\boldsymbol{x}) | \boldsymbol{x} \in U_{12} + U_{22}\} = \{\{z, b(z)\} \in U_{12} + U_{22}\}$. Interesting enough, this restriction is a rule generating function.

This concludes the note and we move to investigating the rule application procedure and how it relates to shape valued functions.

Note 3: On the Rule Action Functions

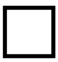
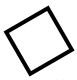
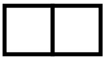
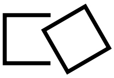
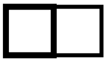
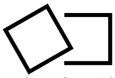
A shape grammar is a set of rules, which apply recursively to create designs, and by extension a language of design.

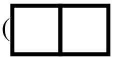
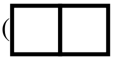
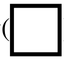
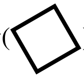
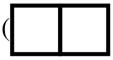
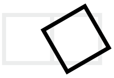
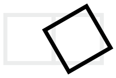
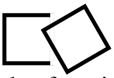
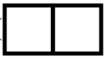
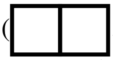
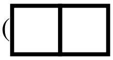
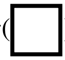
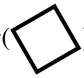
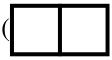
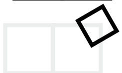
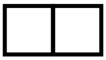
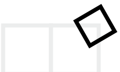
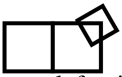
Rules operate in the framework of algebras of shapes to change shapes to which they are applied. A rule is given by schema $\boldsymbol{a} \rightarrow \boldsymbol{b}$ where $\boldsymbol{a}$ and $\boldsymbol{b}$ are shapes belonging to an algebra of shapes. The shape on the lefthand side of the rule is transformed in order to match a part of the shape to which the rule is applied. This part is replaced with the shape on the righthand side of the rule transformed the same way the first shape was. The partial ordering relation from the algebra of shapes together with the appropriate transformation facilitates the matching, while the replacement is handled by the operations of difference and sum, in this order. This can be expressed by:

$$\boldsymbol{t}(\boldsymbol{a}) \leq \boldsymbol{c} \tag{1}$$

$$\boldsymbol{c}' = (\boldsymbol{c} - \boldsymbol{t}(\boldsymbol{a})) + \boldsymbol{t}(\boldsymbol{b}) \tag{2}$$

where $\boldsymbol{a} \rightarrow \boldsymbol{b}$ is a rule, $\boldsymbol{c}$ is the shape to which the rule is applied, $\boldsymbol{t}$ is a transformation under which $\boldsymbol{a}$ becomes a part of $\boldsymbol{c}$, and $\boldsymbol{c}'$ is the result of the rule action. The process starts with the initial rule $0 \rightarrow \boldsymbol{c}$ which, due to its empty lefthand side, may apply under whichever transformation we choose to create the initial shape $\boldsymbol{t}(\boldsymbol{c})$.

For example, rule $\boldsymbol{a} \rightarrow \boldsymbol{b}$ given by  $\rightarrow$  rotates a square by replacing square $\boldsymbol{a}$ with its rotated version $\boldsymbol{b}$. We may follow (1) and (2) to apply it to $\boldsymbol{c}$, which is shape , to rotate one of its squares. In accordance with (1), shape $\boldsymbol{a}$ is translated, becoming $\boldsymbol{t}(\boldsymbol{a})$, to match the square appearing in bold . The rule action now proceedes in accordance with (1). Shape $\boldsymbol{t}(\boldsymbol{a})$ is removed leaving behind shape , which is $\boldsymbol{c} - \boldsymbol{t}(\boldsymbol{a})$. Shape $\boldsymbol{b}$ is translated the same way $\boldsymbol{a}$ was to become $\boldsymbol{t}(\boldsymbol{b})$ and added to $\boldsymbol{c} - \boldsymbol{t}(\boldsymbol{a})$ resulting in , which is $\boldsymbol{c}'$. We could apply the same rule under a different translation $\boldsymbol{t}'$ to match the other square  resulting in .

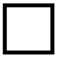
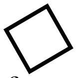
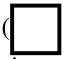
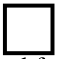
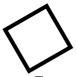
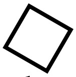
Identity (2) may be seen as a shape valued function $f_{R'}(\boldsymbol{c}, \boldsymbol{t}) = (\boldsymbol{c} - \boldsymbol{t}(\boldsymbol{a})) + \boldsymbol{t}(\boldsymbol{b})$, with two variables $\boldsymbol{c}$ and $\boldsymbol{t}$, as well as two constants $\boldsymbol{a}$ and $\boldsymbol{b}$. The calculations above may now be done with $f_{R'}$. For example, $f_{R'}($$, \boldsymbol{t}) = ($ $- \boldsymbol{t}($$))$ $+ \boldsymbol{t}($$) = ($ $-$ $) +$  $=$  $+$  $=$ . Function $f_{R'}$ describes all possible rule actions of rule $\boldsymbol{a} \rightarrow \boldsymbol{b}$. Because the function does not take into account the matching part, given by inequality (1), it describes much more than the possible rule actions. For example, consider $f_{R'}($$, \boldsymbol{g})$ where instead of the matching transformations $\boldsymbol{t}$ or $\boldsymbol{t}'$ we have an arbitrary one $\boldsymbol{g}$ that, say, shrinks and translates square $\boldsymbol{a}$. Consequently, $f_{R'}($, $\boldsymbol{g}) = ($ $- \boldsymbol{g}($$)) + \boldsymbol{g}($$) = ($ $-$ $) +$  $=$  $+$  $=$ . The result looks strange. Instead of having one of the squares rotated, we are left with the original shape augmented by a small rotated square. Although the rule only rotates a square, the result implies addition. It is clear that the latter calculation, while properly carried out, does not describe an action of the rule above. This is not surprising given that $\boldsymbol{g}(\boldsymbol{a})$ violates (1) by failing to match any part of $\boldsymbol{c}$. Function $f_{R'}$ describes rule actions only for the proper combinations of $\boldsymbol{c}$ and $\boldsymbol{t}$, so its domain needs to be restricted to these.

Let $\boldsymbol{a} \rightarrow \boldsymbol{b}$, where $\boldsymbol{a}, \boldsymbol{b} \in U_{ij}$, be a rule and let set $\mathrm{C}_{ct}(\boldsymbol{a})$ be defined by $\mathrm{C}_{ct}(\boldsymbol{a}) = \left\{(\boldsymbol{c}, \boldsymbol{t}) \in U_{ij} \times T_{ij} | \boldsymbol{t}(\boldsymbol{a}) \le \boldsymbol{c}\right\}$, then function $f_R(\boldsymbol{c}, \boldsymbol{t}) = f_{R'}|_{\mathrm{C}_{ct}(\boldsymbol{a})}(\boldsymbol{c}, \boldsymbol{t})$, or $f_{R'}$ restricted to $\mathrm{C}_{ct}(\boldsymbol{a})$, describes all possible actions of rule $\boldsymbol{a} \rightarrow \boldsymbol{b}$ and nothing else.

If we are to use function f_R to calculate rule actions in a course of a design derivation, then shape $\boldsymbol{c}$ is known at each step of the derivation before we use the function. That way f_R is used with fixed $\boldsymbol{c}$ which is equivalent to being a one variable function. So, we should define one instead.

Let function $f_{r'}$ be defined by $f_{r'}(\boldsymbol{t}) = (\boldsymbol{c} - \boldsymbol{t}(\boldsymbol{a})) + \boldsymbol{t}(\boldsymbol{b})$ and let set $C_t(\boldsymbol{a}, \boldsymbol{c})$ be defined by $C_t(\boldsymbol{a}, \boldsymbol{c}) = \left\{\boldsymbol{t} \in T_{ij} | \boldsymbol{t}(\boldsymbol{a}) \leq \boldsymbol{c}\right\}$, then[2] function $f_r(\boldsymbol{t}) = f_r|_{Ct(\boldsymbol{a},\boldsymbol{c})}(\boldsymbol{t})$ describes all actions of rule $\boldsymbol{a} \rightarrow \boldsymbol{b}$ on shape $\boldsymbol{c}$ and nothing else.

Note that domains $C_{ct}(\boldsymbol{a})$ of f_R and $C_t(\boldsymbol{a}, \boldsymbol{c})$ of f_r do not depend on shape $\boldsymbol{b}$ so that the functions may describe actions of different rules provided that they share the lefthand side. The functions for two such rules are technically different, but the only difference is in constant $\boldsymbol{b}$ which reflects the righthand side of each rule.

Let us use rule  $\rightarrow$  this time on shape $\boldsymbol{c} = \boldsymbol{a}$ so that matching transformation $\boldsymbol{t}$ is an identity. We first calculate domain $C_t(\boldsymbol{a}, \boldsymbol{c})$. Because there is only one part of $\boldsymbol{c}$ to be matched by $\boldsymbol{a}$—namely $\boldsymbol{c}$ itself—the domain depends on the symmetry of $\boldsymbol{a}$. In this case $C_t($, $) = D_4$ the dihedral group of symmetries of a square which has four rotations and four reflections. The rule may apply in eight different ways, so $f_r(\boldsymbol{t})$ is calculated for eight values of $\boldsymbol{t} \in D_4$ yielding two different outcomes  and .

In practical grammars which generate designs in say certain architectural styles we need domains C_t small in order to control the process and avoid surprises. We use devices like labeled points to break the symmetries of $\boldsymbol{a}$ and $\boldsymbol{c}$ and often have domains that are as small as singletons. In contrast, when exploring with grammars surprises are welcomed and so are big domains.

There are other nonstandard shape grammars with more elaborate rule action descriptions which could lead to different and more elaborate rule action functions and domains. Such are collision protecting, biconditional, and quad grammars [9] all in the class of grammars for making [12]. Examining those is beyond the scope of this work.

Note 4: On Boolean and Shape Valued Functions

Shape valued functions are Boolean, however, not all Boolean functions are shape valued functions. The fact that the Boolean part of an algebra of shapes is not a Boolean algebra but a generalized Boolean algebra or GBA has to do with it.

A GBA is a relatively complemented distributive lattice with 0, but not necessarily 1.[3] It has Boolean operations of sum (+) and ($\cdot$), as well as a binary operation of difference ($-$) defined as $a - b$ is the relative complement of b in interval $[0, a + b]$. Note that $b - a$ is the relative complement of a in the same interval. The latter operation is possible because relative complements in a relatively complemented distributive lattice are unique.

[2] Note that domain $C_t(\mathbf{a}, \mathbf{c})$ is the set of solutions of inequality $\boldsymbol{t}(\boldsymbol{a}) \leq \boldsymbol{c}$.

[3] For shapes it means that there is no the greatest shape of all.

Boolean algebras are in fact GBAs with 1 and the complement operator (′) in place of the binary difference operation. The relation between the two is given by

$$a' = 1 - a \tag{3}$$

$$a - b = a \cdot b' \tag{4}$$

Expressions defining Boolean functions consist of letters, which are constants and variables and are elements of the underlying Boolean algebra as well as symbols for sum, product, and complement. A literal is a letter or its complement, but cannot be 0 or 1. A term is either 1 a single literal or a product of literals in which no letter appears more than once. A sum of product expression or SOP expression is either 0 a single term or a sum of terms. The standard way of representing Boolean functions is via SOP expressions.

Note that there is a difference between expressions and the functions defined by them. An n-variable Boolean function f: $\boldsymbol{B}^n \rightarrow \boldsymbol{B}$ —where $\boldsymbol{B}$ is a Boolean algebra–is a special kind of $(n + 1)$-ary relation or a set of $(n + 1)$-tuples of elements of $\boldsymbol{B}$. Function f is a subset of direct power $\boldsymbol{B}^{n+1}$ with projections pr_1 to pr_n representing the variables and pr_{n+1} representing the result of f. In contrast, expressions are strings of symbols embodying the syntax of function definitions. The relation between functions and expressions is one-to-many as a function may be defined by several different expressions. Two expressions are equivalent if they are defining the same function.

Although general Boolean expressions (or GB expressions) with differences do not appear Boolean, they actually are, as the differences could be turned into complements via identity (4). Consequently, all GB expressions are Boolean, so that all GB functions are Boolean functions. In contrast, complements cannot be removed from Boolean expressions via identity (3) as this requires existence of 1. Thus, only some of the Boolean algebra expressions define GB functions. The set of Boolean expressions is partitioned into the set of GB expressions and that of non-GB expressions. Boolean expressions that do not require 1 or complements are clearly GB expressions. In addition, some expressions with complements may also be in this category.

For example, a one-term Boolean expression $a \cdot x'$ is also a GB expression. It may, according to (3), be written as $a - x$, thus avoiding the complements.

We will now proceed to establish the necessary and sufficient conditions for a Boolean expression to also be a GB one.

Definition 1 If a term is 1 or all of its literals are complements of letters then it is an *exposed complements* term. It is a *covered complements* term otherwise.

For example, x', a', $a' \cdot b' \cdot x'$ are exposed complements terms while, $a' \cdot b' \cdot x \cdot y$, a, $a \cdot b$ are covered complements terms.

Lemma 1 A term, different than 1, can be expressed by $a_1 \cdot a_2 \cdot \ldots \cdot a_n \cdot b_1' \cdot b_2' \cdot \ldots \cdot b_m'$, where $a_1, a_2, \ldots a_n, b_1, b_2, \ldots b_m$ are letters. Covered complements terms have $n \in$

$\{1, 2, 3, \ldots\}$ and $m \in \{0, 1, 2, \ldots\}$, while exposed complements terms have $n = 0$ *and* $m \in \{1, 2, 3, \ldots\}$. Note that for $n = 0$ ($m = 0$), there are no a_i (b_i) letters.

This follows from the definition of the term, Definition 1, and commutativity of the product.

Proposition 1 GB expressions are equivalent to SOP Boolean expressions containing covered complements terms only.

This stems from the fact that a covered complements term can be expressed without the aid of complements while an exposed complements term cannot. Let $a_1 \cdot a_2 \cdot \ldots \cdot a_n \cdot b_1' \cdot b_2' \ldots \cdot b_m'$, where $n \geq 1$ and $m \geq 0$, be a covered complements term, in accordance with Lemma 1. It could, in accordance with De Morgan's laws,[4] be transformed into $a_1 \cdot a_2 \cdot \ldots \cdot a_n \cdot (b_1 + b_2 + \cdots + b_m)'$, and further, in accordance with (3), into $a_1 \cdot a_2 \cdot \ldots \cdot a_n - (b_1 + b_2 + \cdots + b_m)$ (*).

For example, covered complements terms $a{\cdot}x'$ and $a'{\cdot}b'{\cdot}x{\cdot}y$ may be expressed as $a - x$, and $x \cdot y - (a + b)$, respectively.

In contrast, an exposed complements term (other than 1) cannot be expressed without the aid of complements. At best, all but one complemented letter may be removed, or $b_1' \cdot b_2' \cdot \ldots \cdot b_m' = b_1' - (b_2 + b_3 + \cdots + b_m)$.

Finally, a Boolean expression having covered complements terms only can be transformed into a GB expression which is a sum of constructs (*), thus completing the proof.

We mentioned earlier that the standard way of representing Boolean functions is via SOP expressions. A similar construct could be developed for GBA expressions.

Proposition 2 GB expressions may be represented in SOP form, with terms $a_1 \cdot a_2 \cdot \ldots \cdot a_k \cdot (c_1 - b_1) \cdot (c_2 - b_2) \ldots \cdot (c_m - b_m)$, where $k, m \geq 0, \cup_{i=1\ldots m}\{c_i\} = \{a_{k+1}, \ldots a_n\}$, $n > k$ and each letter $a_1, \ldots a_n, b_1, \ldots b_m$ is different.

Product $t = a_1 \cdot a_2 \cdot \ldots \cdot a_k \cdot (c_1 - b_1) \cdot (c_2 - b_2) \ldots (c_m - b_m)$ lends itself to an equivalent Boolean product $t_B = a_1 \cdot a_2 \cdot \ldots \cdot a_k \cdot c_1 \cdot c_2 \cdot \ldots \cdot c_m \cdot b_1' \cdot b_2' \cdot \ldots \cdot b_m'$, in accordance with (3) and the distributivity of the product. Product $c_1 \cdot c_2 \cdot \ldots \cdot c_m = a_{k+1} \cdot a_{k+2} \cdot \ldots \cdot a_n$ because letters $c_1, \ldots c_m$ exhaust set $\{a_{k+1}, \ldots a_n\}$ and all duplicate letters may be removed due to the idempotency[5] of the product. Now product t_B becomes $a_1 \cdot a_2 \cdot \ldots \cdot a_n \cdot b_1' \cdot b_2' \cdot \ldots \cdot b_{mm}'$ with the familiar look of a covered complements term—in accordance with Lemma 1. This completes the proof because according to Proposition 1, SOP Boolean expressions with covered complements terms are equivalent to GB expressions.

Proposition 2 Implies that product t is a GB term which requires for the Boolean definition of a literal to be adapted to GB.

Definition 2 A GB literal is a letter or a difference of letters, but cannot be 0.

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[4] De Morgan's laws: $(\boldsymbol{a} + \boldsymbol{b})' = \boldsymbol{a}' \cdot \boldsymbol{b}'$ and $(\boldsymbol{a} \cdot \boldsymbol{b})' = \boldsymbol{a}' + \boldsymbol{b}'$.

[5] Idempotency of the product: $x \cdot x = x$.

Products of terms are terms, but sums and complements of terms are expressions. The following lemma informs how the types of argument terms influence the type of their product.

Lemma 2 The following holds:

(i) the product of terms of the same type is ether a term of that type or 0,
(ii) the product of terms of different types is either a covered complements term or 0.

Multiplying two exposed complements terms will result in an exposed complements term. The resulting term consists of complements of letters only because both of the argument terms do. The product of a covered complements term with any other term is also a covered complements term. Because a covered complements term contains at least one letter, the same letter appears in any product involving this term. Consequently, the resulting term is a covered complements term. Multiplying two terms may also result in 0 if the complement of a letter appears in one of the argument terms and the letter in the other.

The following proposition shows how the type of the resulting expression depends on the types of expressions that are combined to produce it.

Proposition 3 The following holds:

(i) the product or sum of two expressions of the same type is an expression of that type, or 0,
(ii) the product of two expressions of different types is a GB expression, or 0,
(iii) the sum of two expressions of different types is a non-GB expression,
(iv) the complement of an expression is of different type than the original expression, or 0.

Statements (i) and (ii) follow from the distributivity of product over sum and Lemma 2. Statement (iii): the sum inherits all of the exposed complements terms from the non-GB argument expression, so it too becomes a non-GB expression. Statement (iv): the complement of expression $f = a + b + c + \ldots$ where a, b, c, … are terms is—in accordance with de Morgan laws—$f' = (a + b + c + \ldots)' = a'b'c' \ldots = \left(x_1' + x_2' + \ldots\right)\left(y_1' + y_2' + \ldots\right)\left(z_1' + z_2' + \ldots\right)\ldots$ where $x_1, x_2, \ldots, y_1, y_2, \ldots, z_1, z_2$ … are literals appearing in terms a, b, and c, respectively. If f is a non-GB expression, then at least one of the terms a, b, c, … is an exposed complements term. Let a be that term so that all of its literals x_1, x_2, … are complements of letters which makes x_1', x_2', … the letters. If we set $\left(y_1' + y_2' + \ldots\right)\left(z_1' + z_2' + \ldots\right)\ldots = t_1 + t_2 + \ldots$, where $t_1 + t_2 +$ … are terms, then $f' = \left(x_1' + x_2' + \ldots\right)(t_1 + t_2 + \ldots) = x_1't_1 + x_1't_2 + \ldots x_2't_1 + x_2't_2 + \ldots$. Each term of f' contains one of the letters $x_1', x_2', \ldots$, so that all of the terms are of the covered complements type. This, in accordance with Proposition 1, renders f' a GB expression. If f is a GB expression, then all of its terms are covered complements terms having at least one literal which is a letter. Let those literals be $x_1, y_1, z_1 \ldots$

then term $x_1' y_1' z_1' \ldots$ has all of its literals as complements of letters, which makes it an exposed complements term. The latter term is clearly in f' which renders f' a non-GBA expression.

Final Note

The paper consists of four independent notes tackling different aspects of shape valued functions and their place in the shape grammar theory.

The first three notes look into how shape valued functions fit into shape grammar theory, while the last note examines the functions themselves.

In the first note we were investigating rule schemas with the assumption they are actually shape valued functions—the former using the language of shape grammars and the latter of mathematics. That proved not to be true. Most of the schemas were easy to turn into functions, while some were difficult, but there were some that could not be turned.

In the second part we dealt with schemas that involve boundary operators. These were simple, intuitive, and widely used. However, they proved difficult to place into the framework of an algebra of shapes. It was clear that because shapes and their boundaries belong to different algebras, we needed a combination of algebras to have them both. However, most of these combinations are based on the direct product and appear compartmentalized, preventing "hopping" between the algebras necessary for the boundary operator to work. The solution came from an unlikely place. An algebra of shapes developed earlier not for practical use but to explore sum-of-algebras constructions proved to be the right choice. A commutative sum of algebras of shapes is not compartmentalized because it is not based on the direct product but on the set union instead. It provides a great environment for the boundary operator to freely "hop" between the algebras.

The third note dealt with the rule action procedure which we turned into a shape valued function. In doing so, we took advantage of function restrictions and domains. The note is short as we just dealt with standard grammars. More elaborate rule actions procedures, like the ones related to grammars for making, are left for future research.

Another important example of shape valued functions is also left for future research. These are continuous functions between shapes allowing for continuity of derivations with shape grammars when shapes are represented by their decompositions.

The last note differs from the first three as it examines the nature of shape valued functions. The latter are seen as generalized Boolean functions, or GB functions, because the Boolean part of an algebra of shapes is a generalized Boolean algebra. As such, they are compared to standard Boolean functions. Expressions defining GB functions form a subset of the set of Boolean expressions. Several definitions, lemmas and propositions related to Boolean and GB expressions, as well as their combinations, are given. We did not make use of the latter, but they may be helpful in future dealings with shape valued equations.

The importance and popularity of Stiny's rule schemas probably renders the first two notes the most interesting ones from a shape grammatist's perspective. An account of schemas and complementary functions from these notes is summarized in the following table.

Type	Schema	Function	Restriction	Comments
Typical	$\boldsymbol{x} \rightarrow \boldsymbol{t}(\boldsymbol{x})$	$f_t(\boldsymbol{x}) = t(\boldsymbol{x})$	N/A	Rule generating function
Inverse	$\boldsymbol{t}(\boldsymbol{x}) \rightarrow \boldsymbol{x}$ $\boldsymbol{x} \rightarrow \boldsymbol{t}^{-1}(\boldsymbol{x})$	$f_t^{-1}(\boldsymbol{x}) = \boldsymbol{t}^{-1}(\boldsymbol{x})$	N/A	Rule generating function
Typical	$\boldsymbol{x} \rightarrow \boldsymbol{x} + \boldsymbol{a}$	$f_a(\boldsymbol{x}) = \boldsymbol{x} + \boldsymbol{a}$	$f_a\|_A(\boldsymbol{x}) = \boldsymbol{x} + \boldsymbol{a}$	$A = \{\boldsymbol{y} \in U_{ij} \| \boldsymbol{y} \cdot \boldsymbol{a} = 0\}$ $A' = \{ f_a\|_A(\boldsymbol{x}) \| \boldsymbol{x} \in A\}$ $g(\boldsymbol{x}) = \boldsymbol{x} - \boldsymbol{a}$ Rule generating functions
Inverse	$\boldsymbol{x} + \boldsymbol{a} \rightarrow \boldsymbol{x}$	Not available	$f_a\|_{A^{-1}}(\boldsymbol{x}) = g\|_{A'}(\boldsymbol{x})$	
Typical	$\boldsymbol{x} \rightarrow \boldsymbol{x} + \boldsymbol{t}(\boldsymbol{x})$	$f_g(\boldsymbol{x}) = \boldsymbol{x} + \boldsymbol{t}(\boldsymbol{x})$	N/A	Rule generating function
Inverse	$\boldsymbol{x} + \boldsymbol{t}(\boldsymbol{x}) \rightarrow \boldsymbol{x}$	Not available	N/A	
Typical	$\boldsymbol{x} \rightarrow \mathrm{prt}(\boldsymbol{x})$	$f_p(\boldsymbol{x}) = \mathbf{I}(\boldsymbol{x})$	N/A	$f_p, f_p^{-1} : U_{ij} \rightarrow \wp(U_{ij})$ Not rule generating function
Inverse	$\boldsymbol{x} \rightarrow prt^{-1}(\boldsymbol{x})$	$f_p^{-1}(\boldsymbol{x}) = \mathbf{F}(\boldsymbol{x})$	N/A	
Typical	$\boldsymbol{x} \rightarrow b(\boldsymbol{x})$	$f_b(\boldsymbol{x}) = b(\boldsymbol{x})$	N/A	Rule generating function
Inverse	$\boldsymbol{x} \rightarrow b^{-1}(\boldsymbol{x})$	$f_b^{-1}(\boldsymbol{x}) = b^{-1}(\boldsymbol{x})$	$f_b^{-1}\Big\|_B(\boldsymbol{x}) = b^{-1}(\boldsymbol{x})$	$f_b^{-1} : U_{ij} + U_{i+1j} \rightarrow \wp(U_{ij} + U_{i+1j})$ $B = \{\boldsymbol{y}\|z = b(\mathbf{y}), z \in U_{ij} + U_{i+1j}\}$ Not rule gen. functions
Typical	$\boldsymbol{x} \rightarrow \boldsymbol{x} + b(\boldsymbol{x})$	$f_{xb}(\boldsymbol{x}) = \boldsymbol{x} + b(\boldsymbol{x})$	N/A	Rule generating function
Inverse	$\boldsymbol{x} + b(\boldsymbol{x}) \rightarrow \boldsymbol{x}$	Not available	$f_b^{-1}\Big\|_{B'}(\boldsymbol{x}) = b^{-1}(\boldsymbol{x})$	$f_b^{-1} : U_{ij} + U_{i+1j} \rightarrow U_{ij} + U_{i+1j}$ $B' = \{\{\boldsymbol{y}, b(\mathbf{y})\} \in U_{ij} + U_{i+1j}\}$ Rule generating function

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Making Grammars for Computational Lacemaking

Katerina Labrou and Sotirios D. Kotsopoulos

A pair of formal grammars capturing a traditional Cretan bobbin lace-making technique is defined. The analog, manual process of braiding and the craftsman's interaction with physical tools and materials determine making rules. Generating geometric configurations of lace pattern designs determines parametric shape rules and symmetry transformations. Pairing a grammar for braiding and a parametric shape grammar for designing captures the specified bobbin lacemaking technique and the generation of a traditional Cretan lace pattern language.

Introduction

There is a growing interest in analyzing traditional craft techniques motivated by the ambition to renew the creative potential of computational fabrication and crafts. Traditional crafts are a repository of knowledge on material usage and artistic refinement. Their design and fabrication methods have emerged through longstanding exploration of materials and experimentation on how artifacts are made and how they look and feel. The computational examination of craft poses challenges in analyzing human cognition and interfacing with tools, materials, and the world. It is a way to learn about human creativity, dexterity, and ingenuity in a targeted manner. In parallel, computational craft analysis renews design and fabrication methods in exciting ways by integrating enduring creative practices (see for example, Muslimin [10]). This study is the first to address the generative specification of a traditional

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Cretan bobbin lacemaking technique. The presented analysis describes how braids are made with hand tools, focusing mainly on the process's performance and perceptual aspects. The multi-sensory approach of making grammar is central to this analysis. The originality of this study is that two formal grammars, namely a braiding grammar and a pattern generation grammar, are combined to capture the Cretan bobbin lacemaking technique while acknowledging the craft's original tools, materials, and physical limitations. Initially, simple weave varieties are distinguished and classified based on manual weaving rules that generate the interlacing of specific thread types. Then, the generation of lace pattern designs is treated as constructing visual patterns based on symmetry. Combining a braiding grammar, including rules of physical making that generate stitch patterns, and a parametric shape grammar with shape rules and transformations that generate geometric pattern designs determines the Cretan bobbin lacemaking technique. The two grammars describe the weaving process as a sequential rule application and provide a basis for implementing and automating this traditional bobbin lacemaking technique with finite-state automata.

Background

Semper [11, 12], the first to examine ornamentation formally, approached weaving as a fabrication process. Interestingly, Semper identified the origins of architectural morphology in the weaving techniques. A resonance of these ideas appears in the work of textile artist and printmaker Albers [1]. Albers [2] examines the origins of weaving and experiments with textiles' aesthetic and structural nature: "*Like any craft, weaving may end in producing useful objects, or it may rise to the level of art*." According to Albers, the weaved objects exhibit an internal coherence in form, function, and material. Form rises through the actions of the artisan and the intricacies of the material.

The anthropologist Ingold [3, 4] presents an empirical perspective, suggesting that weaving is analogous to form evolution in nature. Ingold's approach to craft [3] surpasses the physical-artificial object discrimination of the hylomorphic model, which is based on imposing ideas of form on the material. In weaving, the artifact is shaped within a dynamic force field, an ongoing cycle between the maker's intentions, manifested by rhythmic hand movements defining structural relations between the material units. Each artifact is "*different, completely reflecting the mood and the temperament, as well as the physical stature, of its maker*" [5].

Recently, Knight and Stiny [7] emphasized the significance of weaving as a computational practice of growth, procedure, and formation. Craft, material, and cognitive considerations are expressed formally in making grammars [7], where generative rules capture sensory interactions and hand movement. The determining features of making techniques are transferred into computational rules used in producing material things. Knight's knotting grammar [6] is a typical making grammar inspired by the Incas' traditional *khipu.* The grammar generates single or multiple overhand knots along a string [6]. Operations and interactions with the physical objects and materials are described by doing and sensing grammar rules. The procedural character of craft is discussed in Knight [8] *Craft, Performance and Grammars*, where three generative procedures of the same creative process are compared. Knight defines three grammars demonstrating alternative constructive systems for creating traditional Indian *kolam* patterns. The first grammar is a modular set grammar using shape transformations, namely reflective symmetries, to generate geometric patterns. The second grammar introduces materiality through appropriately placed grid lines that guide a shape generation process. The third grammar is a making grammar introducing *sensing* (seeing) rules—involving a line looping around a grid of *pulli* that can be sensed in various ways—and *doing* rules that involve drawing. Despite the differences in *kolam*-making and lacemaking, sensory interaction determines pattern generation rules in both.

The analysis of the Cretan bobbin lacemaking follows two kinds of formal principles: physical pattern making (stitching) and geometrical pattern making (design). The pairing of a making grammar for braiding and a parametric shape grammar for designing describes Cretan bobbin lacemaking. The interactions of threads and the manual and perceptual aspects of the process are expressed with rules, accepting that the procedural mode of generative grammar is well aligned with the procedural nature of the craft.

Method

Bobbin lacemaking exhibits a wide range of variations worldwide. A traditional bobbin lacemaking technique developed in Crete, Greece, is examined here. Cretan bobbin lace pattern designs are analyzed, and rule descriptions of their production method are determined to explore the generative potential of this craft. First, rules capture the hand movements producing a lace strip. Second, another set of rules captures combinations of basic stitch patterns based on an underlying grid that sets the designs. A grid generation algorithm recaps how consecutive stitches are braided to form a lace strip. The grid method resembles the Ice Ray Lattice grammar [13], where rules generate designs based on a grid.

Generative Specification of Cretan Lacemaking

Bobbin lacemaking techniques vary by design theme, stitch type, thread type, and tool type. All four features affect lace quality. The Cretan bobbin lacemaking is a good fit for study due to the small number of threads used in the procedure, typically seven thread pairs, much lower than other bobbin lace techniques. Furthermore, bobbins make the association of hand movement and pattern making easier. The outcome of the braiding process is a thread composition that is used to create the overall lace pattern design. Lace stitching patterns vary, and so do their designs. The

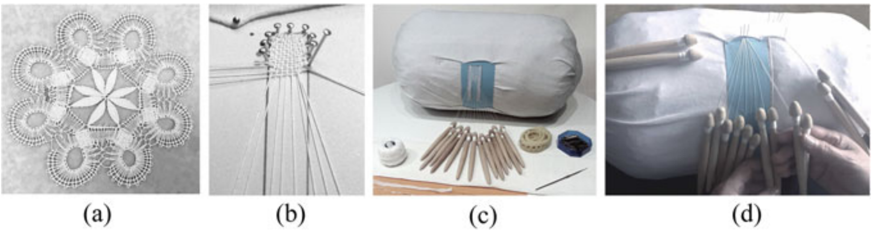


Fig. 1 **a** Floral lace pattern design, photograph by the authors (Association of Friends for the Preservation and Promotion of Cretan Bobbin Lace 'Christina,' Greece). **b** Tape lace in progress. **c** Tools. **d** Holding the bobbins for weaving

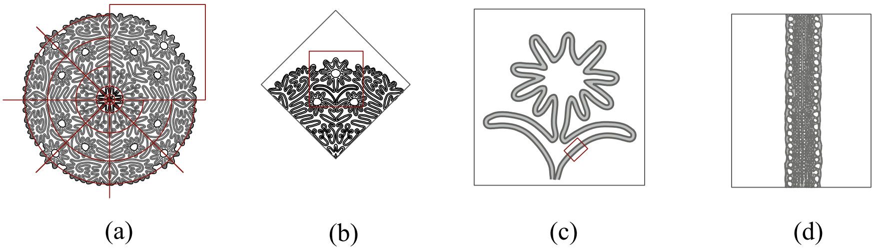


Fig. 2 **a** A lace design pattern exhibiting rotational symmetry. **b** Flower theme exhibiting bilateral symmetry. **c** The flower shape part, and **d** Tape detail

Cretan bobbin lace designs are renowned for geometries produced by a line that drifts freely within the structure. They are customarily inspired by natural themes like branches, flowers, or leaves, often synthesized to create complex compositions (Fig. 1a) characterized by symmetry. Symmetry is considered an essential feature of beauty. It derives from drawing the design theme on tracing paper, folding it axially, and duplicating it (Fig. 2a).

The geometric and structural unit of Cretan bobbin lace patterns is the tape lace (πανάκι; *panáki*) (Figs. 1b and 2d). The geometry of the design is printed on a carton before weaving, and two parallel guidelines are drawn to mark the edge. Then, the drawing is pinned on a cylindrical pillow (Fig. 1c), and three pins are placed along the upper margin of the drawing at equal intervals (Fig. 1b). Seven threads are tied on both ends on fourteen bobbins and are hitched on the pins to start weaving. The lace is created boustrophedon, from left to right and downwards. If needed, additional pins are placed on the borders of the drawing to keep the threads in place.

Observing the braiding process is the basis of contriving rules. The braiding process includes preparation, braiding, and finishing. The lace pattern emerges through the recurrence of the basic stitch types. Threads are worked in one or two pairs with the bobbins to produce a stitch of entangled threads. The physical enactment is illustrated with two-dimensional figures capturing how hand movements operate on the threads (Figs. 3 and 4).

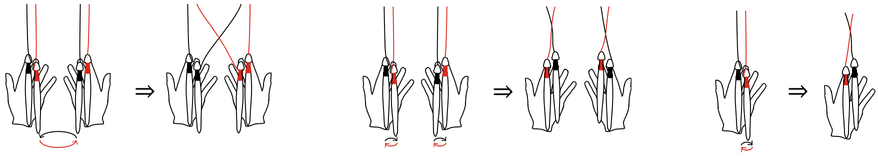


Fig. 3 Main movements: cross (left), double twist (center), single pair twist (right)

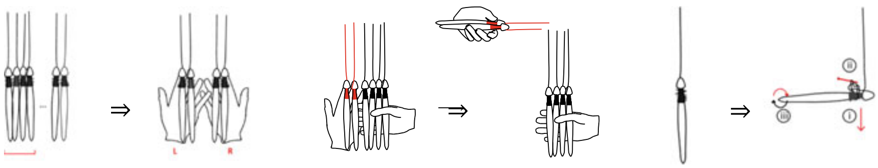


Fig. 4 Auxiliary movements: thread selection (left), pulling of threads on the side (center), and thread length adjustment (right)

The threads are interwoven sequentially from the leftmost boundary to form a row of stitches. Each row consists of two basic stitch types: internal or side. Internal stitches are used for weaving across the width of a linear pattern. Two internal stitches are used: cloth stitch (C) (πλέξη; *pléxi*) and tulle stitch (T) (τούλι; *toúli*). Side stitches are used along the sides of tape lace. Two types of side stitches are the *link* (D) (δέμα; *déma*) and the *selvage* (U) (ούγια; *oúyia*) [9]. A *link* is typically used to join adjacent weaves in complex patterns. A *selvage* is a dense stitch appearing at the edge of the lace. Side stitches connect two consecutive rows of the linear pattern.

Two sets of mandatory movements are distinguished based on whether they create new thread crossings. The *main braiding movements* produce the interlacing of threads. The *auxiliary braiding movements* assist the braiding process. Main braiding movements include passing the threads on top to create new thread crossings. Three kinds of main braiding movements are: cross (left), double twist (center), and single pair twist (right) (Fig. 3).

Auxiliary movements include selecting a thread by grasping the bobbins, pulling the bobbins on the side to stretch the threads, or adjusting the length of a thread (Fig. 4). Other auxiliary movements include placing a pin on the lace design geometry at the beginning of the weaving process or making a knot between two threads at the very end.

The main and auxiliary movements are explored next in the context of a making grammar. These two distinct movement types are transferred into rules to generate simple lace designs based on the traditional technique. Alternative stitch representations are also explored, producing lace variations.

From Hand Movements to Lace Patterns

Stitches emerge from consecutive manual operations on threads. There is a correspondence between a stitch pattern and the sequence of hand movements that produce it. A pair of formal grammars describe the making of tape lace generation. The first, *braiding grammar*, translates the movements of the manual technique into rules, linking the hand maneuvers to stitch patterns. The second, *lace pattern grammar*, combines stitch patterns to produce geometric lace designs. The braiding grammar generates the physical building blocks of the designs, and the lace pattern grammar uses these blocks to realize a selected geometrical imprint.

The Braiding Grammar

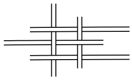
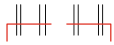
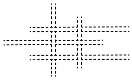
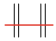
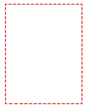
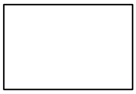
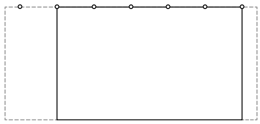
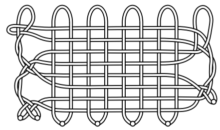
In the braiding grammar, interfacing with tools and materials determines rules for stitch patterns (Table 1, Things). The critical actions are grasping, braiding direction, and visual attention. They are indicated with red marker lines (Table 1, Actions). The making process is analyzed into steps based on the effect of each action on the threads. The production process imitates the respective activities on threads in 3-d space. The stitches are produced graphically in an algebra for lines on the plane (U_{12}). The process is reduced to the essential aspects necessary for the analysis. The number of pins used in the pre-processing stage equals the number of the thread pairs. The initial shape is a shape in the algebra [$U_{02} \times U_{12} \times W_{12}$], including the pinheads, the design imprint, and the work area boundaries (Table 1). Lace stitches are produced by consecutive rule applications on the initial shape.

Following basic graphical conventions, main braiding movements that correspond to braiding actions are converted into rules involving threads and tools. Thread modifications captured by each rule are based on experiments with cotton threads (DMC no. 100). Auxiliary movements are converted into preprocessing, selection, stretching, pin positioning, and post-processing rules. Rules capturing attention focus are also defined to support the production process. Lines and markers introduced to assist the derivation—but not belonging to the pattern—are erased at the end.

The complete description contains black lines, colored and dashed lines, and symbols, in the product shape algebra [$U_{02} \times U_{12} \times W_{02} \times W_{12} \times W_{12}$] [14]. Following the shape grammar conventions, a double arrow $\Rightarrow$ denotes a transition in a derivation, resulting from applying a rule R on a shape S to transform it into a new shape S'. A rule has the form M $\rightarrow$ N, where M, N are shapes, and the arrow $\rightarrow$ denotes the replacement of M with N. A transition S $\Rightarrow$ S' is:

$$[U_{02} \times U_{12} \times W_{02} \times W_{12} \times W_{12}] \Rightarrow [U_{02} \times U_{12} \times W_{02} \times W_{12} \times W_{12}].$$

Table 1 Materials and actions: algebras and representational conventions

Things	Algebras	Shapes	**Actions**	Algebras	Shapes
Threads	U_{12}		Grasping—opposite hands (red signs)	W_{02}	
Thread extensions	W_{12}		Grasping—any hand (red sign)	W_{02}	
Pin head (inactive)	U_{02}	○	Braiding direction (red sign)	W_{02}	
Pin head (active)	U_{02}	●	Visual attention (red dashed line)	W_{12}	
Knot	U_{12}				
Design imprint	U_{12}		Initial shape [$U_{02} \times U_{12} \times W_{12}$]: 		
Working area boundaries	W_{12}		Produced shape [Ø × U12 × Ø × Ø × Ø]: 		

Any component of U_{02}, U_{12}, W_{02}, W_{12}, or W_{12} can be the empty shape. The initial shape is a shape in the product [$U_{02} \times U_{12} \times W_{02} \times$ Ø $\times$ Ø], and a produced pattern without markers is a shape in [Ø $\times$ U_{12} $\times$ Ø $\times$ Ø $\times$ Ø] (Table 1).

The production begins with applying the thread creation rule R. 1, a pre-processing rule (Table 2, Pre-process). Thread selection (R. 2, 3), thread stretching, and pin position rules (R. 4–7) account for the processing of threads that do not interlace (Table 2, Thread Selection). The thread selection rule R. 2 accounts for the grasping of bobbins in the physical process, starting from the sides. Rule R. 3 performs a sequential selection of threads. Thread stretching and pin position rules R. 4–7 perform a pull on the selected threads to tighten them and reveal the pattern. Side stitch rules R. 6, 7 apply when the threads on the drawing sides are selected. They represent the action of using a pin to adjust the weave position. Rules R. 6, 7 affect the shape of adjacent stitches.

Braiding rules R. 8–10 represent the movements: cross, double twist, and single pair twist (movements shown in Fig. 3), which produce new stitch configurations (crossings) with the selected threads (Table 3, Braiding). Post-process rules R. 11, 12 perform the act of forming a knot with two threads at the end of the process

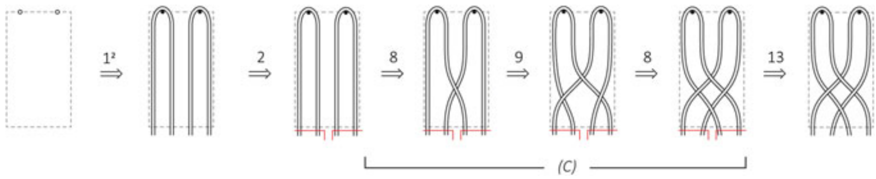


Fig. 5 Derivation C

and shortening the strands (Table 4, Post-process). Rules R. 13–16 terminate the production and refine the design by erasing all markers (Table 4, Drawing). Focus on select subparts of the design is directed with the attention rules R. 17, 18 that isolate a part of the pattern for further development (Table 4, Attention).

Basic stitch types—cloth (C), tulle (T), link (D), and selvage (U)—are produced using two pairs of threads. Derivation (C) in Fig. 5 demonstrates how two pins generate a stitch of the type: cloth. The index number beside the rule number denotes how many times the rule is applied, i.e., 1^2 means that R. 1 is applied twice.

In derivation (C), the cloth stitch derives from a specific application sequence of making rules on the initial shape: thread creation on two pinheads (R. 1), thread selection (R. 2), three consecutive braiding moves (R. 8, 9, 8), and thread deselection (R. 13).

Sequences of braiding rules express compound actions applied at once. Applying the braiding rules 8, 9, and 8 noted as (C) determines such a sequence. Examples of rule sequences for tulle stitch (T) and selvage (U) are presented in derivations (T) (Fig. 6) and (U) (Fig. 7). An example of applying the rule sequence (T) as a single step is demonstrated in Fig. 6, in derivation (T-T). Like the derivation (T-T), any sequence of braiding rules can be used to determine a single transition in a derivation involving compound rules.

In the example of Fig. 7, an index indicates the number of times a set of rules is applied. Derivation (T^6-U) describes the creation of an entire row of the tape lace by applying six times (T) and one time (U). Rule sequence (U) for creating a selvage is defined in derivation (U). A standard routine associated with the final steps—postprocessing and termination—is labeled (F). It corresponds to the rule sequence (11-$(3\text{-}11)^5$-11-13-12-14-15-16), and it allows all auxiliary elements and markers to be erased, terminates the production process, and reveals the clean design.

The Lace Pattern Grammar

The lace pattern grammar combines stitches to produce lace designs. Thread operations captured by rules generate stitch patterns in the braiding grammar. Each stitch pattern becomes a structural unit in the lace pattern grammar, where stitch patterns combine to configure a design (Fig. 8). The rules of the lace pattern grammar specify all the combinations of stitches to generate designs following the principles of the

Table 2 Pre-processing and thread selection rules

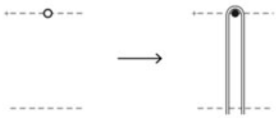
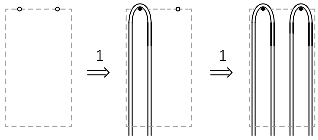
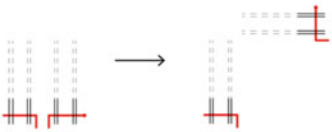
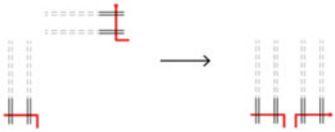
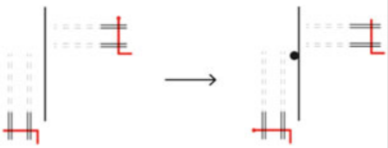
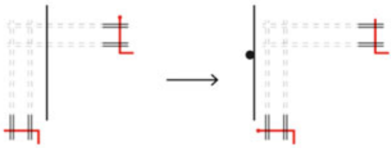
Pre-process	
Rule 1: 	Rule 1 application example: 
Thread selection	
Rule 2: 	Rule 3: 
Rule 4: 	Rule 5: 
Rule 6: 	Rule 7: 

Table 3 Braiding rules

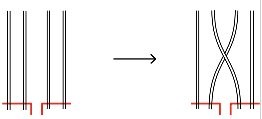
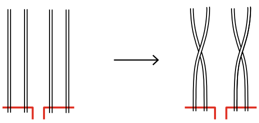
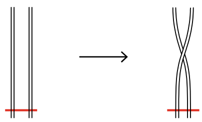
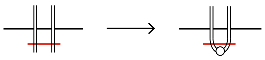
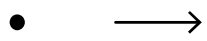
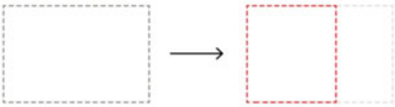
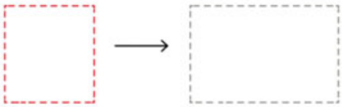
Braiding		
Rule 8: 	Rule 9: 	Rule 10: 

Table 4 Post-process, erasing markers, and attention rules

Post-process			
Rule 11: 		Rule 12: 	
Drawing			
Rule 13: 	Rule 14: 	Rule 15: 	Rule 16: 
Attention			
Rule 17: 		Rule 18: 	

Cretan technique. The braiding grammar produces four stitch pattern types, C, T, D, and U. Variations of each type are also introduced since a stitch may require slight modification depending on the type of neighboring stitches. Stitch patterns generated with the braiding grammar are analyzed to determine side and surface stitches (Fig. 8). Nooses in the first row and knots in the last row are patterns used just once.

An underlying grid common to all lace designs in the language is the initial shape of the lace pattern grammar (Fig. 9). The grid (*parti*) has rows and columns; it is a shape in the product algebra [$U_{02} \times U_{12} \times W_{02}$]. Setting the number of rows sets the length of the tape lace. Markers in the algebra U_{02} indicate the beginning (•), the top of side stitches (▷), the first row (▶), and the end of the stitch selection (Fig. 10).

Four rule classes in lace pattern grammar capture the stages of the making process: (a) a selection rule (S), (b) stitch type determination rules, (c) pattern mapping rules, and (d) an erasing rule to remove the grid when the design is complete (Table 5). All rules and descriptions are defined in the product shape algebra [$U_{02} \times U_{12} \times W_{02} \times W_{12} \times W_{12}$], the same as the braiding grammar. Grid regions are treated by their linear boundaries by the selection rule (S). A red line indicates the selected shape (Table 5). Grid markers guide the selection. Stitch type determination rules apply sequentially from the top left shape (marked with (•)) to the final bottom right shape. The mapping rules apply to each *parti* sub-shape after all neighboring sub-shapes are assigned a stitch type. This substitution process is unambiguous because pattern mapping is univocal. The top leftmost sub-shape of the *parti* is selected first by the selection rule (S), and a stitch type determination rule adds a marker. It is always determined as a stitch of type *cloth* or *tulle*. Then markers are applied on all the *parti* sub-shapes to determine a stitch type. The stitch type choice for each

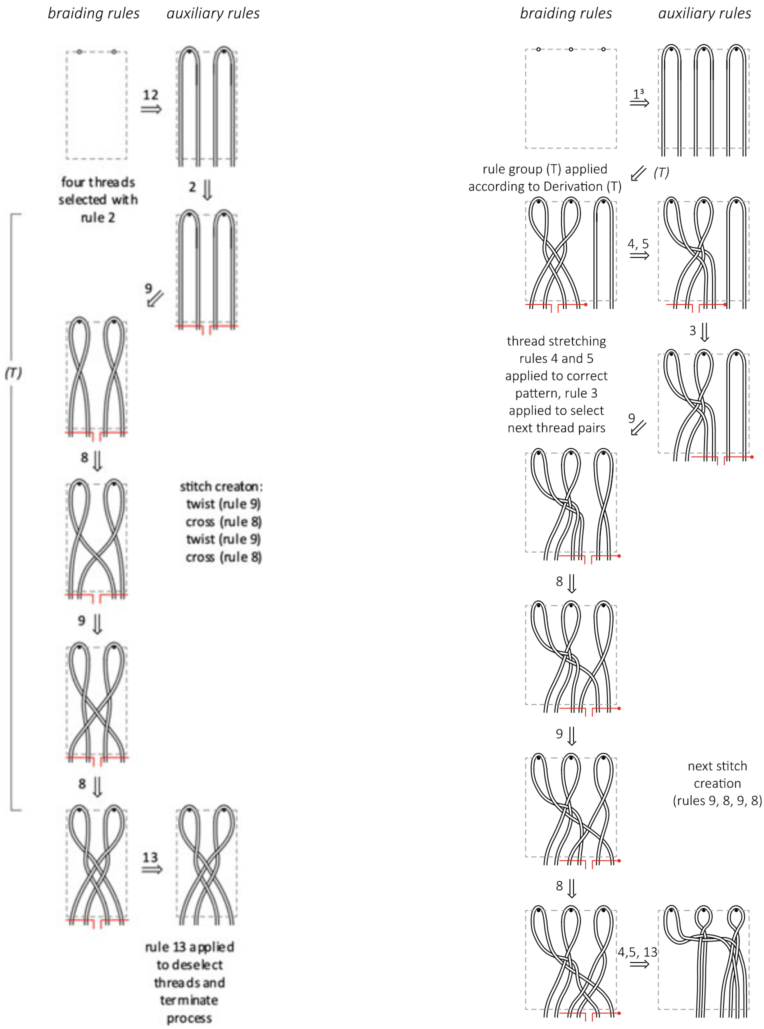


Fig. 6 Derivations (T) of a single tulle stitch and (T-T) of two consecutive stitches

parti cell is constrained by the preceding one, based on the stitch combination rules (Table 5). The marking proceeds boustrophedon from the top left *parti* cell. After all adjoining stitch types are determined, stitch patterns are mapped. The stitch pattern mapping follows the same order as the stitch-type selection. The derivation of a tape lace pattern is presented in Table 6. The rules generate a lace pattern design in three stages. First, the stitch types are assigned by the stitch type determination rules that assign markers (Table 6, in columns 1, 2, and the top two figures in column 3). Second, the mapping rules map the respective stitch type patterns (Table 6, in columns 3, 4, 5, and 6). Third, the *parti* lines are erased, revealing the lace pattern

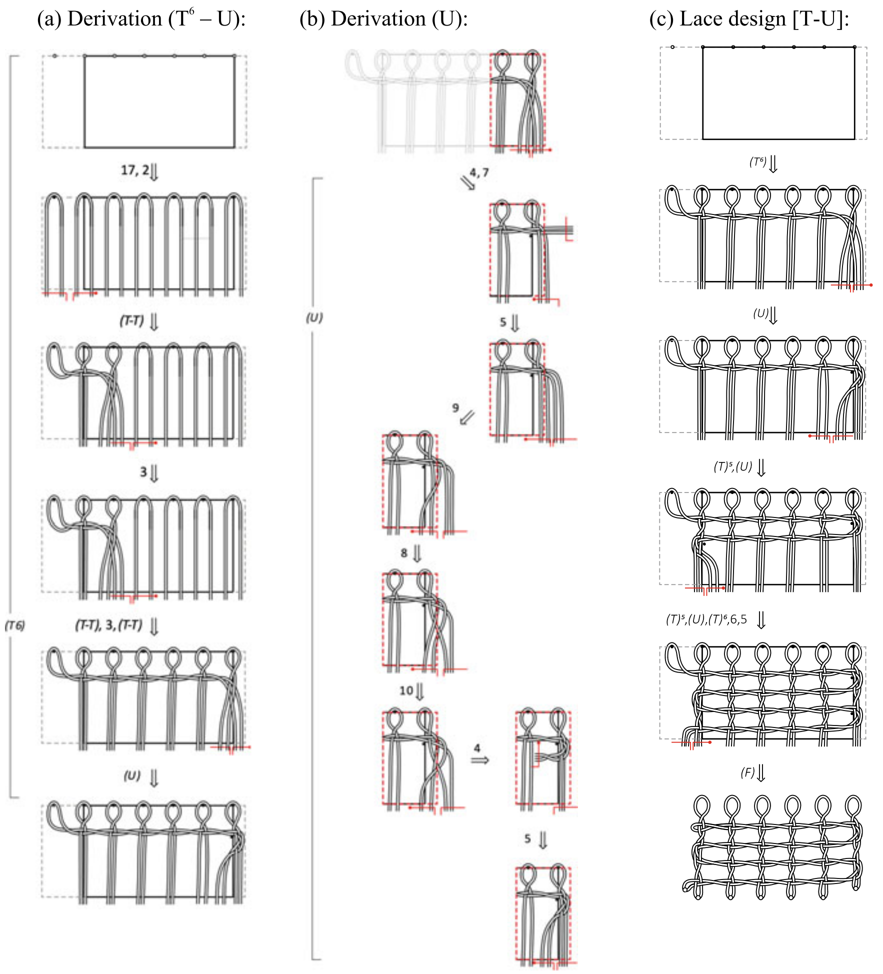


Fig. 7 Derivation (T^6-U) of the first row, derivation (U) of a selvage, and derivation (T^6-U-T^5-U-T^5-U-T^6) of an entire lace design [T-U]

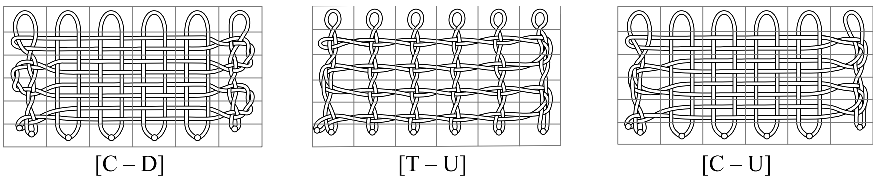


Fig. 8 Tape lace designs featuring three combinations of stitches placed on a grid

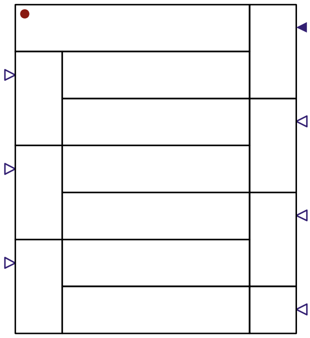


Fig. 9 The initial shape of the lace pattern grammar is the underlying structure (*parti*) of the specific tape lace design language

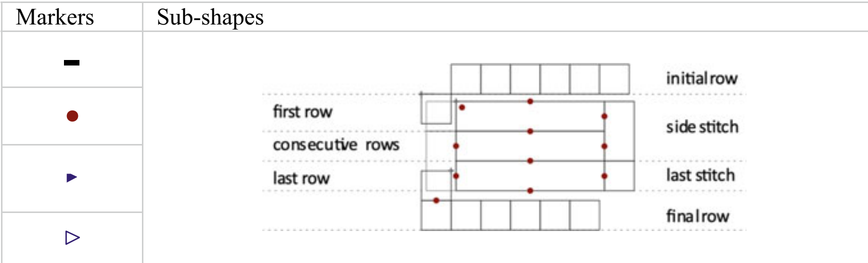


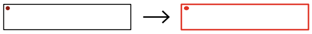
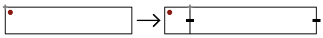
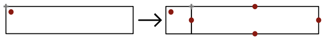
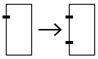
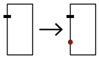
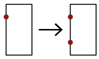
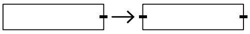
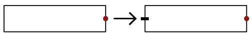
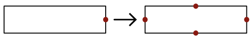
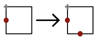
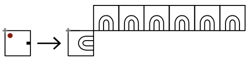
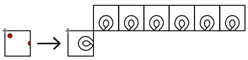
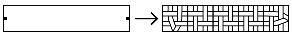
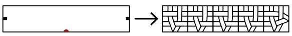
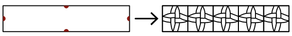
Fig. 10 Markers and sub-shape index

design (Table 6, final shape in column 6). Variations of designs can be generated similarly. Modifying the length of the *parti* by adding extra rows alters the set of possible designs. Furthermore, the number of thread pairs can vary depending on the available width to include extra stitches, resulting in a deviation from the traditional Cretan style.

Discussion

A pair of formal grammars capturing a traditional Cretan bobbin lacemaking technique was defined. A braiding grammar, describing making rules, generates stitch patterns inspired by the traditional braiding process. A parametric lace pattern grammar produces lace designs through shape rules and symmetry transformations. Each of the two grammars captures different aspects of the same craft. The braiding grammar captures manual stitch creation and local interaction with tools and materials, leading to physical form generation. The lace pattern grammar develops the

Table 5 The lace pattern grammar rules

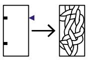
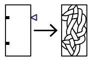
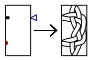
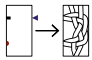
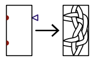
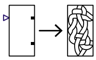
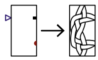
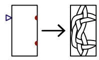
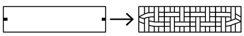
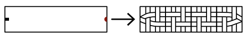
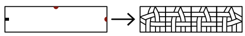
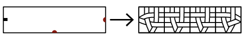
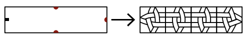
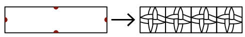
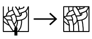
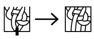
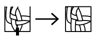
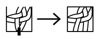
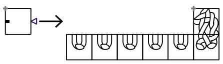
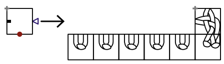
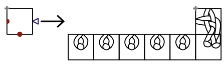
Selection rule		
		
Stitch type determination rules		
Rule 1: 	Rule 2: 	
Rule 3: 	Rule 4: 	Rule 5: 
Rule 6: 	Rule 7: 	Rule 8: 
Rule 9: 	Rule 10: 	Rule 11: 
Mapping rules		
Rule 12: 	Rule 13: 	
Rule 14: 	Rule 15: 	
Rule 16: 		

(continued)

global geometrical composition based on symmetry. The braiding grammar generates lace blocks. The lace pattern grammar combines them to build the lace designs.

Illustrating the two grammars was constrained by graphic conventions emanating from the need to describe three-dimensional objects on the two-dimensional graphic plane. Three-dimensional tangible tools and the weaver's interaction with the materials had to be captured with plane figures. The descriptive and productive aim of the two grammars was to balance the sensory and representational features of the making process. The stitch patterns produced by the braiding grammar become the building blocks that generate designs via the rules of the lace pattern grammar.

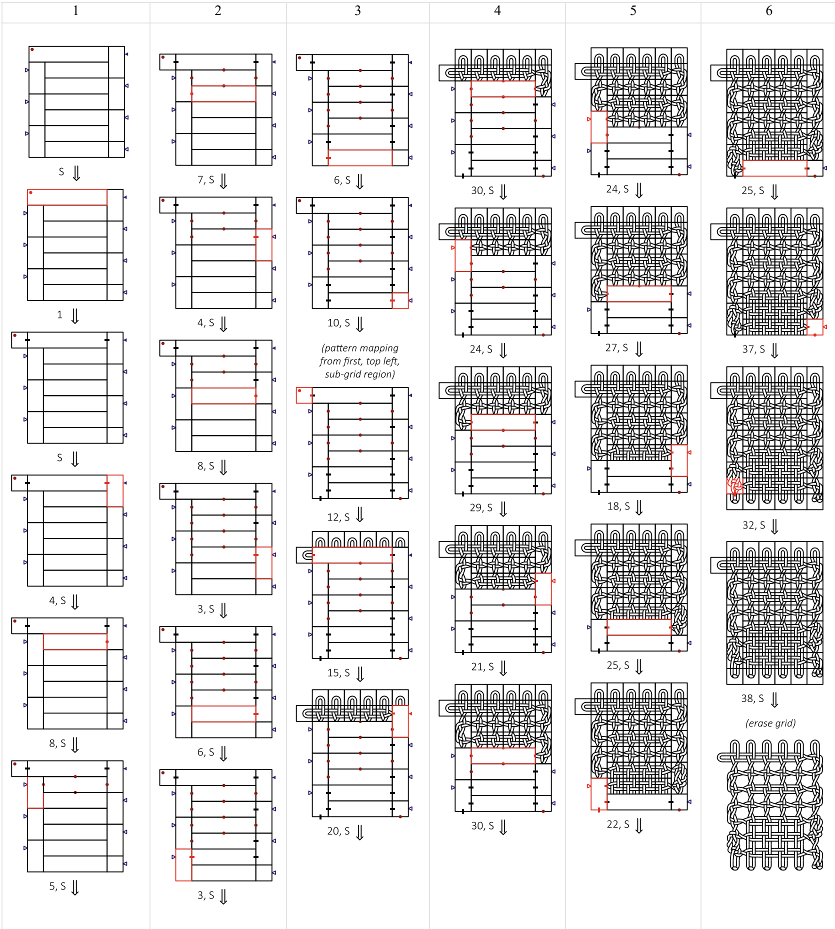
Table 5 (continued)

Rule 17: 	Rule 18: 	Rule 19: 	Rule 20: 	Rule 21: 
Rule 22: 	Rule 23: 	Rule 24: 		
Rule 25: 	Rule 26: 	Rule 27: 		
Rule 28: 	Rule 29: 	Rule 30: 		
Rule 31: 	Rule 32: 	Rule 33: 	Rule 34: 	
Rule 35: 	Rule 36: 	Rule 37: 		
Erase grid lines				
Rule 38: — →				

Another challenge was observing and documenting the skilled artisans enacting the traditional making process. The most demanding was observing their hand movements to analyze the productive action and capture it with rules. However, analyzing the parts of a continuous craft process resembles partitioning a shape; one distinguishes "maximal parts." A craft instructor uses a particular "maximal" way of partitioning a continuous process of hand movement, dividing it into a small number of comprehensible executable steps that the apprentice can perceive. For example, the drafting instructor partitions the drawing process of the shape in Fig. 11a into six strokes, two horizontal and four vertical (Fig. 11b), to produce six maximal lines. The six lines are executed in strict order and with a specific direction (Fig. 11c).

Similarly, in the braiding grammar, the rule R. 10 produces a new stitch configuration, namely a *crossing* (Fig. 12a) from two initial threads through a specific movement. It all begins by selecting and holding a pair of parallel threads (Fig. 12b), which are then handled from the parallel position to cross through a specific hand movement, as the diagram of Fig. 12c illustrates.

Table 6 Pattern derivation



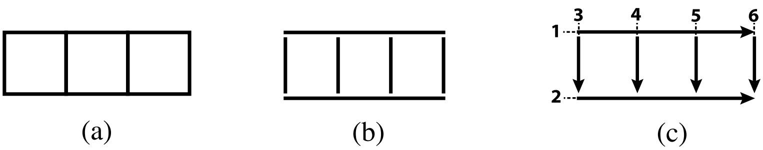


Fig. 11 **a** A shape. **b** Partition of the shape into six maximal lines. **c** Partition of the process, order, and direction of hand strokes

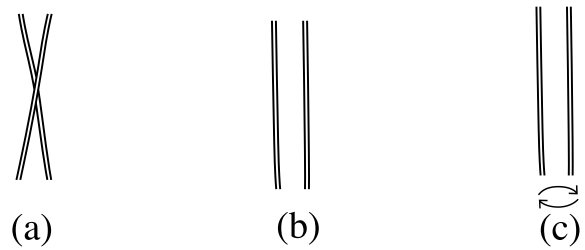


Fig. 12 **a** Outcome. **b** Threads. **c** Movement

When the apprentice becomes proficient, the partitioning of creative activity can take alternative routes. The segments of a long, making process may fuse or divide independently for each artisan as the artisan advances a technique. The making process becomes fluent for the skilled artisan, and the distinction of discrete execution steps fades away as eye-hand movements and motor reactions become involuntary and unconscious.

The presented pair of grammars is one amongst many possible alternative grammars capturing the analog making process of the traditional Cretan bobbin lacemaking technique. For transparency, the braiding and lacemaking procedures apply sequentially:

(a) Computational lacemaking is transparent because it preserves high correspondence with the traditional analog process.
(b) The link between the braiding and lace pattern grammars is clear: the braiding grammar produces lace blocks, and the lace pattern grammar inputs the blocks to output lace designs.
(c) The production of lace, by the braiding and lace pattern grammars, is versatile. The sequential process follows the physical limitations of the traditional technique; it is intuitive and easy to follow.

The crafts are a unique analog repository of artistic skill, knowledge, and imagination. The computational study of craft challenges cognitive analysis and interfacing with tools, materials, and the world. It is an opportunity to apprehend human creativity, dexterity, and ingenuity in a targeted manner. In parallel, the computational analysis of craft contributes to the evolution of creative processes in new directions.

The analysis of traditional lacemaking is an example. Defining the braiding and designing rules captures the productive and creative principles of the lacemaking technique constructively. It then becomes possible to begin thinking about digital modeling and automating this crafting process. To this end, we are exploring a chain of basic automata to generate patterns that comply with the grammatical analysis. An algorithm based on finite-state machines will implement and extend the lace pattern grammar to produce digital lace patterns. A future step will be to incorporate improvisation and chance in the generation of designs that may cross the boundaries of the traditional craft but still comply with the grammatical rules. Conclusively, the rich repository of craft is reappraised by introducing grammatical and digital handiwork methods. A new field of exploration opens in which improvisation and intuition remain essential but transfer into different stages of the creative crafting process. Computation reinterprets the figuration and implementation of crafts.

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An Agent-Based Approach to Adaptive Design Based on Influences Mediated by Artifacts

Meichun Liu and Tsailu Liu

The effects of social influence on human decisions have been well documented, but computational models that can effectively recapitulate the influences mediated by artifacts are yet to be studied. This paper presents an adaptive design framework adopting an agent-based approach to understanding the effects of influences mediated by artifacts. An experiment utilizing augmented artifacts to mediate social influence was conducted, revealing that participants are susceptible to mediated influences, which generate emergent effects resulting in system adaptivity. An agent-based model designed with principles of homophily and preferential attachment was developed to simulate the design mechanisms in the framework. The model was validated by the empirical results using betweenness centrality as the measure for adaptivity, showing global adaptation from local interactions. The adaptive design framework was demonstrated to be an effective approach to exploring and envisioning the emergent behavior and systemic implications of design interventions from the bottom-up in a complex system.

Introduction

In the world of design there has been an increasingly holistic view of design problems that acknowledges the importance of the whole of the problem space from the initial stages of design. Attempting to embrace the real-world interdisciplinary problems, designers and engineers have gradually shifted their focus from solving complicated problems to solving complex issues, and from designing ideal systems to designing

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complex systems [1, 2], and [3]. A complex system is intrinsically adaptive [4] and evolves and reorganizes its component parts to adapt to changes in the environment. Designing an artificial system that can support an adaptive, human-centered, and user-participatory scheme for the needs of user groups has been advocated by multiple scholars [5, 6], and [7]. With the aim of integrating systems thinking into the design process, many scholars have proposed frameworks, guidelines, and design tools and methods (e.g., [1, 8, 9], and [10]).

Among the present approaches to studying adaptive systems, agent-based modeling and simulation (ABMS) has become an important approach, and is particularly useful with regard to helping envision the emergent patterns arising from individual micro-level behaviors to higher levels of the system [11]. It is also a potent tool for predicting the possible outcome of design interventions over extended temporal and spatial scales because a complex system typically displays nonlinear dynamics during changes in scale and thus demands proper envisioning techniques [12]. However, the output of agent-based models is often not validated against empirical data, and can be difficult to calibrate due to the complex, nonlinear, and discontinuous interactions between agents.

In this paper, we establish an adaptive design framework based on mediated influences adopting an agent-based approach. The agent-based model (ABM) constructed in this research is examined and validated by an empirical experiment. The agents in this framework are hybrid agents composed of humans and artifacts. Those agents form a network that adapts to and evolves with the decisions made by members of the system.

The remainder of the paper is structured as follows. First, a brief overview of related work in the fields of complex adaptive system, distributed situation awareness, ABMS, and design strategies for influencing behavior is provided. Next, the aims of this work are explicated in the form of hypotheses derived from the adaptive design framework outlined in this study. The methods used to test the hypotheses are described in the section titled "Study Design," in which the model design, experimental materials, and methodology are presented. In the following section titled "Analysis Results," the data collected in the experiment are used for hypothesis testing and model validation. Finally, the paper concludes with a discussion of the findings and suggestions for future work.

Related Work

Designing in a Complex Adaptive System

Many systems exhibit complexity by evolving and reorganizing their component parts to adapt to the changes and the problems posed by their surroundings. In complexity science, an "adaptive process" refers to the changes a system or an entity makes to respond to changes over time, as pointed out by Holland [13]. The process of adaptation often is related to the learning process and can give rise to a kind of complexity that exhibits emergence, self-organization, and evolution [3] and [13]. Autonomous and adaptive agents play a pivotal role in the discourse on adaptation in a complex system and thus, the concept of adaptation is closely related to agents and the agency of a given component [14] and [15].

A design that engages in a system comprising human activities is referred to as social systems design [1], which is often called sociotechnical systems design to emphasize the technical aspect that supports human activities. One prominent characteristic of modern sociotechnical systems is that both human agents and artificial elements are distributed in the system, forming a complex network linked by their contextual relationships. Rzevski [3] sees complexity as an opportunity for incorporating adaptivity into the design of organizations, processes, and products. Nevertheless, many of the designs of complex sociotechnical systems are mainly approached with an engineering mindset (e.g., [3] and [16]). Even though techniques such as human operator models are deployed in current systems engineering and automatic controls, this is far away from what real people do, as Boy [2] points out. Therefore, he suggests a change from logical human models to conceptual human models in human-in-the-loop simulations. The approach expands from narrow mathematical models to human-centered systems design for the purpose of the development of artifacts concurrently with the people and organizations that are related to them. This co-design approach resonates with the concept of “designing within the system” [1] and “designing with users in use” [17]. It is a bottom-up iterative process that encourages designers to focus on the autonomous actions of agents who drive the adaptive behavior of a system. The hybrid-agent approach adopted in this study manifests this co-designing mindset, treating humans and artifacts as unified decision-making entities that exert their agency collectively.

Distributed Situation Awareness

Based on the situation awareness (SA) framework, technology and information displays can present information that helps people achieve SA according to their circumstances [18]. From a systems ergonomics perspective, SA is understood as a process that takes place when individuals interact with the material world to accomplish their goals [19]. Extended from the concept of SA, the DSA framework, proposed by Stanton et al. [20], acknowledges that the information held by agents distributed in a system collectively contributes to the overall DSA. In accordance with the concept of distribution cognition [21], the underlying assumption of DSA is that cognitive processes occur within a system rather than at an individual level. This perspective makes it possible to identify hybrid agents based on the boundaries of the units of shared cognitive processes, rather than within rigid, physical boundaries.

Agent-Based Modeling and Design Strategy

Several studies have investigated how micro-level influences give rise to population-level dynamics, which provide insights into design intervention strategies at the system level and ideas for engaging users in the co-design process. In a study carried out by Nowak et al. [15], social influence was modeled as a mechanism of the social learning process. They presumed that individuals are more likely to copy the most frequent or most desirable behaviors of others. Their simulation results revealed that agents can perform socially rational collective behavior by imitating other agents who have achieved higher utility without centralized decision making. Almaatouq et al. [22] developed web-based experiments and ABMs to identify the role of dynamic networks in promoting adaptive behavior among agents. The results show that network plasticity and feedback provide adaptiveness that can benefit both individual and collective judgment. On e-commerce platforms, He and Chu [23] provided empirical evidence that in a recommender system, the opinions of other similar users, particularly those in one's social network, account significantly for effective collaborative filtering and choice making.

The above studies suggest that people are susceptible to the influences of others, especially acquaintances, regarding decision-making through the spread of opinions and information flow in their network [24] and [25]. However, the social influences mediated by physical artifacts are less studied than digital traces left by users (e.g., the study of social physics [26]) conceivably due to difficulties in establishing causal relationships between social interactions and their influences on behaviors. The framework proposed in this study utilizes digitally enhanced artifacts to overcome the hurdle, collecting data generated from asynchronous interactions among participants. It expands the venues where researchers can study and test design strategies that influence individual behavior, which may give rise to system-level changes.

Aims and Hypotheses

Reflective of the ongoing shift in the focus of design activities from complicated problem-solving to complex system-regulating, understanding how design interventions can influence human decisions and how the agent-based participatory design process can lead to group adaptation can provide insights into complex systems designs. The current work is aimed toward creating an agent-based model and an empirical experiment to investigate how design artifacts may affect choices made by individual agents at a local level, and how these decisions contribute to the overall adaptation at a global level. Two hypotheses are formulated to address the research questions.

H1: People are susceptible to mediated influences regarding their decision-making.

H2: Mediated influences can promote system adaptivity by affecting decisions made by individual agents.

Based on the SA framework, technologies can afford SA information that makes it possible to understand a given situation and make a projection in order to achieve goals [18]. The decisions made by others can provide a reference for possible choices that can lead to collaborative filtering, which is an effort to solve a problem together [27]. Guided by these principles, an empirical experiment was devised to investigate the effect of social influences mediated by digitally augmented artifacts and test the first hypothesis.

The second hypothesis is grounded on emergent properties displayed in many sociotechnical systems. Although the phenomenon of emergence has been studied extensively in complex science, utilizing augmented artifacts designed for facilitating design interventions in order to affect system adaptivity is a new approach to systemic design that has yet to be studied.

Study Design

ABMS and a quasi-experiment were developed as two main approaches to test the hypotheses stated above. An agent-based model, HO-PA model, of an adaptive network was conceptualized based on homophily (HO) and preferential attachment (PA) to explore the elements and mechanisms that drive agent behavior. An experiment of 30 participants with a within-group design was conducted followed by a post-experiment survey. Two design interventions are devised in the experiment for agents to receive the information associated with decisions made by other agents and provide feedback to the system. The first is the information mediated by digitally enhanced artifacts for agents to use as a reference. The second is the feedback mechanism used to update the choices made by the agents.

The design of the ABM is scripted with behavioral rules and mechanisms in a way similar to the design of the empirical experiment. In the model, the concept of social influence is translated into HO and PA, which are fundamental principles in social networks. HO suggests that people tend to make connections with those who are similar to themselves [28]. This is manifested as a tendency toward focal closure, which is the process of forming links to others with common characteristics and can be observed in many social networks [29]. This tendency has significantly influenced a few important phenomena in human society, including segregation, perception biases, and information propagation [30, 31], and [32]. Another principle, PA, is the idea that agents tend to accumulate new edges in proportion to the number they already have. This process is known to give power-law degree distributions to a network [33]. PA is a common feature in many sociotechnical networks, including large web-based networks, human mobility networks, and scholarly collaboration networks [33, 34], and [35]. Although the underlying forces that drive the two tendencies may vary, models that are constructed under these common concepts can capture the natural properties of social networks much better than those designed with purely random or normal distributions of links [36].

HO-PA Model

Figure 1 shows the structure of the HO-PA model. In the ABM, agents are designed as nodes that follow scripted behavioral rules to perform a series of stochastic movements to interact with other agents to form a network. The parameters that affect an agent's behavior include (1) similarity-rate: the level of similarity of another agent regarding its attribute that a given agent can connect with, (2) assimilation-chance: the chance that an attribute of an agent can convert or be converted by another linked agent, (3) homophily-preference: the preference of HO over PA, which are complementary qualities, (4) max-number-percentage: the percentage of agents with the most links that an agent can connect with, (5) neighbor-radius: the distance within which an agent can reach other agents, and (6) rewire-rate: the disconnecting rate of existing agent pairs. In addition, the parameters associated with the system include (1) tick-number: the number of time steps (ticks) the model runs and (2) number-of-nodes: the number of agents (nodes) in the model.

The model was constructed in NetLogo [37]. Initially, agents with randomly assigned attributes were scattered and moved through an empty two-dimensional torus world. At every time step, agents make movements, choose available neighbors to connect with, and disconnect with some of their linked partners. Consequently, agents create one or several networks after specific steps have been completed. Depending on the setting of the homophily-preference parameter, agents are attracted to other similar agents from among their neighbors or choose a dissimilar but popular neighbor to connect with. When the similarity rate is set to a high level, agents are prone to only connect with other similar agents. Additionally, the assimilation chance and rewiring rate are two other critical factors that affect model dynamics. The former represents how agents were influenced by other agents and the latter defines how likely it is that an agent will decouple with a partner.

Empirical Experiment

The aim of the empirical experiment was to test the hypotheses and validate the ABM. As shown in Fig. 2, the experiment framework was intended to reflect the effects of HO and PA using augmented artifacts to interface social influences that could potentially generate the phenomena of interest in a laboratory setting. Hypothetically, the effects of changes in the similarity-rate parameter of the HO-PA model would be observed in the experiment by facilitating the treatment (the presence of references). At different times in the experiment, the references afforded by the artifact were provided or withheld from the same participant to evaluate their impact.

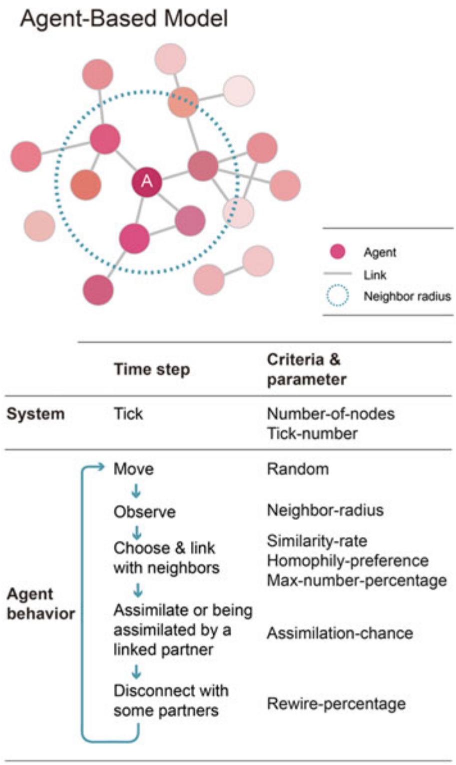


Fig. 1 HO-PA ABM structure

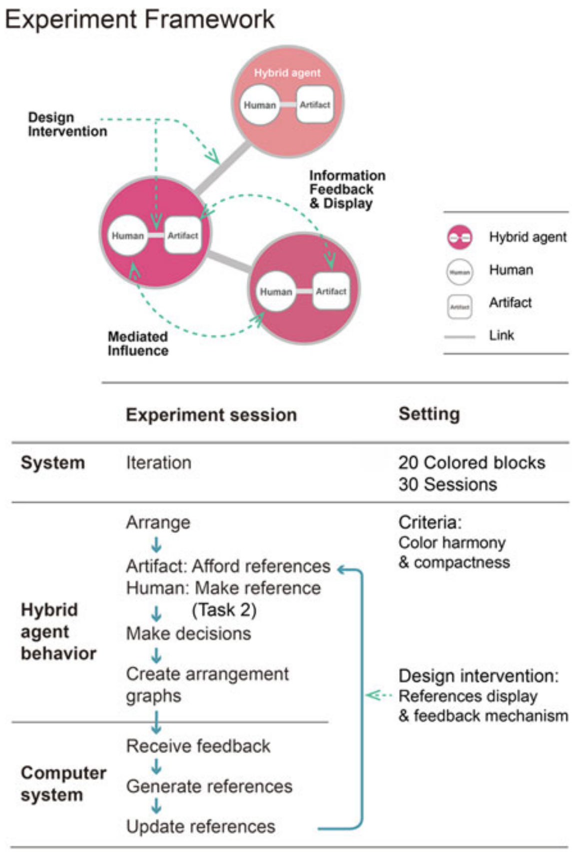
Materials

Two sets of 20 colored blocks (magenta and green) attached with RFID tags were used to represent agents in the ABM. The colors were chosen from the 330 Munsell chips, which have been used in most color-naming studies [38]. All pieces were labeled with randomly assigned alpha-numeric codes. The "references" were the codes of the three most commonly connecting neighbors of each of the 20 colored blocks. They were displayed on the LCD display when the colored block was scanned on the RFID reader, which was constructed with a Raspberry Pi 3 computer (see Fig. 3). The initial data collected during the pilot testing served as "seed data" that were applied to the database before the first experiment. Python and MySQL were used in this study to process data, run the commands, and manage the database.

Sample and Procedure

This project was approved by the University Institutional Review Board and complied with Human Research Protections Guidance on COVID-19, since this in-person study was held during the COVID-19 pandemic in 2021. A group of 30 subjects (53%

Fig. 2 Experiment framework



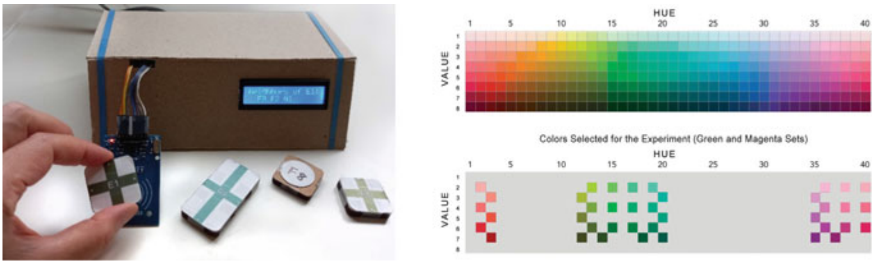


Fig. 3 The RFID reader (left) and the colors selected from the Munsell chips (right) used in the experiment

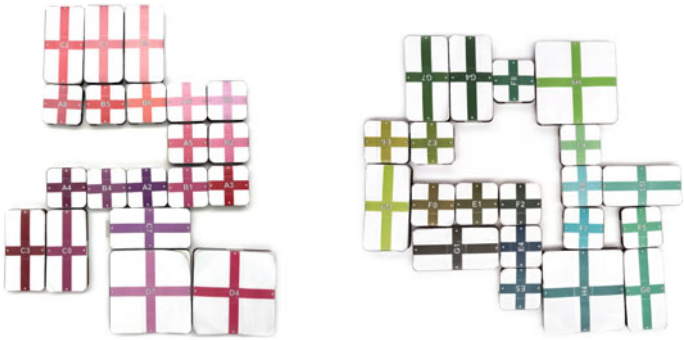


Fig. 4 Examples of arrangement from the magenta (left) and green (right) sets

females, 47% males, age range = 20–59) was recruited in the cities of Raleigh, NC, and Philadelphia, PA, USA for the experiment. Each participant was asked to perform four tasks and complete a survey, which took approximately one hour in total.

In Tasks 1A and 1B, each participant was asked to arrange the two sets of colored blocks in sequence to create a network according to two equally weighted criteria: (1) color harmony: the color of neighboring pieces connected at the arrows should be as harmonious as possible and (2) compactness: the final area should be as small as possible. Also, each piece has to be connected with at least two others by aligning the arrows of the connecting pieces with up to two loose ends. A loose end is a piece connected to only one other piece.

In Tasks 2A and 2B, each participant repeated the previous tasks, except that references were made available via the LCD display. Participants were told that the references were generated from the decisions made by previous participants, where they could decide whether to use the reference information or not. After each experimental session, the results of the arrangement were added to the database, and the reference information was updated. Examples of the arrangement results are shown in Fig. 4.

Analytical Method

To assess the adaptivity of the network system, the reference and the arrangement graphs were transcribed and represented in matrix forms, with 0 to indicate no relations and 1 to indicate links between nodes, and analyzed in software. In each experimental session, 2 reference graphs and 4 arrangement graphs were created. The reference graphs (1A-R and 1B-R) were constructed from the codes of three colored blocks that were presented as the references displayed on the RFID reader. For the four arrangement graphs, 1A and 2A were generated from the magenta set, and 1B and 2B were generated from the green set based on the performed tasks.

The collected data were analyzed in JPathfinder and Gephi to evaluate the effects of the treatment. The *network similarity* function in JPathfinder was used to measure the similarity between graphs. Two identical networks yielded a similarity of 1, and networks without any shared links yielded a similarity of 0 [39]. The network analysis tools in Gephi [40] were used to calculate the betweenness centrality of the nodes in the network.

Analysis Results

Analysis 1: The Graph Similarity of Arrangement Graphs

To test the hypothesis that people are susceptible to mediated influence regarding their decision-making, a paired samples t-test was performed by using IBM SPSS 27.0 program to examine the difference between Task 1 and Task 2 for the same participant. The assumption was that if the participant was influenced by the references, the arrangement graph created in Task 2 (Graph 2A and 2B) would be more similar to the reference graph (Graph 1A-R and 1B-R) than the graphs created in Task 1 (Graph 1A and 1B). Details concerning the overall significance of the t-test and the between-graph similarity are provided in Table 1, which shows that the average similarity of Task 2 to the reference graph is 6.3% more similar than that of Task 1 (M = 0.063, SD = 0.086, $p < .001$). The t-test and p-values rejected the null hypothesis that the participants are not influenced by the references regarding their choices of arrangement in Task 2. Such a difference may seem trivial; but accumulatively, it affects system dynamics and network characteristics at the system level, as depicted in the next analysis.

However, in the case of order effect, familiarity and practice were potential confounding variables that caused the higher similarity rates in Graph 2A and 2B than in 1A and 1B. Based on the post-experiment survey results, 70% of the participants responded 4 or 5 (4 = agree, 5 = strongly agree) to the question: "The reference has influenced my decision-making." For those who responded 1–3 (1 = strongly disagree, 2 = disagree, 3 = neither agree nor disagree), the average score of differences in graph similarity between Task 2 and 1 was 0.0267 (lower than the overall average of 0.063). For participants who responded 4 and 5, the average score of task differences was 0.079. In other words, people who had a higher score of differences between tasks were those who responded that the references had influenced their decision-making. Also, practicing did not yield more satisfying results as there was no correlation between similarity scores and satisfactory levels of the results regarding the four tasks. Therefore, the higher similarity rates in Task 2 were more likely caused by the references rather than the order effect.

Table 1 The paired samples T-test of the differences in similarity between Task 1 and Task 2

	Paired differences					t	df	Sig. (2-tailed)
	Mean	Std. deviation	Std. error mean	95% confidence interval of the difference				
				Lower	Upper			
Similarity score 2–Similarity score 1	0.0631	0.0865	0.0158	0.0309	0.0954	4.00	29	0.000
Similarity score 2A–Similarity score 1A	0.0580	0.0983	0.0179	0.0213	0.0947	3.23	29	0.003
Similarity score 2B–Similarity score 1B	0.0683	0.1068	0.0195	0.0284	0.1082	3.50	29	0.002

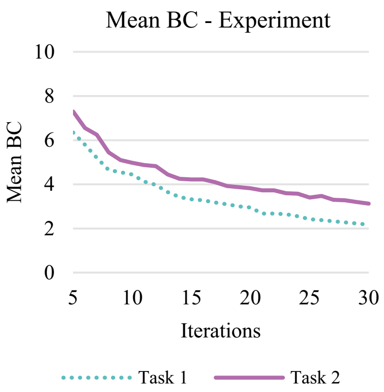
Note Similarity score 1 is the average of similarity score 1A and 1B. Similarity score 2 is the average of similarity score 2A and 2B. Similarity score 1A is the similarity between graph 1A and graph 1A-R. Similarity score 1B is the similarity between graph 1B and graph 1B-R. Similarity score 2A is the similarity between graph 2A and graph 1A-R. Similarity score 2B is the similarity between graph 2B and graph 1B-R. The significance level was set at $p < .05$ in all analyses

Analysis 2: Betweenness Centrality of Arrangement Graphs

In a social network, network centrality is often used to assess an agent's relationship with other agents and its role in the network as a whole. Among different centralities, betweenness centrality (BC) plays an important role in the analysis of many types of networks, including social networks, computer networks, and transportation networks [41, 42], and [43]. It gauges the extent to which a node facilitates the flow of information from one part of the network to another. BC has been recognized as an important means by which to identify the influence of a given role in the flow of communication between work groups [44] and is the most sensible of all centrality measures to the variations of the network structure [45] and [46]. Viewed in a design context, BC can be used to characterize the significance of a given design feature or interaction point, such as a touchpoint in a service design system, in relation to its influence over the flow of design interventions or services. Therefore, BC is chosen as the indicator in this research to appraise the network characteristics related to system adaptivity.

In this analysis, the iterations of four arrangement graphs (1A, 1B, 2A, and 2B) along the experimental sessions were aggregated to generate time series data to test the second hypothesis suggesting that a mediated influence can promote system adaptivity by affecting decisions made by individual agents. All arrangement graphs were iterated once during every experimental session. The mean BC and the standard deviation of BC (SDBC) of the aggregate arrangement graphs (AAG) at different times of the experiment were calculated and presented in the form of line graphs

Fig. 5 The avg. mean BC of the AAG during iterations



Experimental setting: colored blocks (20), iterations (5-30)

(see Figs. 5 and 7). The data from the first four experiments were eliminated due to the extreme values resulting from insufficient data samples at the early stages. Table 2 displays the results of the paired samples t-test of the difference in the mean BC and SDBC of the AAG from the 5th to 30th experimental sessions. The test results show that the mean BC and SDBC of the AAG created in Task 2 were higher than in Task 1 by 0.89 and 0.73 on average respectively. The results support the idea that mediated influence can promote system adaptivity, as measured by changes in the mean BC and SDBC. This indicated that the design intervention facilitated in Task 2 exerted an effect on the system, which adapted by displaying a network property that was significantly different from Task 1.

Agent-Based Model Validation

We validated the HO-PA model by comparing the simulation results to the empirical data set and performing a sensitivity analysis. A few assumptions were made in the ABMS to capture the features and mechanisms observed in the real world: (1) a tick in the model equated to one experimental session, (2) 20 nodes in the model corresponded to the 20 colored blocks, and (3) the similarity-rate parameter corresponded to the effects of "references" on the arrangement graphs. Other parameters were determined by the preference of the subject group and the experimental setting. For example, since each experiment is independent, the rewire-rate parameter is zero and all colored blocks were available to the participants (neighbor-radius = 20).

Among all of the parameters, similarity-rate has the most realistic relevance to the underlying principles that influenced participants' decisions. A network with a high BC and SDBC indicates that relatively few nodes play a central role in distributing

Table 2 The paired samples t-test of the BC and SDBC of the time series data of AAG 1A, 1B, 2A, and 2B obtained from experiments #5 to #30

	Paired differences					t	df	Sig. (2-tailed)
	Mean	Std. deviation	Std. error mean	95% confidence interval of the difference				
				Lower	Upper			
Avg. mean BC of AAG (Task 2–Task 1)	0.8942	0.1418	0.0278	0.8369	0.9515	32.15	25	0.000
Avg. SDBC of AAG (Task 2–Task 1)	0.7319	0.1560	0.0306	0.6689	0.7950	23.92	25	0.000
Mean BC of AAG 2B–Mean BC of AAG 1B	0.6962	0.1356	0.0266	0.6414	0.7509	26.18	25	0.000
SDBC of AAG 2B–SDBC of AAG 1B	0.7191	0.3859	0.0757	0.5632	0.8750	9.50	25	0.000
Mean BC of AAG 2A–Mean BC of AAG 1A	1.0923	0.2544	0.0499	0.9895	1.1951	21.89	25	0.000
SDBC of AAG 2A–SDBC of AAG 1A	0.7448	0.4338	0.0851	0.5696	0.9200	8.75	25	0.000

Note AAG = Aggregate Arrangement Graph. The avg. mean BC of the AAG of Task 1 is the average mean BC of AAG 1A and 1B. The avg. mean BC of the AAG of Task 2 is the average mean BC of AAG 2A and 2B. The same applies to avg. SDBC. The significance level was set at $p < .05$ in all analyses

information. Therefore, a higher mean BC and SDBC of the AAG implies that participants were more prudent in terms of selecting the connecting pieces in Task 2 than in Task 1. This behavior was comparable to a higher standard of choosing a connecting partner in the ABM when the similarity-rate parameter was set at a high level. Therefore, simulations with a higher similarity-rate setting generated a higher BC and SDBC while other parameters remained constant.

Model Calibration

The model calibration process yielded two best-fit parameter combinations that were identified through a series of parameter sweeps. The control parameter "similarity-rate" was sampled using a grid-based sampling strategy. Each set of parameter combinations performed 900 simulation runs using the Monte Carlo sampling method. Figure 5 presents the line graphs of the average mean BC of the AAG from the empirical data. The simulation output of the mean BC of the calibrated model, and the values of the best-fit parameters are provided in Fig. 6. The model output revealed that when the similarity-rate parameter was set at 80 and 60, the changes in the mean BC of the network over time steps were similar to those of the AAG generated under the treatment (Task 2) and control (Task 1) condition over iterations. Likewise, Fig. 7 shows the line graphs of the average SDBC of the AAG. The simulation output of the SDBC of the calibrated model and the best-fit parameter values are presented in Fig. 8, which shows that when the similarity-rate parameter was set at 60 and 40, the changes in the SDBC of the network were comparable to those of the AAG generated under the two experimental conditions over time.

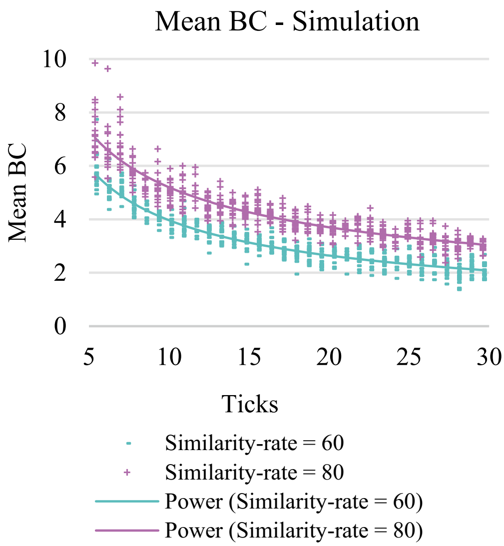


Fig. 6 The simulation output of mean BC over the 5th to the 30th ticks

Parameter values: number-of-nodes (20), tick-number (5-30), similarity-rate (60, 80), assimilation-chance (0), homophily-preference (70), max-number-percentage (50), neighbor-radius (20), rewire-rate (0).

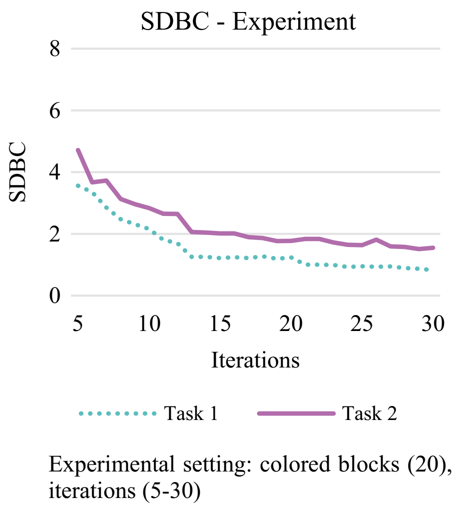


Fig. 7 The avg. SDBC of the AAG during iterations

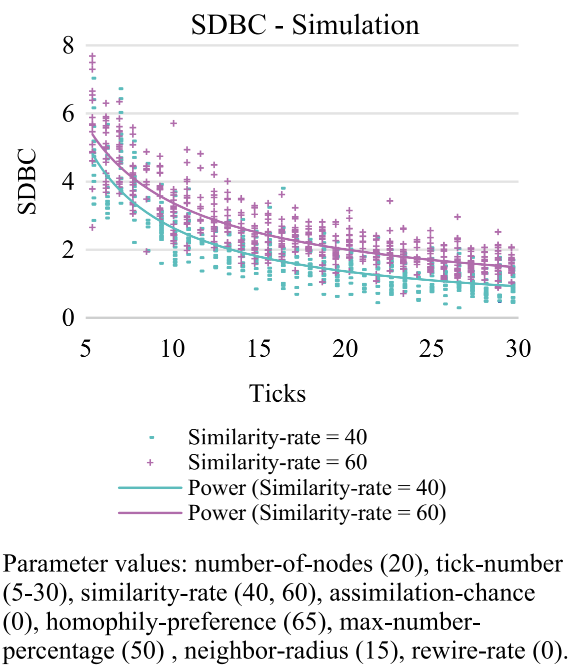
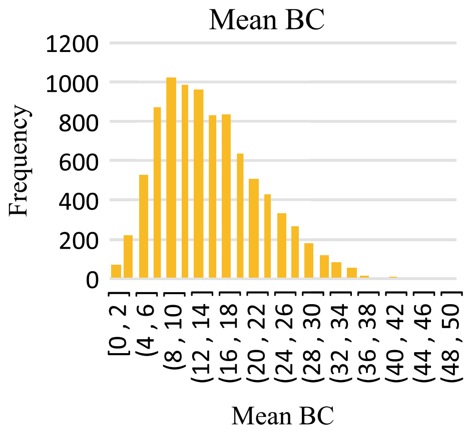


Fig. 8 The simulation outputs of SDBC over the 5th to the 30th ticks

Global Sensitivity Analysis

We use PyNetLogo, which interfaces NetLogo modeling software with Python [47], to perform the global sensitivity analysis (GSA) of the HO-PA model with mean

Fig. 9 Output distributions for mean BC over 9,000 simulation runs



BC as the outcome to examine each input parameter. SALib in Python was used to estimate the Sobol indices to represent the input importance of each parameter. The total Sobol index includes the interactions with other inputs when calculating the contribution of each input. The first-order Sobol index estimates the fractional contribution to its own output variance. The second-order Sobol index estimates the contribution of pairwise variable interactions on the variances in the output.

A histogram is used to visualize output distributions for mean BC over a total of 9,000 simulations (Fig. 9). Bivariate scatter plots are used to show the relationships between each input parameter and the outputs, with the Pearson correlation coefficient (r) being calculated for each parameter (Fig. 10). For example, the rewire-rate ($r = 0.597$) and number-of-nodes ($r = 0.694$) parameters have relatively strong positive correlations with the mean BC. Total (ST) and first-order (S1) Sobol indices were used to estimate each input's contribution to the variance in the mean BC (Table 3). The number-of-nodes and rewire-rate parameters have the highest ST and S1 indices, indicating that they contribute roughly 56% and 44% respectively when accounting for interactions with other parameters, and roughly 52 and 35% of their own output variances. To visualize all three indices (ST, S1, and S2), a diagram that includes the second-order pairwise interactions between inputs is shown in Fig. 11.

Conclusion

The goal of this research is to study the effect of influences mediated by artifacts in an adaptive design framework based on agents. The framework is established on an assumption that people are susceptible to mediated influences when making decisions, and this propensity can lead to system adaptation if the system supports adaptive mechanisms by which to channel design interventions and provide feedback. The empirical experiment provided evidence that confirmed the assumption.

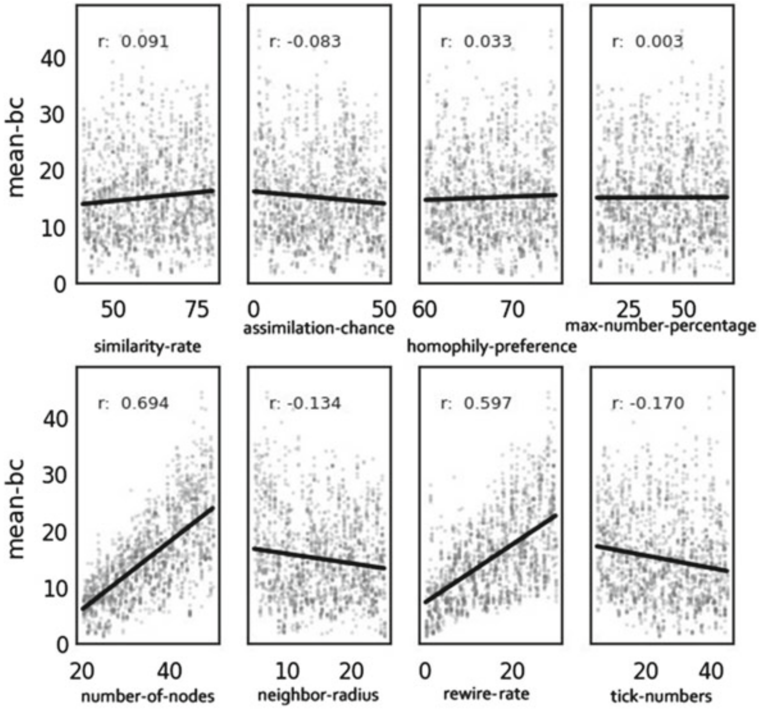


Fig. 10 Scatter plots with linear trendlines and Pearson correlation coefficient (r)

Table 3 The Sobol sensitivity indices of input to output variance

Parameters		ST	ST confidence intervals	S1	S1 confidence intervals
1	Similarity-rate	0.0279	0.0079	−0.0003	0.0219
2	Assimilation-chance	0.0213	0.0055	0.0044	0.0199
3	Homophily-preference	0.0292	0.0097	−0.0061	0.0273
4	Max-number-percentage	0.0264	0.0081	0.0073	0.0191
5	Number-of-nodes	0.5637	0.0771	0.5180	0.0838
6	Neighbor-radius	0.0462	0.0116	0.0070	0.0290
7	Rewire-rate	0.4382	0.0595	0.3538	0.0763
8	Tick-number	0.0570	0.0136	0.0262	0.0322

Note ST = Total Sobol index, S1 = First-order Sobol index

In the empirical study, we devised two mechanisms to facilitate design interventions that allowed participants to interact asynchronously and, consequently, drive the system dynamics. Our study shows that the graphs created in the treatment condition (when the references were present) were 6.3% more similar to the reference

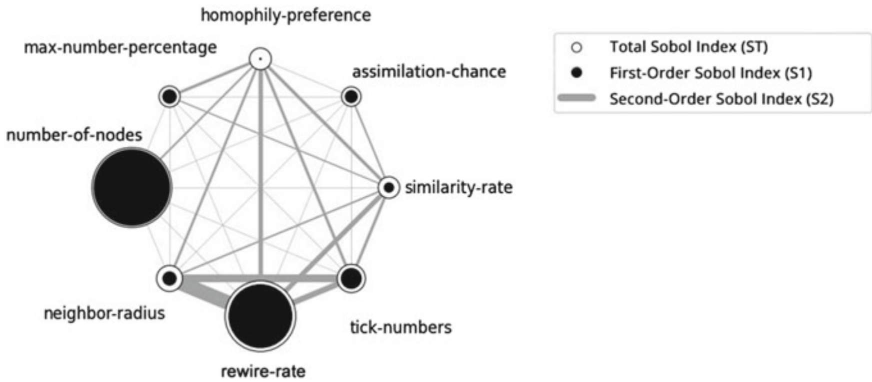


Fig. 11 Total, first-order, and second-order Sobol indices for mean BC. *Note* The size of the ST and S1 circles represents the number of normalized total and first-order indices. The width of connecting lines between the parameters indicates the relative importance of their pairwise interactions on output variance

graphs on average than when the references were absent. This local adaptivity in response to the general choices also gave rise to global adaptivity. As the measures for system adaptivity, the mean BC and SDBC of the AAG generated under the treatment condition were on average 0.89 and 0.73 higher, respectively than in the control condition.

We constructed an HO-PA agent-based model to explore and envision the behavior of the proposed adaptive design system. Among different factors that influenced agent behavior, the level of similarity to other agents was comparable to the effect of mediated influences in the experimental situation. The simulation outputs of the model demonstrated that a higher similarity-rate can generate a higher mean BC and SDBC, which were aligned with the empirical data under the treatment condition. This outcome may have been due to participants being more prudent in terms of selecting the connecting pieces under mediated influences. However, more research is needed to understand the underlying mechanisms of the phenomenon. Also, since the empirical study adopted a quasi-experimental approach, a lack of random assignment of participants poses limitations to the findings and should thus be generalized with caution.

The adaptive framework proposed in this research treats humans and artifacts as unified decision-making entities, cooperating as hybrid agents to perform tasks and interact with other agents. Under this condition, humans and artifacts adapt to their environment and accomplish their goals as joint units. From the perspective of distribution cognition, they hold the information that can contribute to the overall distributed situation awareness of the system, where cognitive processes occur. Also, the adapting behavior occurs in both the system and agents. The system, which includes artifacts, adapts to agent behavior by changing the information flow being circulated in the system and mediated by artifacts. Meanwhile, agents adapt to their environment by learning, adjusting, and trying different strategies. The interactions between agents can generate emergent phenomena that lead to adaptivity at the system level. This study offers a pragmatic approach to exploring and predicting factors that not only affect individual behavior, but also system dynamics at different scales, such as different community sizes and the overall predilections of group members over time.

In this study, we presented one type of design intervention using mediated influences based on group decisions. However, in order to achieve a more general framework, the adaptive design framework should be examined with other types of design interventions, which may influence system dynamics in ways different from this research. For example, design interventions that encourage dissimilar agents to interact with each other may alleviate the phenomenon of segregation, which can result from discriminatory preferences of community members [30]. Also, according to the ABM sensitivity analysis, variables such as the rewiring rate and the number of agents have significant effects on the model output. However, the data obtained from our empirical research only validated the ABM's adaptive behavior due to changes in its similarity-rate parameter. Therefore, investigations into the effects of other variables on system behavior are possible areas for further studies.

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Visualization of Design Data in the Wild: Interactive Evaluation and Exploration of Combined Performance and Geometric Data

Ashley Hartwell, Eamon Whalen, Bryan Ong, and Caitlin Mueller

With the growth of computational design, geometric and performance-based design data has become increasingly important. Computation empowers designers to generate designs based on specific qualitative features, or to evaluate their performance based on user interests. This work presents a visualization framework that pairs performance mapping with geometry representations to promote exploration of multi-dimensional design spaces, without requiring an underlying parameterization. This is achieved through the use of design competition data which is presented as a hybrid of formal and intuitive design for which objectives of quantitative and qualitative performance hold value. Specifically, this is illustrated with two competition case studies: the SimJEB dataset, a crowd-sourced dataset of engine bracket designs and their respective finite-element simulation results, and entries from the 1890 Tower of London design competition. This approach has use in design applications in which it is desirable to quantitatively and qualitatively assess performance in a sizable design space.

Background and Motivation

Two seemingly distinct paradigms exist in the ideation phase of the design process that stem from different types of design approaches. On one hand, traditional parametric modelling methods can allow for systematic design space exploration through sampling, single- and multi-objective optimization, and other hybrid approaches. This has the benefit of rigor but the serious limitation of rigidity in the parameterization process. On the other hand, more intuitive, less systematic processes increasingly make use of visual surveying of large sets of relevant images, e.g. using Pinterest or

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Instagram. The advantage here is increased flexibility and diversity of design references, but the disadvantage is that they are hard or impossible to effectively navigate and understand in terms of quantitative and physical performance.

One case in between formal and intuitive approaches to design "shopping" [1] is the design competition, which combines diverse, crowd-sourced ideas with a standardized set of boundary conditions and goals. This paper considers design competitions as a way to collect well-behaved but still "wild" design data, and presents a visualization framework for data sourced through this method. Such data has value in its own right as a collection of candidate design ideas, but can also be used with machine learning algorithms that infer new design spaces and performance landscapes from the discrete instances. While this application remains challenging in the near term, the rapid advancement of areas such as geometric deep learning suggest that such approaches will be possible in the coming years.

Design Competitions

Since 448 BC, when the city of Athens used an architectural competition to dictate the construction of a memorial on the acropolis, design competitions have been key to the development of civilization, and an important way to build diverse qualitative datasets of designs [2]. The ideas and data gathered within these open calls can reveal much about how design processes evolve over time, design influences and trends of the period, as well as spark global collaboration. One such competition was the Tower of London design competition (Fig. 1) in 1890, which received 68 entries from across the world, in hopes of building a landmark in Wembley Park to rival the Eiffel Tower in Paris [3]. The selection jury admitted disappointment with the clear influence the Eiffel Tower's design played across a large quantity of submissions [4] and ultimately the structure was never completed, only reaching 150 feet of the design height of 1200 feet due to excessive costs and shifting foundations from the weight of the tower [5]. At the time the selection committee viewed the designs in a catalog or text- and image-based book with just the images of the tower and sometimes incomplete designer submitted information on base typology, height, material, projected weight and cost.

It's not unreasonable to wonder that with the right assessment tools, perhaps the jury would've been able to easily compare the features of the submitted design space for performance metrics such as cost and weight, or even filter out "unoriginal" typologies that too closely resembled the Eiffel. This issue is still relevant, and as significantly larger quantities of human generated design data is made available, the right tool is needed to explore the design space, ascertain design quality, develop intuition for geometric form and performance relationships, and inform design selection.

In modern times, design competitions and their archives serve a similar role of spurring and capturing collaborative design processes and current design trends. One such architectural competition archive is Konkurado, which is a public database of

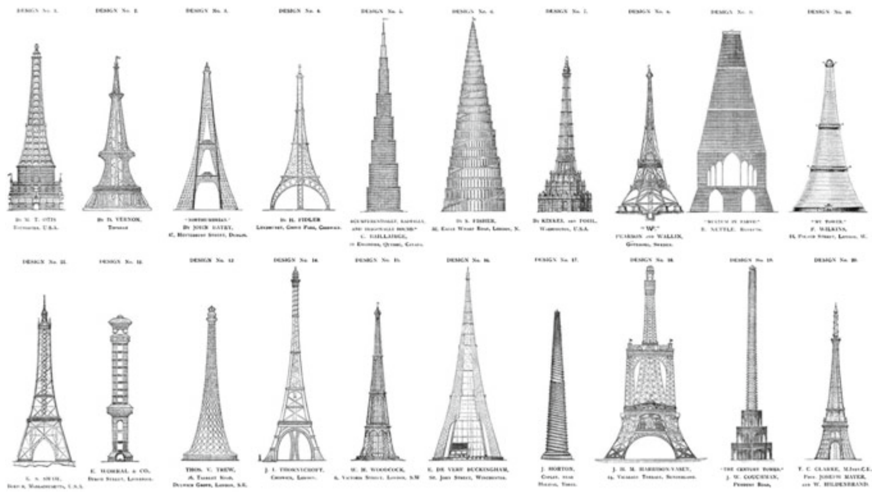

Fig. 1 Selected entries from the Tower of London design competition [6]

mainly Swiss architectural design competitions for public and private procurement [7]. Outside of architecture, we've seen many designers in practice and in research use competitions, workshops, hack-a-thons, and formalized ideation processes to inform design practice, concept generation and selection, and to build on existing expertise.

Wild Data

Within the context of data-driven processes including machine learning, design competition entries can be thought of as a particularly well-behaved example of "wild data," a term used in data science to refer to the output of automated web-scraping and manual harvesting from sources such as social media, found images etc. Typically, wild data is not constructed with research questions in mind or with conventional methodologies such as surveys and field experiments [8]. Non-competition wild design data is being used increasingly in data-driven design research, but is challenging because of the unstructured nature of design tasks and functions. For example, photographs of buildings on Instagram may have too little in common to be useful in creating a meaningful learning or generative model for a constrained architectural objective. Competition-based data addresses this by providing a universal brief, with the same boundary conditions and goals, that all submitted designs respond to.

Regardless of how a dataset is created, digital representations of design concepts for structures and objects are increasingly of value. As computational capabilities advance, digital technologies may aid in extracting high-level understanding of human-produced designs. Wild design data and the inferences drawn from it have the potential to complement existing computational design and performance evaluation methods to connect systematic and intuitive design approaches in a natural way [9]. This synergy may become more possible through the collection of sizable datasets for a variety of problems.

However, parallel to the creation of these large datasets is a need to provide new methods of data visualization that empower design exploration, evaluation and selection from their contents. Often the focus within data visualization is on parametric or synthetic design spaces to gain insight. Specifically, we need ways to evaluate organic human-generated or hybrid "wild" design contents for at least the following use cases:

- Judging the quality of the design data so that it can be used with confidence in generative models; quality relates both to human reasoning about geometry, form, and aesthetics, and simulation-based performance metrics
- Selecting designs from the dataset, e.g. in a design competition, and understanding why specific design choices are better and how to make improvements
- Extracting insights about design strategies, form-performance relationships, etc. for new "rules of thumb" and generalized design knowledge
- Developing intuition for design performance without requiring a comprehensive parametrization or understanding of how a concept is generated.

Data visualization offers a valuable way to achieve the overarching goal of developing systemized knowledge of a design space. This paper presents an interactive data visualization approach as a way to connect human intelligence with large-scale computational data across various levels of curation.

Literature Review

To contextualize the new research presented in this paper, this section provides a brief review of previous work, and differentiates this paper's contributions from the state of the art. In the literature, there are several existing approaches to collecting and visualizing wild design data for similar purposes to those proposed here, detailed below.

Human-Curated "Databases" That Are Text and Image/Based

With respect to mechanical design, one of the largest publicly available image- and text- databases are those for a nation's patented inventions. The United States Patent and Trademark Office (USPTO) has databases featuring over 11 million patents issued by the organization that can be accessed via text or PDF images from the present dating back to 1790 [10]. Similarly, the European Patent Office (EPO) offers the tool Espacenet, that allows users to access over 130 million patent documents from similar bodies worldwide [11]. Not only does this serve as a historical record of authorship, but it also can facilitate mechanical design teaching with the study of prior art.

In other fields, such as architecture, civil, and structural engineering, the study of precedents (a building analogy to prior art) is just as important, despite less formalized mechanism for information dissemination. Still, several image- and text-based built project databases have been created with the built environment in mind. While individual design firms often compile portfolios of their built projects for their websites, Structurae contains over 70,000 built projects across engineering and design firms [12]. This database contains images and project information that is contributed by community members of the database. There are many other examples of similar resources that are extensive but based entirely on text and images, which makes them difficult to use in a quantitative, data-driven context.

Machine Learning and Datasets for Various Design Applications

The importance of being able to quantify design data is an increasing interest in computational design due to the advancement of machine learning (ML) methods and applications, especially those which are supervised and require training data. ML datasets that handle geometric representations have been proposed in several previous works in academia and industry. Generative adversarial networks (GANs), a machine learning technique that can synthesize design concepts based on data provided in a training set, have been particularly key in design applications. The use of GANs to generate and recognize high quality 3D objects comparable to traditional supervised learning methods was demonstrated with MarrNet which takes in 2D images of an object and produces 2.5D sketches and a full 3D reconstruction [13]. A method was proposed that allows the generation of full indoor scenes and furniture layout in under 2 s using deep convolutional image-based models [14]. In other design applications, SimJEB is a collection of finite element simulation results paired with corresponding CAD designs for a set of Jet Engine Brackets [15]. This dataset was created to empower geometric deep learning and engineering surrogate models for performance-based design generation. However, without visualization, there is no way to rapidly evaluate the performance of the GAN or the quality of the geometric data.

Synthetic Design Data

Synthetic design data, or data generated programmatically (often from parametric models), is created for ML when quality data for an application is too scarce or is too expensive (fiscally or temporally) to collect via traditional methods. Synthetic datasets can be used to create methodologies for creative design space exploration or reveal nuances about the process itself, e.g. for long-span roof structural typologies [16, 17]. While this form of data has been important in advancing ML in the architectural domain, the resulting ML models are restricted by the self-similarity of designs in the synthetically produced training set. Wild data that more accurately represents the diversity of human creativity could be more effective for building robust, generalizable, and useful ML models in the future.

Visualization of User-Supplied Data and Design Space Exploration

In parallel to the rise of ML and AI, several tools have been developed to provide designers comprehensive ways to explore the design space. HexaLab was developed as an online assessment tool for 3D geometries represented as hexagonal meshes [18]. Design Explorer is an open-source tool for exploration and analysis of parametric design spaces for a predetermined (synthetic) set of designs [19]. ShapeDiver hosts parametric definitions from Grasshopper for online viewing and real time manipulation with no explicit analysis capabilities [20]. These platforms are powerful but either rely on synthetic parametric design data, or allow for attribute assessment without design performance comprehension and comparison.

Network analysis analogs have been made for early design generation and exploration tasks and where the nodes represent concepts, performance scores (or metrics), are attached node attributes, and edges are weighted by design similarity. This allows users to observe the emergence of clustering near quality designs, quantitatively evaluate distinctness of new designs added to a set, and apply machine learning techniques to predict and generate designs deemed "high quality" [21]. While this method is valuable for rigorous understanding of performance throughout the design space and relationships between designs, they do not allow for intuitive exploration and design selection for lay users due to the decoupling of the geometric representation visualization from the evaluation.

Lastly, several interactive tools have been created to enable interactive design space exploration and selection using the design by shopping paradigm introduced by Balling [1] which states that we can allow designers and users to explore a design space first and then choose the solution after ascertaining their preferences. This method is particularly effective for multi-objective problems that wish to include qualitative variables and user aesthetic preference. Stump et al. developed a data visualization interface for engineers to use design by shopping in complex design spaces with interactive and linked views of parallel coordinate plots and two- and three-dimensional views of pareto solutions. The work showed its technical application with a satellite design problem from a parametric design space [22]. In addition, the interactive multiscale-nested clustering and aggregation framework (iMSNCA) was developed to aid in design by shopping of large multidimensional datasets that prominently feature simulation and performance-based design. This is executed with a user interface design with data displayed in a scatterplot(s) that allows the user to view all data attributes and metrics, select ones of interest to view and perform real-time clustering, aggregation, and filtering operations on the data set [23]

The tools are suitable for fully technical problems but not completely sufficient if a design space also features geometric or form representation and has no underlying parametrization. These "wild", and organically generated design spaces constitute a significant way that engineers and designs create today and data visualization that allows for a joined exploration of the geometric representation of a design ensures that candidates are adequately evaluated and compared. Without a tool that facilitates design by shopping for "wild data", there is a limit on the adaption of quality designs generated in fully human and hybrid contexts.

Research Aims

Previous approaches to design data lack generalized, intuitive visualization techniques that help designers uncover relationships between qualitative and quantitative design performance with large-scale datasets. Online visualization aids for large datasets provide users with autonomy to explore three dimensional shapes and meshes, or are designed for parametrically generated design and simulation results, but offer no clear reconciliation for designs and their performance analyses that cannot be reduced to a small set of core variables.

There is a need for a framework that allows designers to rigorously explore diverse data sets produced organically and aid in design review and selection.

Hence, we propose an interactive visualization that allows users to accomplish the following:

1. Extract design insights in a large geometric and 3D mechanically simulated dataset
2. Discover relationships between shape and structural performance in a lightweight (non-computationally intensive and intuitive) manner
3. Explore the geometric variety that exists in the crowd-sourced design data
4. Make effective design choices in a time-efficient manner.

Method

Conceptual Overview

The wild design data visualization framework presented here works with 3D CAD representations of design geometries and respective quantitative data. The visualization tool is implemented in Javascript with the D3 visualization library [24] and operates in a web browser. In this paper, it is presented specifically for the crowd-sourced SimJEB dataset described in the section "Visualization of User-Supplied Data and Design Space Exploration" and shown in part in Fig. 2; the dataset contains 371 human-generated design concepts for a jet engine bracket [15]. The visualization framework applied to SimJEB and shown in the following sections is publicly available at https://simjeb.github.io/ [25].

The SimJEB dataset is notable among design datasets in that each design has been analyzed under the structural loading conditions specified by the competition for which they were submitted, and this performance data is packaged with the design geometry. In addition, each design datum was manually assigned one of six typology tags, which reflects the design's primary geometric and aesthetic gesture. A labeled view of the visualization framework is shown in Fig. 3.

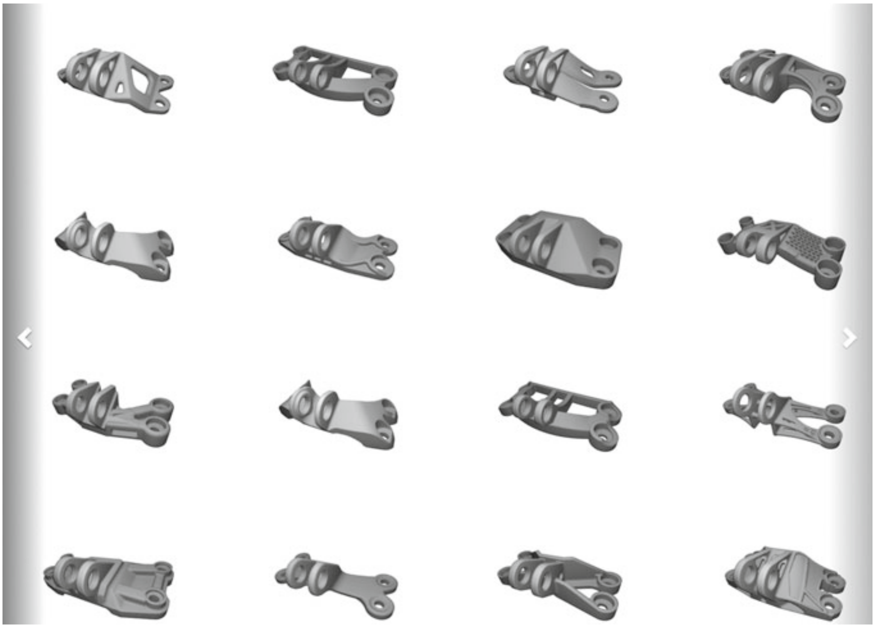

Fig. 2 Screenshot of design gallery of SimJEB bracket geometries

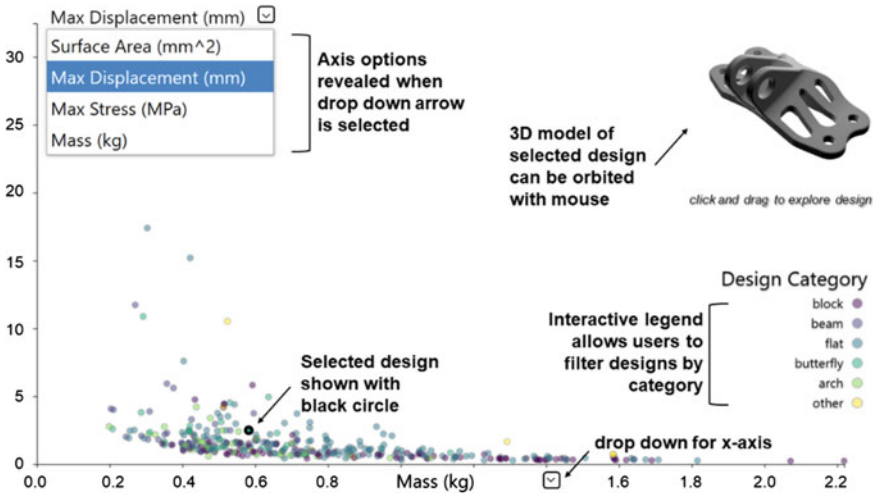

Fig. 3 Annotated image of the user interface provided for the SimJEB dataset

Although this is shown for the SimJEB dataset, this paper's visualization framework can also be considered more generally for other wild design data collected within the same context (e.g. competition or brief).

Data Processing and Representation

There are several ways of visually displaying complex 3D geometric and spatial data, including 3D models, multi-view images, and wireframes. One problem with static images is that the selection of fixed views of the models can bias a user or hide interesting characteristics not visible with that view. An interactive 3D window gives users the ability to manipulate the view of the selected design as desired.

Quantitative data that captures the performance of the design for at least two metrics of interest is necessary for full use of the visualization tool. For the metadata, all of the fields are quantitative except for the design typology category, which is a qualitative nominal field. This information can be solicited from users directly, or added in post-processing upon uploading the data into the visualization. This categorization is important because it gives users of this visualization a way to filter the data and search for trends via design typologies.

User Interface: Performance Maps

We can uniformly study wild design data with performance metrics even if they do not all share an underlying parameterization. One common way of understanding subsequent relationships between designs is via a bi-objective plot, which situates the designs in a dataset by their values along two axes of interest. This is similar to scatterplot, with the exception that there is no requirement for one axis to hold an independent variable and the other to hold a dependent variable in the dataset. By plotting two objectives against one another, one can examine both correlations and tradeoffs in performance. This approach has a similar spirit to Ashby plots [26], which were developed to visually understand relationships between diverse materials based on their properties. If there is a tradeoff observed between the two metrics, the best performing designs with respect to two objectives will lie on the Pareto front, which represents a set of solutions for which choosing another solution cannot improve the performance of one objective without sacrificing another [27]. The performance maps in this work offer users the options to select the metrics displayed on each axis based on individual design goals with drop down arrows provided on the side of the axis label.

Additional features of interest on the performance maps include a design category (or typology) filter via an interactive legend and design preview and selection tooltips. Users can select a design category or categories, which grays out non-selected designs for visual clarity as shown in Fig. 4.

This can be useful in identifying clustering in a large dataset and isolating designs of interest. As the user considers performance, hovering over data points will pull up a small tooltip that shows a small image of the design and clicking on the point

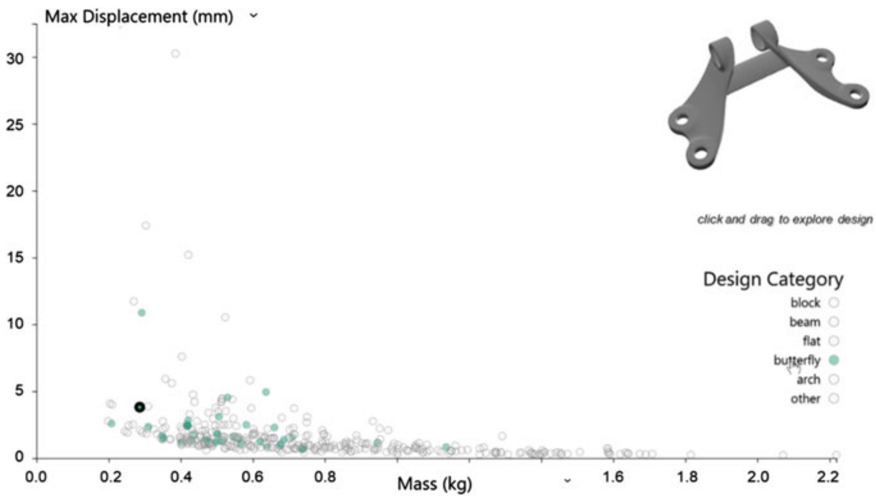

Fig. 4 View of SimJEB visualization with "butterfly" design typology filter selected

loads the design in the 3D viewer in the top right corner for further exploration and manipulations. The tooltip allows users to easily reference the linked geometries prior to selection and make visual comparisons between points distributed near the selected design. The current selected design is always highlighted on the plot.

Results: SimJEB Dataset Case Study

Selecting a Design: Sample Exploration

Given the problem of selecting an engine bracket design that minimizes two performance metrics of importance to the users, mass and maximum displacement, this tool helps a user evaluate and select a design. Additional constraints on typology can be imposed due to preference on aesthetics and/or manufacturing processes. For this example, the arch typology will be chosen as the typology of interest. One can start by imposing a filter on the designs via the clickable legend. This means that only the green points that represent this typology will be selected. To find an optimal design with respect to these two objectives, the search should begin near the utopian point, or the corner of the chart that shows the hypothetical design solution that minimizes both performance metrics independently. One can hover over designs in this region to show a tool tip that gives a preview of the 3D geometry as shown in the bottom left of Fig. 5 and click a point to load the image in 3D viewer in the upper right corner for further inspection.

Now that the user has found a design that minimizes the objectives of interest, mass and maximum displacement, the user can also evaluate how this design performs with respect to other metrics, such as surface area. This metric correlates to material use and maximum stress, as shown in the right of Fig. 5. The user may then decide if they would like to stick with the selected arch design or view other options.

This process can be iterative, and users are able to change performance metrics on each axis and design typology filters until all desired information is gathered. In this example, there are 4 different objectives considered, but the full SimJEB dataset has 25 quantitative performance metrics from simulation results and bracket properties in its metadata file. The implementation of this performance map visualization is flexible enough to handle as many objectives as the user uploads in their personal dataset.

Finding Patterns in Data

Another way this visualization can be used is to find instances of clustering of data by design category. An example of this is seen in the SimJEB dataset when considering the objectives of maximum displacement and surface area. In Fig. 6, the block

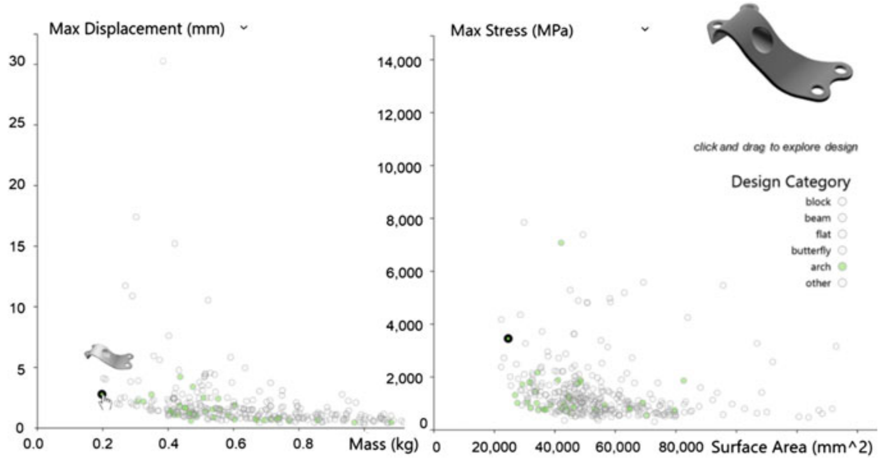

Fig. 5 Side-by-side screenshots of the data visualization with a filter for arch typologies applied. (Left) The tooltip image of the geometry associated with the point appears as the cursor hovers over a point on a plot showing maximum displacement vs mass of the bracket designs. Clicking the point selects the design and loads it in the 3D CAD viewer shown (Right). The same selected point remains highlight when other performance metrics are chosen for consideration

category and butterfly category are highlighted and reveal a clustering of designs with respect to these two metrics.

In this example the user can observe that if their goal is to minimize these two objectives, butterfly design typologies generally are a better option as that cluster is

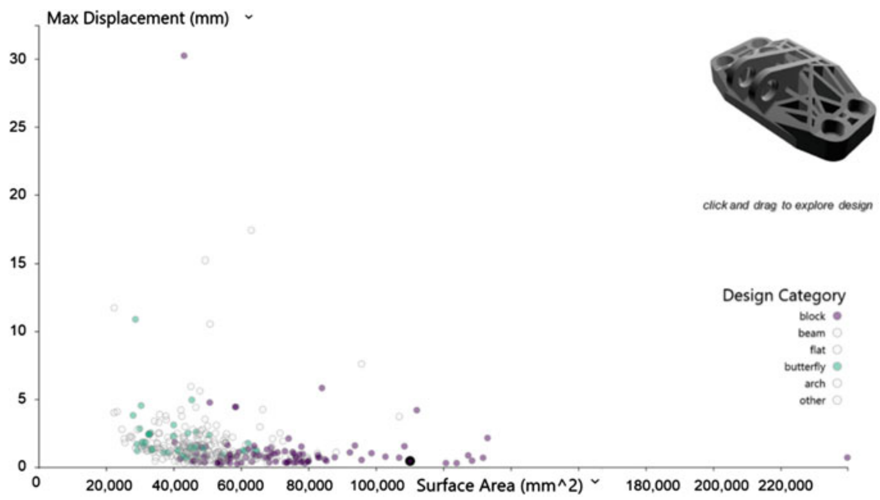

Fig. 6 The interactive filter was used to highlight block and butterfly design typologies revealing distinct clustering between the groups

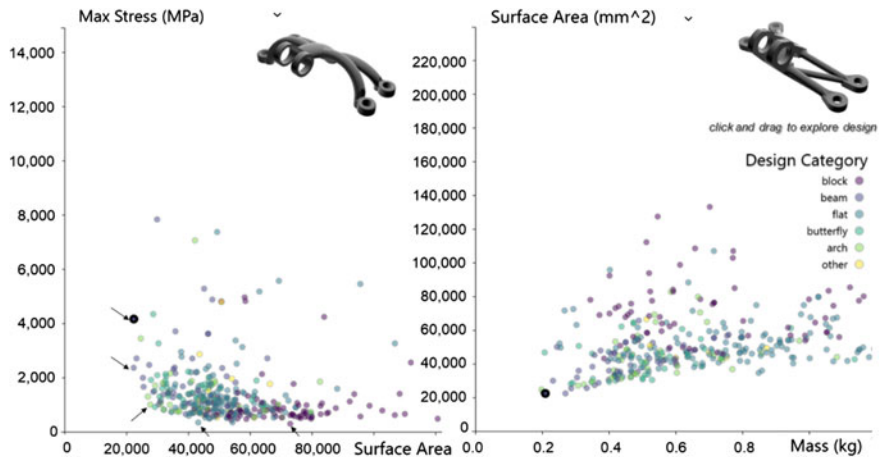

Fig. 7 (Left) Arrows on performance map highlight designs that make up the Pareto set. (Right). Here the user can observe a positive correlation between the two new metrics

closer the utopian point in the bottom left corner of the performance map, than the block typologies.

In addition to clustering, users can also observe correlations with this visualization. In the SimJEB dataset, when the user views surface area vs. mass, the performance map in Fig. 7 on the right shows positive correlation between these two objectives across all design categories. Conversely, these plots can be used to view design tradeoffs as well and allow users to trace along the Pareto front for two objectives and use the tooltip functionality and selection to view the geometry of the designs. Figure 7 highlights some of the designs on the Pareto front when considering the objectives maximum stress and surface area.

Results: Tower of London Competition Revisited

In the section "Background and Motivation", the Tower of London design competition was introduced as an example of a crowdsourced dataset with the same given guidelines and goal. Unlike the SimJEB case study presented in "Results: SimJEB Dataset Case Study", the performance metric information is self-reported by the designers instead of the results of finite element analysis. The construction of the winning design began shortly after the competition, but ultimately stalled due to lack of capital and foundations that were ill equipped for the weight of the tower. Put in terms of performance metrics, the selected design was both too heavy and too expensive. This provides a context to see what better performing designs the visualization framework we propose in this work could have highlighted.

For this proof of concept demonstration. The Tower of London metadata was structured in the same way as the SimJEB dataset; for each datum, the ID or design number was recorded with the associated height, base type, weight, material, and cost, as well as the authorship information and country of origin and associated geometric representation. The data was cleaned where data with missing information for height and cost were removed from the set, and non-specified base typologies were assigned to the category of other. Of the 68 designs submitted, 43 remained after the cleaning procedure. Next the two metrics of importance, weight and cost, were normalized for the tower scale by dividing those values by the reported vertical height of the tower.

The results of this study are shown in Fig. 8, where the dataset is plotted in a performance map with the two normalized metrics of weight per height versus the cost per height. Here we see that the winner selected is not the best performing design in its typology set, let alone in the overall dataset of submission. If one seeks to optimize for cost or weight individually, or from a multi-objective perspective, there are other compelling options, with the cheapest option topology bearing some resemblance to the winning shape despite belonging to a different category. However, it isn't until we display the data with respect to the two dimensions coupled with their accompanying designs that these conclusions can be easily drawn. A performance map like this may have changed the winning design selected by the jury.

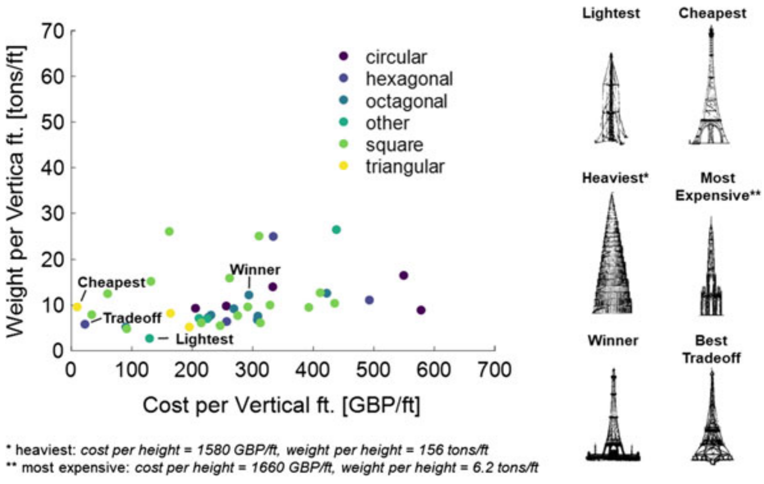

Fig. 8 Performance map of the design space of submitted concepts for the Tower of London competition in 1890. Here the two metrics highlighted are coupled with an array of tower representations for the points called out in the plot

Conclusions

The interactive data visualization presented in this paper demonstrates a new way to visually analyze wild design datasets with multiple dimensions of quantitative data (properties of importance and/or performance data) and geometric representations. This visualization uses performance as an organizing principle, which allows users to explore a range of dataset types, including both organic, open-ended design spaces (such as that of a design competition) and synthetic datasets generated from a parametric or grammatical design space. It is interactive in both how the quantitative data is displayed and how the 3D geometry can be examined. It also decouples this geometry exploration and data analysis from complex and propriety CAD and data visualization tools by making use of open source JavaScript libraries. In demonstrating this approach on two quite distinct case studies, this paper makes the case that data visualization can play a general and widely applicable role in design, especially as more quantitative data becomes available. By creating new ways of visualizing complex design sets, it is possible to increase understanding of underlying data in geometric and performance-based datasets and help streamline the design realization process.

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Dimensions of Prototyping Knowledge: Characterising Prototype Evaluation Methods and Their Contributions to Design Knowledge

Ricardo M. Real, Chris Snider, Mark Goudswaard, and Ben Hicks

Prototyping in New Product Development (NPD) encompasses a broad selection of methods used to generate knowledge about a product or process. Whilst some methods focus on the creation of a prototype in its intended domain, others centre on its testing and evaluation, contributing to an understanding of the prototype's performance against a set of design requirements or objective. Where prior works have explored the contributions to design knowledge afforded by methods of creation, methods used to evaluate prototypes lack a similar characterisation. This paper presents a study investigating the contributions of 24 different evaluation methods to design knowledge, adopting the concept of Knowledge Dimensions in a participant study to characterise methods by their contribution to 10 dimensions for prototyping knowledge. Results were reviewed independently before comparison with the results of a prior study on creation methods, showing significant differences in the contributions to design knowledge from creating and evaluating prototypes.

A Background to Knowledge Dimensions, Making and Evaluating

Prototyping is a critical part of the engineering design process, supporting a range of design activities from ideation and exploration, to design refinement and optimization, to inter-stakeholder communication and record keeping [1]. Prototypes themselves may be of many forms, with the process of prototyping comprising an orchestration of physical and digital representations of varying fidelity [2]. These prototypes are used to generate learning for purposes such as product look/feel, role/function, and technical implementation [3]. Underlying almost all prototyping

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processes is the aim of learning [4, 5], the generation of knowledge that will increase the understanding of a proposed design solution for one or multiple stakeholders and for different purposes, ranging from technical detailing, to supporting decision-making, to capturing user voice and needs or increasing cross-stakeholder engagement. This learning is generated in varying forms throughout prototyping, from tacit and organic learning during prototype fabrication, to formal tests and experiments [6, 7] of prototypes. Hence, while not always explicit (with the exception of user studies) consideration needs to be given to the media, stakeholder, purpose and evaluation methods to generate the right type (*dimension*) of knowledge, and to do so most efficiently within the cost and time constraints of the overall process. With prototyping comprising a range of media, activities, purposes, and outputs, it stands that a relationship (mapping) may exist between the media and activities that are chosen, and the learning that is generated. Prior work [8] has investigated such a mapping, highlighting different dimensions for knowledge that are required within a typical product design process to develop a solution, and proposing suitability and alignment of prototyping media with a set of 'knowledge dimensions' for product development. However, prior work focused on the generation of knowledge through the creation of a prototype, as opposed to by evaluating that which has been created. It follows that this work aims to extend this investigation to consider the alignment between knowledge generated and evaluation methods applied during prototyping. In so doing, it aims to understand the suitability of evaluation methods for targeted knowledge generation, supporting targeted prototyping method selection and ultimately more efficient prototyping processes. This paper first discusses related works and the need for the reported study, the methodology, and finally the findings from an analysis of evaluation methods against dimensions for knowledge in prototyping. The paper concludes by examining the coupling of evaluation methods with methods for prototype creation presented in prior works [8], exploring the selection and sequencing of prototyping tools (creation/evaluation) and the potential contributions to design knowledge across dimensions afforded by their coupling.

Prototyping Media and Evaluation—Short Background

Prototyping media itself is highly variable, with selection dependent on the learning required, stage of the design process, and the preferences of the designer [5]. In early process stages, it is common for media to be more generalised and lower fidelity, such as foams, clay, additive manufacture, junk modelling, and constructions kits [9], with testing then focused on individual functions, characteristics, or behaviours to prove them out in isolation. As the design process progresses and the product representation matures so does prototyping, requiring higher fidelity media (i.e. as-final materials, electronics) and fabrication processes (i.e. machining, full production processes) [10]. Evaluation methods equally increase in fidelity, either testing specific parameters to high degrees of precision, or performing comprehensive evaluation across many aspects of subsystems of a prototype. This range of fidelities exists for both physical and digital prototyping, with digital comprising a range of geometric modelling, analytic models, and simulations at fidelities appropriate to the learning required. This broad space of purpose and media present many options for a designer. While this freedom is beneficial for aligning prototyping media with the requirements of highly variant prototyping activities, it also creates uncertainty in the overall alignment of the methods chosen and the outputs required over the design process. Engineers often report that prototyping methods are chosen on an ad-hoc basis [11], and identify a lack of formal guidance on prototyping method selection [12, 13]. This uncertainty raises a risk and opportunity—through better understanding of prototyping methods and guidance on method selection, the prototyping process may be streamlined towards more efficient methods, while maintaining (or increasing) the relevance, detail, and utility of learning that is generated [8].

Knowledge Dimensions—Short Background and Definition

In order to successfully design a product or system, it is necessary to generate a range of data and knowledge that informs decision-making, develops understanding (i.e. of operation, behaviour, manufacture, etc.), and gives confidence in the design. In the field or architecture [14] Schon and Wiggins propose a minimum set of 'Knowledge Domains' against which a designer will probe various aspects of a design representation in a conversation with the materials of a designs solution, registering visual information and attributing meaning to observations beyond the medium itself. In so doing and at each process stage, designers will generate the knowledge required to bring a design from idea to production, with knowledge across the set of domains required to achieve this goal. In context of the range of prototyping methods, activities, and learning that occurs throughout the prototyping process, this range of knowledge domains suggests an interdependence between the methods that are employed and the type of knowledge generated. Should certain media or activities create bias through their working methods towards certain domains, it may be that more informed method selection may allow streamlined or higher quality prototyping processes. For example, ensuring that the media selected provide broad coverage across domains, or focus on those domains of critical importance in a given situation. To create distinction against the Knowledge Domains of Schon and Wiggins [14], this work re-casts to 'Knowledge Dimensions' (KDs), adapting and expanding each domain to the context of NPD, as proposed in prior work [8]. The 10 knowledge dimensions described in Table 1 remain consistent with those of prior works in their definition.

Aim

This work aims to investigate the relationships between prototyping media, evaluation activities, and the knowledge generated. Where prior works have explored

Table 1 Knowledge dimensions for prototyping [8]

ID	Knowledge dimension	Description
KD1	Programme use	What the design is intended to do (function)
KD2	Environment	How the design performs in the conditions for use
KD3	Resources	What is needed to make the design (materials/tools/time)
KD4	Design elements	Features or components that will comprise the design
KD5	Form	Shape and size of the design including look and feel
KD6	Manufacturing processes	How the design will be made, and the required steps
KD7	Configuration	The arrangement of design elements, how it fits together
KD8	Character	How the design is supposed to look (brand/product family)
KD9	Explanation	How the prototype communicates what it does
KD10	Lifecycle	The envisaged life of the design (creating/use/disposal)

the concept of dimensions for knowledge in prototyping [8, 14] such works have placed focus on the generation of knowledge (KDs) in the creation of a prototype, employing media and methods to realise a design in its respective domain, and not on the knowledge generated through an evaluation of what has been created. This work then studies the relationship between KDs and methods of evaluation commonly employed in the prototyping practice to probe a design along a particular set of dimensions of interest. In so doing it will support better understanding of the relationships between prototyping activities and knowledge, leading towards active guidance for method selection to support efficient and effective prototyping processes and ultimately improved design processes.

Method

To determine the scope and contribution to prototyping knowledge generated by a range of evaluation methods, a study was conducted in which participants with expertise in Engineering Design and Rapid Prototyping were asked to score 24 different evaluation methods by their perceived contribution to each of the 10 dimensions for knowledge. Study participants had previously been involved in an analogous study of prototype creation methods [8], thus grounding the presented work in a shared understanding of study context and methods.

Participant Backgrounds

The reported study was conducted in a Design and Manufacturing research group (DMF) within the Department of Mechanical Engineering at the University of Bristol, UK. Whilst the sample of 6 participants is relatively small, participants shared a broad understanding of prototyping processes and expertise in Rapid Prototyping. Participant industry experience was captured as part of the entry survey, with three participants indicating 5+ years, two between 1 and 5 years, and one with 5+ years 'other' experience in Design Engineering related fields. All participants were actively involved in design research, of which, two have further experience leading taught modules in undergraduate Mechanical Engineering.

Study Materials

A rating sheet comprising a table with 24 categories for evaluation methods was distributed amongst study participants. The sheet allowed for evaluation methods to be scored on a 5-point Likert scale by the degree to which participants perceived each category to contribute to each of the 10 dimensions (Table 1). Participants had an existing familiarity with the study materials having been briefed using the same examples as in the anterior study of creation methods [8]. This included briefing with an example consumer cordless drill, and access to an annotated technical drawing of the drill as reference throughout. An extract of the rating sheet completed by participants is given in Table 2. Supplementary to the rating sheet was an extended list of example evaluation methods for each category, reflecting the level of fidelity, and domain (physical/digital) captured in the study.

Table 2 Extract from study rating sheet given to participants with example mediums for 1–5 scoring (qual/qualitative—quant/quantitative—VLF/virtual low fidelity)

Process type	Medium	Example	Time	KD1	KD2	…	KD10
			1–5	*1–5*	*1–5*		*1–5*
Qual VLF	*User test*	*Focus groups, end-users* etc.					
Qual VLF	*Expert test*	*Expert reviews, technical observations*					
Quant VLF	*Mechanical*	*FEA, CAE, simulation*, etc.					
Quant VLF	*Dynamic*	*Motion studies, CFD, simulation*, etc.					
…							

Formulation and Categorisation of Evaluation Methods

As is true of prototype creation methods, methods of evaluation encompass a breadth of processes with variation in properties such as accuracy, precision, and execution time required to measure a prototype along one or more dimensions of interest. Where an exhaustive list of evaluation methods is unfeasible, the methods selected in this study represent the range of characteristics afforded by processes commonly used to evaluate prototypes in product development. These include *qualitative methods* concerning subjective or tacit interpretation of the prototype (for example its look and feel), and *quantitative methods* where the properties of a prototype are measured to determine performance or other functional aspects. Further, the fidelity of methods is also considered, to give a practical example, *low fidelity* may include a simple cm rule measurement (± mm), whilst *high fidelity* measurement may introduce additional precision e.g., using laser or optical probes (± µm) to evaluate dimensional properties of the prototype. Methods were grouped as per the definitions above, however their contributions were scored individually by all participants.

The method categories shown in Table 3 were replicated for level of fidelity (high/low), and again for domain (physical/digital) creating a total of 24 categories for evaluation. The distinction between categories being the medium, i.e., evaluating a physical or digital artefact, and the precision to which evaluation is performed, Table 4.

These categories were selected to support analysis and align with wider research aims, see Sect. "A Background to Knowledge Dimensions, Making and Evaluating",

Table 3 Method categories for evaluation

	Category	Description of methods
Qualitative	User testing	Such as focus groups and user evaluation
	Expert testing	Functional observation, experience driven
Quantitative	Mechanical	Determine mechanical properties e.g. strength
	Dynamic	Study of motion and behaviour
	Mathematical	Calculations/modelling
	Verification	Dimensional/surface measurement

Table 4 High level categories (bracketed values show the number of methods evaluated in each category)

Grouping	Description
Physical/digital (12/12)	Evaluation in the physical or digital domain
Fidelity high/low (12/12)	Degree to which dimensional precision is controlled
Qualitative/quantitative (16/8)	Measuring subjective or tacit properties of the prototype

Table 5 Rating sheet scoring and descriptions. Knowledge contributions (left) time scoring (right)

Score	Knowledge contribution	Time
1	Little to no information in this dimension	<20 min
2	Minor non-specific information	20–60 min
3	Some information in dimension	1–5 h
4	More focused information in dimension	5–24 h
5	Dimension specific and purposeful information	24 h+

namely spanning the prominent digital/physical boundary in prototyping [2], recognising that fidelity of prototyping may vary depending on process stage and activity, and that both method domain (physical/digital) and level of fidelity required may impact the selection of prototype evaluation methods in NPD.

Study Process

The study process comprised a participant briefing to communicate study materials, following which a briefing document was distributed to participants with definitions for each dimension and example evaluation methods. Prior to the rating session a 1 h workshop was held to develop mutual participant understanding of the study. Participants were then instructed to independently complete the rating sheet by assigning a Likert-type score between 1 and 5 to each of the 24 evaluation categories. Scores were assigned based on participant agreement with the scale of knowledge contributed to each of the 10 dimensions as per the key in Table 5 (For correlation, the key is aligned with that used in the previous study [8]). Process time estimates were also scored by participants on this scale. A time limit was not given for completion of the task. Rating sheets were collected on completion and processed to extract median individual and grouped scores for non-parametric analysis using IBM SPSS 27.

Comparison Between Prototype Creation and Evaluation Methods

Results from the study of prototype evaluation methods were compared to the results from the prior study of creation methods, see [8], where the scale of contribution to different dimensions is shown to vary significantly depending on the process, domain, and level of fidelity employed. Where in the prior study analysis and discussion is focused on the knowledge generated in the creation of a prototype, this paper investigates the knowledge generated via its evaluation. Results from each study were appraised separately and compared to identify relationships in their contributions to

KDs. Further, the potential for combinations of creation and evaluation methods to optimise knowledge contributions across dimensions were reviewed.

Results

Participant responses were first assessed using a Friedman's repeated measures test ($x^2(9) = 151.605$, $p < 0.001$) showing a significant distribution in the knowledge generated from various evaluation methods against dimensions.

Reviewing the mean ranks for evaluation methods permits several observations to be made regarding their contribution to knowledge dimensions. Firstly, high scoring evaluation methods focus primarily on functional KDs, either partially or entirely. The highest scoring KDs (Programme Use (**KD1**), rank 7.18; Environment (**KD2**), rank 6.37) focus on functional completion, requirements completion, and operation of function within the product environment. Of slightly lower rank and prominence are KDs related to design features and structure (Configuration (**KD7**); Design Elements (**KD4**)), reflecting the focus of engineering evaluation on technical implementation. Finally, lower ranking methods (Character (**KD8**); Resources (**KD3**)) suggest a lack of breadth across methods to inform against these KDs. Typically, within this survey such KDs were considered to be informed by qualitative methods, including expert/user evaluation.

Top-3 Evaluation Methods

Table 6 extracts the top-3 evaluation methods scoring the highest median value for each KD. Results show physical methods to be most contributory across KDs, as 22 of the 30 methods are physical. This may reflect a broader capability of physical evaluation to assess across different aspects of physical products, where in contrast virtual methods are often highly focused and targeted in the learnings that they are intended to generate. This is supported by the top-3 results for Environment (**KD2**) where methods are all physical. Virtual methods are more prevalent in quantitative evaluation, whilst there is no indication from participants as to why this is the case—on review it could be due to the ease and speed at which virtual methods allow for quantitative evaluation, such as in the Resources dimension (**KD3**) where 2 of the top-3 methods are virtual. It is notable that some KDs (such as Character (**KD8**) and Explanation (**KD9**)) are the same, suggesting that interpretation of such KDs may occur in similar or the same tests. High fidelity methods account for 26 top-3 results, this finding suggests that certain low fidelity methods, such as user evaluation of Programme use (**KD1**), are capable of generating fast, and dimension specific knowledge comparable to that of high fidelity. A supporting analysis of process times is reported in the following sections to further explore relationships between domain, fidelity, and time (Table 7).

Table 6 Overall contribution to KDs by pooled evaluation methods

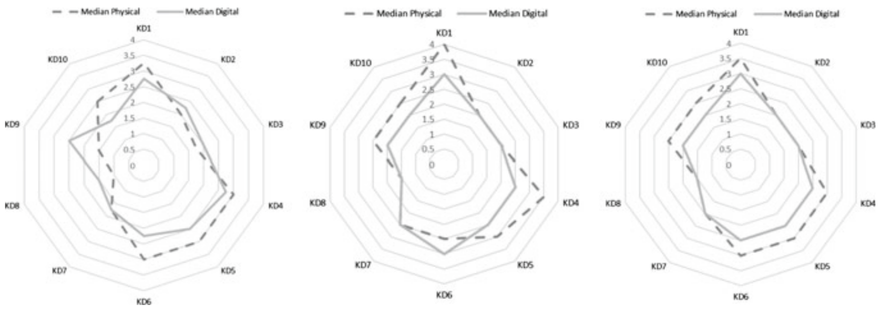
	Evaluation methods	
Pos	KD	Mean rank
1	Programme use (**KD1**)	7.18
2	Environment (**KD2**)	6.37
3	Configuration (**KD7**)	5.72
4	Design elements (**KD4**)	5.67
5	Lifecycle (**KD10**)	5.46
6	Form (**KD5**)	5.31
7	Manufacturing (**KD6**)	5.25
8	Explanation (**KD9**)	5.06
9	Resources (**KD3**)	4.66
10	Character (**KD8**)	4.32

Table 7 Top-3 evaluation methods for each dimension. P/V indicates physical/virtual, LF/low fidelity, HF/high fidelity. Bracketed values give the median survey scores

KD	Top-3 evaluation methods (median scoring)		
KD1	P: User LF (4)	P: User HF (4)	P: Mechanical HF (4)
KD2	P: Verification HF (5)	P: Engineer HF (4)	P: User HF (4)
KD3	V: Process HF (3.5)	P: Engineer HF (3)	V: Verification HF (3)
KD4	P: User HF (4)	P: Mechanical HF (3.5)	P: Dynamic HF (3.5)
KD5	P: User HF (3)	P: Engineer HF (3)	V: Verification HF (3)
KD6	P: Engineer LF (3.5)	P: Dynamic HF (3)	V: Dynamic HF (3)
KD7	P: Process HF (4)	V: Process HF (4)	P: Engineer HF (3)
KD8	P: User HF (4)	P: User LF (4)	V: User HF (3.5)
KD9	P: User HF (4)	P: User LF (4)	V: User HF (3)
KD10	P: Mechanical HF (4)	P: Dynamic HF (4)	V: Mechanical HF (3)

Physical Versus Digital Evaluation Methods

Figure 1 compares Physical to Digital methods across KDs, higher scores indicate a greater knowledge contribution in the respective dimension. Physical methods exhibit higher scores to that of digital (Fig. 1c). Whilst scores for physical and digital are aligned in the Environment (**KD2**), Resources (**KD3**), Configuration (**KD7**), and Character (**KD8**) dimensions, digital methods overall are shown to score less



(a) Low fidelity physical vs digital

(b) High fidelity physical vs. digital

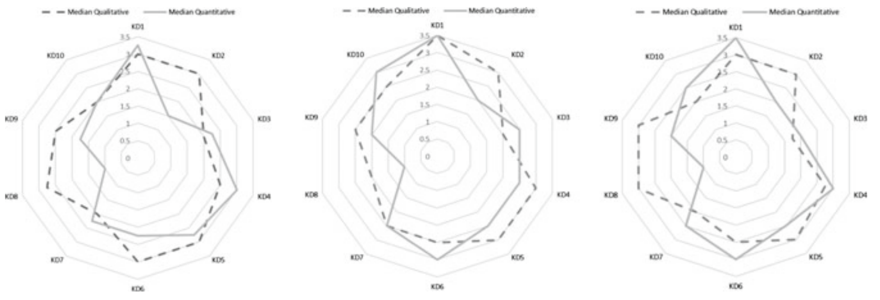
(c) All methods physical vs. digital

Fig. 1 Physical versus digital evaluation methods

than or equally to physical. Further characterising methods by their level of fidelity, it is observed that both digital and physical low fidelity methods generally score lower than high fidelity methods. High fidelity physical methods appear slightly targeted, with specific dimensions scoring very highly (Programme use (**KD1**); Design Elements (**KD4**)) and most others at medium levels. Interestingly, in some dimensions higher fidelity methods were scored as less informative (i.e. Manufacturing (**KD6**) for physical; Explanation (**KD9**) for digital). This perhaps reflects that high-fidelity evaluation may be more targeted towards specific aspects of more mature designs rather than broader exploration, meaning that information generated may be more confirmatory and less explorative.

Qualitative Versus Quantitative Evaluation Methods

When comparing quantitative and qualitative methods at low fidelity (Fig. 2a) it is evident that Environment (**KD2**), Form (**KD5**), Manufacturing Process (**KD6**), Character (**KD8**), and Explanation (**KD9**) are more strongly contributed to by qualitative methods. This finding is mostly congruent to the results of high fidelity (Fig. 2b), suggesting a perceptible distinction in the contributions of qualitative and quantitative methods to different groups of knowledge dimensions. Quantitative high fidelity methods are observed to contribute best in the dimensions of Resources (**KD3**), Manufacturing Process (**KD6**), and Lifecycle (**KD10**). For qualitative high fidelity methods these dimensions include Environment (**KD2**), Design Elements (**KD4**), Form (**KD5**), Explanation (**KD9**); dimensions of a prototype conceivably more subjective in interpretation. Additionally, Fig. 2c shows the pooling of high and low fidelity methods to accentuate the scoring of qualitative methods, particularly in the dimensions of Character (**KD8**) and Explanation (**KD9**). This finding highlights the potential value of low fidelity methods towards specific knowledge



(a) Low fidelity quantitative vs. qualitative evaluation

(b) High fidelity quantitative vs. qualitative evaluation

(c) All methods quantitative vs. qualitative evaluation

Fig. 2 Quantitative versus qualitative evaluation methods

dimensions, and is further evidenced by low fidelity methods featuring in the top-3 results for Character (**KD8**) and Explanation (**KD9**). It is of note that all low fidelity methods in the top-3 results are in the qualitative category, perhaps due to the subjectivity of evaluation in these dimensions. Thus, design interpretation at lower fidelity is shown to yield similar results to high fidelity in some dimensions.

High Versus Low Fidelity

Comparisons between high and low fidelity methods show high fidelity methods to outperform low fidelity in each dimension by a variable margin (Fig. 3). Programme use (**KD1**) is seen to be the primary dimension of contribution for both levels of fidelity. High fidelity methods exhibit a notable improvement in scores for Lifecycle (**KD10**), Character (**KD8**), Resources (**KD3**), and Configuration (**KD7**), with high fidelity methods on average scoring 20% more than their low fidelity counterpart. Dimensions in which differences are less pronounced include Design Elements (**KD4**), Form (**KD5**), Manufacturing Process (**KD6**), and Explanation (**KD9**).

Investigating such differences in Table 8 suggests low fidelity methods in these dimensions to offer a high knowledge contribution. The most significant change (38%) occurs in the dimension of Lifecycle (**KD10**), this is perhaps due to higher fidelity methods for lifecycle evaluation being more aligned with the products intended use, thus more representative of the performance of a developed product.

Evaluation Process Time Analysis

Process time scores were investigated to expand findings with further insight from the analysis of median participant time scores. Results for time data were segmented

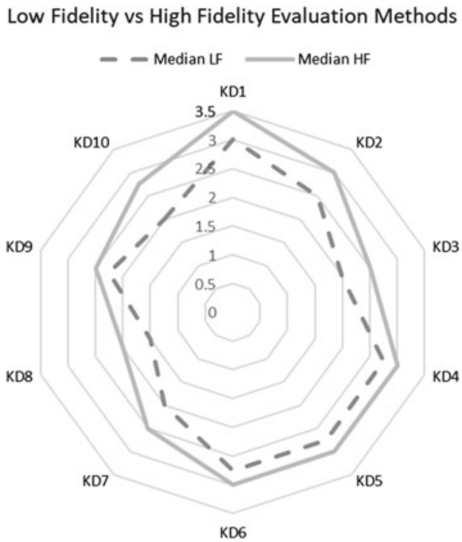


Fig. 3 Low fidelity versus high fidelity evaluation methods

Table 8 Median scores for low fidelity (LF) and high fidelity (HF) evaluation methods

	KD1	KD2	KD3	KD4	KD5	KD6	KD7	KD8	KD9	KD10
LF	3	2.5	2	2.75	2.75	2.75	2	1.5	2.25	2
HF	3.5	3	2.5	3	3	3	2.5	2	2.5	2.75
%	17	20	25	9	9	9	25	33	11	38

into physical/digital, and quantitative/qualitative evaluation methods for comparison (Fig. 4).

Prominently, scores for digital methods are observed to be lower than that of physical evaluation methods, thus, supporting prior conclusions that digital methods may be best suited to fast, specific evaluation and knowledge generation, where physical methods are deemed more confirmatory and labored in nature. Results further show high fidelity methods to be generally considered more time consuming than at low fidelity, however an exception is observed in physical qualitative evaluation as high fidelity qualitative methods, such as specialised focus groups and expert review, are perceived more efficient in extracting key information from evaluation tasks. Quantitative methods in both physical and digital domains are shown to take longer at higher fidelity, highlighting a potential correlation between increased precision and higher evaluation times.

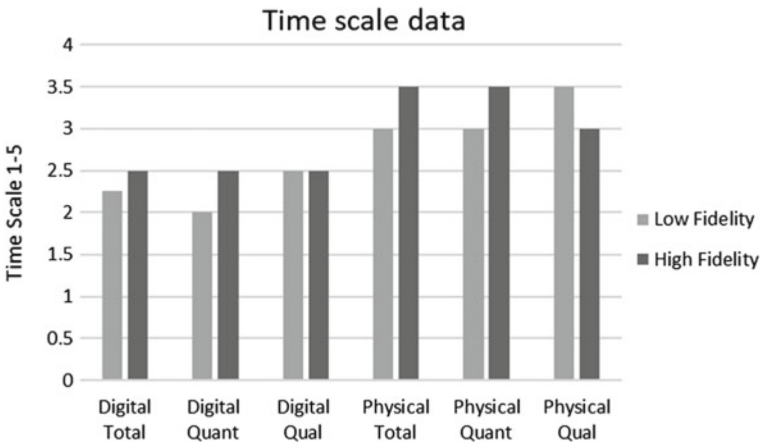


Fig. 4 Median process time scores across physical/digital, high/low fidelity, and quantitative/qualitative

Comparisons Between Prototype Creation and Evaluation Methods

Mean ranks from Friedmans repeated measures analysis of evaluation methods were compared to the mean ranks from the prior study [8] on prototype creation methods (Table 9). A number of significant differences are observed in the distributions of scores for creation and evaluation methods against the 10 dimensions. Thus, highlighting a distinction between the knowledge generated when creating a prototype and that of its evaluation, with a combination of both determined to produce the highest contributions across dimensions when prototyping. In the following section such observations are further detailed and their significance interpreted in the context of NPD, emergent opportunities to better support method selection in stages of a products development are also discussed.

A greater contribution to knowledge of Programme Use (**KD1**) is evidenced by the rankings of methods (Table 9). Knowledge in this dimension (**KD1**) concerns the functionality of the prototype for its intended use, thus a logical result as only through evaluation can knowledge of a designs performance against requirements be comprehensively understood. This result suggests evaluation of the prototype's function to be regarded amongst raters as the knowledge dimension most contributed to by the selection of methods investigated in this study. Notably, Environment (**KD2**) is shown to rank higher, from 7th to 2nd rank in the results of evaluation methods, this is to be somewhat expected as evaluation may contribute to a greater understanding of the prototype in the conditions for its intended use. Further, an apparent interdependency between evaluation of Environment (**KD2**) and Programme Use (**KD1**) is propositioned by these results. Form (**KD5**) is shown to rank higher with creation methods, possibly due to the tangible nature of making a prototype contributing

Table 9 Prototype creation methods from [8] versus evaluation methods (mean ranks)

	Prototyping methods		Evaluation methods	
	KD	Mean rank	KD	Mean rank
1	Form (**KD5**)	6.49	Programme use (**KD1**)	7.18
2	Programme use (**KD1**)	6.18	Environment (**KD2**)	6.37
3	Configuration (**KD7**)	5.91	Configuration (**KD7**)	5.72
4	Design elements (**KD4**)	5.87	Design elements (**KD4**)	5.67
5	Character (**KD8**)	5.34	Lifecycle (**KD10**)	5.46
6	Resources (**KD3**)	5.29	Form (**KD5**)	5.31
7	Environment (**KD2**)	5.26	Manufacturing (**KD6**)	5.25
8	Manufacturing (**KD6**)	5.11	Explanation (**KD9**)	5.06
9	Explanation (**KD9**)	5.06	Resources (**KD3**)	4.66
10	Lifecycle (**KD10**)	4.49	Character (**KD8**)	4.32

to a greater understanding of a products form. Through creation of a prototype, whether physically or digitally, there is an experience of situational backtalk [11, 15] between the prototype and the designer where knowledge is gained through a reflective conversation with the materials of the situation [16]. Configuration (**KD7**) and Design Elements (**KD4**) are ranked closely in 3rd and 4th ranks for both creation and evaluation methods, this again suggests interdependency between these dimensions, and also that contributions to knowledge from making and evaluating to be similar. Lifecycle (**KD10**) ranks significantly higher with evaluation methods, from 10 to 5th rank, indicating that learning in this dimension is better supported through evaluation of a prototype. Furthermore, results for top-3 Lifecyle evaluation methods (Table 7) suggest these to be high-fidelity and predominantly physical. To conclude, where creation methods subjectively focus on knowledge of 'the parts' to a design solution, evaluation methods exhibit a greater contribution to knowledge of 'the whole', with both subsets considered essential to the designer's understanding, and navigation of the solution space.

Discussion

Foremost, that the findings of this study align with that of prior works [8] supports the concept of Knowledge Dimensions as a method for classifying and measuring knowledge contributions across facets of prototyping activity. Further, the framework for delineating knowledge presented by dimensions is shown to facilitate the characterisation of methods often employed in a product development process. By applying the lens of Knowledge Dimensions to methods for evaluating prototypes, several key findings are observed, highlighting the following points for discussion.

Method Alignment with KDs, Suitability, and Selection

The evaluation method employed during prototyping is shown to affect the dimensions that knowledge is generated against, with some methods better suited to particular dimensions. While this is not surprising, it suggests that a level of bias is introduced by both media and evaluation method, hence selection may significantly impact quality of outputs. This is particularly relevant as designers may not always know which method best to employ [17, 18] and may require explicit guidelines to maximise the benefits of prototyping [13], highlighting the potential for KDs to be used for cataloging methods, such that a designer can search by dimensions of interest and retrieve an appropriate list of methods for dimension specific learning. It is also evident that dimensions are not contributed to equally as the ranking of mean scores indicates more methods to inform against higher ranking dimensions. This suggests that KDs such as Programme Use (**KD1**) may be 'easier' to inform against than lower scoring dimensions such as Character (**KD8**), where the dimensions subjectivity may inhibit its means of evaluation. Here, the findings imply an importance of breadth in activity to ensure coverage of dimensions—knowledge across all dimensions is expected to be important for good product development, and hence designers may be wise to plan activities with dimensions in mind for those that are harder or less likely to be informed against.

Digital Versus Physical Domains

Physical evaluation methods are by far the most prominent. This may be attributed to contextual factors such as NPD in the manufacturing industry, where products are often developed for real-world deployment. This suggests physical evaluation to be a more conclusive measure of a prototype's attributes in its intended domain for use. Findings show digital methods are perceived less time intensive than physical evaluation methods. Where digital evaluation requires a virtual representation of the prototype at an appropriate level of fidelity to the projects maturity, this supports the value of twinning physical/digital prototypes in NPD [19] as the rapid evaluation capability of digital tools can be leveraged before validation in the more labored and time intensive physical domain. Surrogate modelling, where by a rudimentary virtual representation is probed to understand relationships between input and output data provides a current example of low fidelity digital evaluation and its utility in NPD. Translating to the framework for knowledge dimensions, 'low fidelity digital twins' could enable fast, dimension specific knowledge of a product or system with reduced set-up requirements, it could be that the 'digital twin' does not have to be '*identical*' for the purpose of fast, specific learning at lower fidelity.

Knowledge from Making and Evaluating

Naturally, it would be difficult (for the most part) to evaluate a concept that does not exist beyond the designer's cognitive model, evaluation in both physical/digital domains require *something* to evaluate. However, the findings of this study show some dimensions to be better contributed to by creation, whilst others by evaluation. Where fidelity is concerned, this suggests that in certain cases low fidelity prototypes can be made to enable more significant learning through their evaluation. This can be seen in the use of ergonomic test rigs often employed by designers; the fabrication of the rig does little by way of contributing to an overall understanding of the final product, however, by evaluating the rig for its intended purpose a significant contribution is made to ascertaining specific properties of the final product. Thus, in dimensions where evaluation methods are considered to be more contributory, the fidelity of the prototype may be of less importance, indicating that knowledge dimensions could be used to support suitable method selection, and further the development of strategies to couple creation/evaluation for more efficient knowledge generation in NPD. From the results it is evidenced that there may be interdependencies between dimensions, where to generate knowledge in one inherently requires a pre-existing knowledge of the other, alluding to a structure/sequence/s in the process of acquiring sufficient product knowledge across dimensions. Whilst this work does not explore these sequences it establishes a foundation for future works to do so, with the aim of identifying sequences in knowledge generation inferred from an investigation of interdependency.

Limitations and Further Work

Whilst the participants surveyed in this work are highly experienced in prototyping, it is recognized that the conclusions of the work require extension through larger samples and real-world observation. To this end, work is ongoing to observe and verify findings in a number of real-world case study design projects. The work here presented characterises learning retrospectively, and suggests potential to use findings to support better method selection and sequencing for higher quality of output and more efficient prototyping processes. This premise presents an interesting avenue for future work—prototyping is often performed on an ad-hoc basis [17], and as such specifying methods may contradict the agile prototyping approach that is common in industry. Based on the guiding principles that this work suggests, future work should consider the real effect of specifying prototyping processes, and the effect on learning and product quality that such rigidity may create.

Conclusion

As the prototyping process encompasses both the creation and evaluation of a prototype along various dimensions of interest, the extent to which various evaluation methods, ranging in domain and fidelity, contribute to design knowledge lacks clear understanding. Using the concept of Knowledge Dimensions this paper presents an investigation into how evaluation methods support learning in the design process, relating different types of evaluation to the information that they generate. The study showed that evaluation methods do not contribute equally to dimensions, with many observed to inform against functional aspects of a prototype, such as its functional completion, requirements completion, and operation of function within the product environment. Further, results highlight a disparity in the characteristics of physical/digital, qualitative/quantitative, and high/low fidelity evaluation methods, showing physical methods to be generally more prominent, with further distinctions found in the grouping of other methods. Results were compared to the findings of prior works on prototype creation methods [8], showing evaluation methods to have a different profile of contribution to prototyping methods against dimensions, suggesting some dimensions to be better informed through evaluation, whilst others through creation. These findings promote the concept of Knowledge Dimensions as a method to characterise, and better understand the contributions afforded to design knowledge from different prototyping methods, enabling more specified selection processes and opportunities for method coupling to support prototype development in NPD.

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Design Generation and Quantum Computing

A New Approach to Facilitated Idea Generation and Application Through a Preliminary Study

Morgan B. Weaver, Alexander Murphy, Christopher Banks, and Julie Linsey

Across brainstorming literature, verbal group idea generation is characterized as ineffective. This argument largely stems from studies showing that nominal groups (individuals working separately and pooling results) produce more ideas than groups working together. Denouncing group brainstorming due to this one measure disregards other benefits gleaned from this collaborative activity. Using facilitators to guide idea generation has been shown to improve productivity while maintaining the benefits of group brainstorming. In this paper, we put forth a theoretical framework for the task of the facilitator and test the impacts of the facilitator on an engineering idea generation task. We show that facilitated groups generate more ideas than unfacilitated groups and are more satisfied with the ideas they produce. The preliminary results and the framework introduced set the stage for future exploration into how facilitation can best be leveraged for idea generation and other group design tasks.

Motivation

One of the primary motivational benefits of group brainstorming as originally proposed by Osborn is the idea of *cognitive stimulation* from generating ideas with other individuals [1]. A diverse set of people bring diverse backgrounds, and this diversity can be leveraged to inspire new ideas and categories of ideas among designers. Paulus and Yang demonstrated that generating ideas with others does provide cognitive stimulation, which results in a greater amount of ideas [2]. By having participants write out ideas and systematically pass them to other participants

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and add ideas to them, they were able to counteract the three negative effects of verbal group brainstorming: (1) production blocking, (2) free riding, and (3) evaluation apprehension. Using this technique groups were able to generate more ideas than nominal groups [2]. Nominal groups are individuals who generate ideas separately and then pool results afterwards creating a sort of ideal standard for productivity in idea generation. Paulus and Yang showed that the three negative traits of verbal brainstorming could be counteracted, and they demonstrated the positive effects from cognitive stimulation from others' ideas.

Paulus and Yang demonstrated that group idea generation is benefited by the stimulation of others' ideas, but the methods implemented only involved writing and participants could not communicate with each other in any other way. Writing and not speaking would help prevent production blocking, but could hinder the sharing of knowledge, which is important in idea generation. Oxley, Dzindolet, and Paulus demonstrated that well trained facilitators enhance cognitive stimulation and help to overcome brainstorming difficulties during verbal group idea generation [3]. Using facilitators with only a few hours of training to guide idea generation of four-person groups, they showed that these facilitated groups could generate as many ideas as nominal groups, which is not common for group brainstorming techniques. Further they demonstrated that facilitated groups were more consistently efficient over the course of the idea generation session than nominal groups. Nominal groups began producing many ideas and then slowed down as ideas were exhausted over time. Facilitated groups continued to produce a similar amount of ideas throughout the idea generation session showing that the cognitive stimulation of others' ideas coupled with a facilitator continued to spur on idea production [3].

Facilitators as a group brainstorming intervention are appealing because they would allow the retention of other brainstorming benefits while being easily implementable in industry. Sutton and Hargadon showed that brainstorming in practice has many tangential positive side effects beyond just efficiency that make it an appealing tool in practice [4]. IDEO, an innovative product design firm, uses facilitators to run their brainstorming sessions [4]. The A-Team at NASA's Jet Propulsion Laboratory has also placed a heavy focus on the use of facilitators for idea generation [5]. Because facilitators are already used in industry, they should be repeatable in other companies. While research has shown that nominal groups are more efficient than real groups [6], nominal groups are not feasible in practice. In summary, facilitators are appealing for improving idea generation because they require minimal training, they overcome inefficiencies of groups, they retain other benefits of group brainstorming, and they are implementable.

This study sets forth a framework for the role of a facilitator in idea generation and implements this framework in a preliminary study to demonstrate its effectiveness. This preliminary study addresses the following question:

How does facilitation affect idea generation for engineering design problems?

This question consists of two sub questions:

(a) *How does facilitation influence the effectiveness of idea generation?*
(b) *How does facilitation effect group members' perceptions of idea generation?*

The first sub question aims to examine the number and types of ideas generated by facilitated and unfacilitated groups. To examine the second sub question, we will use a questionnaire to evaluate group members' satisfaction, enjoyment, and perceived workload of idea generation with and without facilitation.

Background

Brainstorming was originally proposed by Alex Osborn as a technique to use collaborative groups to spark ideas towards innovation and creativity [1]. This methodology and particularly the brainstorming rules Osborn recommended were first found to be effective, showing that groups using the rules were able to generate more ideas and more "good" ideas than groups who did not use the rules [7]. However, further investigation found that brainstorming groups were less effective at generating ideas than the same number of individuals working separately [6, 8, 9]. These groups of individuals generating ideas separately are called nominal groups. When nominal groups ideas are combined and all duplicate ideas removed, they produce more ideas and more good ideas than collaborative brainstorming groups—we will refer to these as real groups [6, 9].

Most of the above research fixated on the efficiency of brainstorming groups, how many ideas they could produce. Sutton and Hargadon, however, argued that efficiency may not be the only purpose of brainstorming, and they showed that there are several other positive characteristics of brainstorming in practice [4]. By conducting an ethnographic study of the brainstorming sessions of a product design firm for an organization, Sutton and Hargadon found the following positive characteristics of brainstorming groups: Brainstorming groups support the organization's memory of technical solutions, they provide skill variety, they support an attitude of wisdom in and outside the session, they create a status auction that maintains a focus on designing products, and they impress clients and generate income. All of these positive side effects play a key role in the use of brainstorming groups in context.

Oxley, Dzindolet, and Paulus showed that facilitators with the right training can improve the idea generation effectiveness of groups [3]. They used graduate student facilitators with three hours of training. They trained their facilitators to perform a set number of tasks to overcome group hinderances and generate more ideas. Facilitators were trained to perform the following actions:

1. Not generate ideas
2. Keep group members on task
3. Call upon under-contributing group members
4. Remind group members of the brainstorming rules
5. Repeat the problem statement
6. Reintroduce past topics that were underdeveloped.

This is a limited number of tasks that does not represent the full role of facilitators in practice or in other studies. Osborn originally prescribed a number of tasks for facilitators during brainstorming [1]. He suggested facilitators generate their own ideas before the session and suggest them to the group only when ideation was slow to spark more ideas. Facilitators were to categorize ideas to guide idea generation. Facilitators were to ask questions of which Osborn provided an entire chapter of examples, and lastly, facilitators were to set goals and prompt individuals for more ideas to urge them on for quantity. One of the goals of this study is to incorporate more tasks of the facilitator into our experiment. This will hopefully increase the effect of the facilitator on idea generation outcomes.

Within engineering design theory, there have been many attempts at tools to improve group brainstorming. Tools have been created such as TIPS [10], 6–3–5 or C-Sketch [11], and Design by Analogy [12]. Shah et al. were the first to attempt to measure the differences in effectiveness of the different methods [13, 14]. This led to Shah et al.'s development of the ideation effectiveness metrics [15]. These metrics have been used in other studies to further discern the benefits in different brainstorming methods [16].

Theoretical Framework for Role of Facilitator

In this paper, we present a new theoretical framework grounded in literature for the role of the facilitator during idea generation. This framework structures the role of the facilitator into four categories: Mediate, Organize, Motivate, Guide. The tasks of the facilitator are informed by literature on the topic of facilitation and by practice of well-known design groups such as IDEO [4] and JPL's A-Team [17]. In the A-Team, the facilitator "guides the participants to the goals of the study, manages conversations, includes as many participant voices as possible, and keeps track of key points, action items, and additional work that is beyond the scope of the study" (pg. 2) [18]. In this description of the facilitator's role, the A-Team facilitator does not contribute their own ideas and serves to guide conversation, mediate participant's contributions, and organize ideas. This closely aligns with the framework presented in this paper. The four main functions of the facilitator framework are defined as follows.

1. *Mediate*—keeping group members on task and encouraging them to follow the agreed upon rules of brainstorming
2. *Organize*—keeping record of ideas that are generated and categorizing them as appropriate
3. *Motivate*—encouraging group members to generate ideas and setting appropriate meaningful goals for idea generation
4. *Guide*—prompt members with potential productive areas for idea generation (e.g., analogies, example solutions, unused physical principles, underdeveloped ideas, etc.)

The function ***mediate*** is intended to improve idea generation productivity by keeping group members on task. Osborn proposed four rules for brainstorming to encourage productive idea generation: don't criticize, quantity is wanted, combine and improve suggested ideas, and say all ideas that come to mind [1]. These rules have been adapted by practicing designers in different forms [4] and are still in use today. These rules such as "don't criticize" and "say all ideas that come to mind" are aimed at reducing evaluation apprehension, which can reduce productivity in group brainstorming [6]. Having the facilitator encourage group members to follow these rules, helps protect the group idea generation environment for free-flowing ideas. At IDEO, a global design firm, facilitators for group idea generation "playfully enforce" their version of the brainstorming rules, which are still largely similar to Osborn's original suggestion [4].

The function ***organize*** is intended to improve idea generation through the cataloging and sorting of ideas. This serves the group by documenting ideas to free up mental workload, displaying the ideas to stimulate further creation, and organizing ideas to help structure the problem/solution space. Organizing the ideas into groups, webs, or hierarchies is a common strategy to improve idea generation. First introduced by Tony Buzan, mind mapping is a tool to quickly organize thoughts using a graphical representation [19]. Research on the use of mind mapping during brainstorming has shown that it can reduce the cognitive load associated with organization and retrieval of knowledge [20]. Lin and Faste argue for the development of digital mind mapping tools to enhance facilitated collaboration [21], and some work has begun on this endeavor [22]. Based on this research, mind mapping was selected for the study presented in this paper as the primary organizational tool used by the trained facilitator to capture participants' ideas during the brainstorming activity.

The function ***motivate*** is intended to encourage group members towards productivity. Motivation can be accomplished through a variety of methods. The concept of goal setting as a powerful mechanism in motivating productivity in different tasks has been well noted for over 50 years [23]. In particular, difficult and specific goals are more effective at increasing productivity than easy or vague goals [23]. Goal setting improves productivity through four main mechanisms: increasing effort, increasing persistence in the task to achieve the goal, increased focus on goal relevant actions over irrelevant actions, and improving individuals' task related knowledge recall [24]. The effectiveness of goal setting is dependent upon providing feedback [24]. The need for feedback emphasizes the importance of the organize role of the facilitator, as this can be a tool through which to track a groups progress. Motivation and goal setting provide a powerful opportunity for the facilitator to impact idea generating groups. By setting specific difficult goals, designers will be more likely to persist and focus on the task of generating ideas.

The function ***guide*** is intended to improve idea generation through prompting and providing inspiration when generation slows down. Providing suggestions is one of the roles that the group idea generation facilitators at IDEO engage in [4]. One kind of providing inspiration comes in the form of analogies, where familiarity with the example analogy has the greatest impact on design innovation [25]. Computational tools for design-by-analogy have been developed that give users power to explore design repositories [26] or conduct patent searches for analogical solutions to a design problem [27]. Wilson et al. found that exposure to far-analogies increased concept novelty while exposure to near-analogies decreased concept variety [28]. An idea generation facilitator can guide the brainstorming process by suggesting near or far design analogies without providing explicit solutions to the design problem. Analogical reasoning has even been shown to increase activity in regions of the brain associated with creativity [29]. If the primary goal of facilitation during idea generation is to increase innovation through broad solution space exploration, providing analogies as guidance for the brainstorming process is critical. Another form of guidance that is afforded by the mind mapping approach is the ability for the facilitator to prompt participants to expand from a particular node in the representation.

The framework presented here is largely a compilation of previous facilitation strategies intended to introduce a structure for all the activities of a facilitator in one place. This framework differs from the previous empirical analysis of facilitators by Oxley, Dzindolet, and Paulus [3] by introducing the organize and motivate categories. Oxley et al. did not explicitly document or organize ideas in any way. They also did not set goals for their groups. These two actions included in the present study could largely impact the productivity of facilitated idea generation.

Methods

The purpose of this study is to evaluate the impact of the proposed facilitator role on idea generating groups. We compared idea generation across three conditions: Facilitated groups, unfacilitated groups (or real groups), and individual participants. This allows us to compare participants generating ideas under the guidance of a facilitator with the two control conditions of unfacilitated groups and individuals completing the task by themselves. Groups and individuals generated ideas for the Peanut Sheller problem, which has been used in many idea generation tasks before. Participants are shown the following statement and customer needs along with a picture of peanuts.

> In places like Haiti and certain West African countries, peanuts are a significant crop. Most peanut farmers shell their peanuts by hand, an inefficient and labor-intensive process. The goal of this project is to design and build a low-cost, easy to manufacture peanut shelling machine that will increase the productivity of the African peanut farmers. The target throughput is approximately 50 kg (110 lbs.) per hour.
>
> Customer Needs:
>
> - Must remove the shell with minimal damage to the peanuts.
> - Electrical outlets are not available as a power source.
> - A large quantity of peanuts must be quickly shelled.
> - Low cost.
> - Easy to manufacture.

Participants are asked to generate as many solutions as they can for the problem. They are instructed to speak ideas aloud; the idea generation is recorded and transcribed. Participants were given two minutes to read and review the problem statement and then given 40 min to generate solutions to the problem.

Prior to beginning idea generation participants in all conditions were informed of brainstorming rules. The following brainstorming rules were written on a clearly visible whiteboard so they could be referenced throughout the idea generation.

1. Go for quantity
2. Defer judgement
3. Build on the ideas of others
4. Stay on topic
5. One conversation at a time.

The brainstorming rules were adapted from those of a global design company [30]. The rules are described to participants as guidelines to encourage creativity. Participants in the facilitated condition are also informed of the role of the facilitator after the brainstorming rules are explained and before being shown the problem statement. Participants in the individual condition do not have "others'" ideas to build off of, but this can be applied to building off of your own ideas as well.

The Role of the Facilitator

This study sets forth a new approach to the role of the facilitator. The framework for this approach has been described previously. For this preliminary study, the facilitator completed the following specific tasks related to each category.

1. *Mediate*—the facilitator will remind group members of the brainstorming rules when they are broken.
2. *Organize*—the facilitator will create a mind map of the participants ideas as they generate them.
3. *Motivate*—the facilitator will set a difficult specific goal for the number of ideas to generate during the session (a goal of 100 ideas was set). The facilitator will also set incremental goals to strive for by particular times during the session.
4. *Guide*—The facilitator will direct the group to specific categories of the mind map to help focus ideation, and the facilitator will set goals for number of ideas within those categories.

In this study, the facilitation is conducted by a graduate student in mechanical engineering. The same facilitator was used for all facilitated groups. The student practiced facilitation in one session prior to the commencement of the experiment and received feedback from peers to improve facilitation technique.

Participants

Participants for this study were recruited through word of mouth and announcements made in a lower-level undergraduate engineering course. Participants were asked to fill out an online survey indicating their availability to participate in the one-hour group idea generation activity. We then followed up with the participants over email scheduling five students per experiment session. The group idea generation task was completed in groups of four. The fifth student was assigned to the individual condition as a control.

Twenty students in total participated in the idea generation study. Eight students were in the facilitated idea generation condition (2 groups of 4), 8 students were in the unfacilitated, control condition (2 groups of 4), and four students completed the task individually, speaking ideas out loud. Of those students, 12 were female and 8 were male. Participants were all enrolled as undergraduate engineering students majoring in mechanical, aerospace, biomedical, or civil engineering. Participants ranged in age from 18 to 24.

Experiment Design

The independent variable for this experiment was idea generating group—participants were assigned to a facilitated group, an unfacilitated group, or to completing the task individually. The dependent variables are the ideation effectiveness metrics [15] and the post-task questionnaire evaluating workload and participants' perceptions of the task. We will explore the effects of the facilitator on all of these measures.

Ideation Effectiveness Metrics

The ideation effectiveness metrics were proposed by Shah et al. in 2003 as a method to evaluate how well idea generation explores and expands the solution space [15]. The four metrics are *quantity*, *variety*, *novelty*, and *quality*. For this study we will examine the first three—quantity, variety, and novelty. Evaluating quality was outside the scope of this preliminary analysis.

Quantity is a measure of the nonredundant ideas generated by the group. For the peanut sheller problem, ideas are counted as components to fulfill unique functions as defined by the functional basis [16, 31]. For example, using foot pedals as power generation for the system would count as one component. If the group recommended using foot pedals to power a different solution this would not be counted again. To evaluate quantity, the recording for each idea generation session was transcribed. A graduate student in mechanical engineering then coded non-redundant concepts in the transcripts using NVivo. The concepts were categorized into separate nodes and repeating concepts were sorted with previous nodes, so that each unique concept would only be counted once. The graduate student rater and a second mechanical engineering graduate student recoded a portion of the data (approximately 8%) to check IRR. The two raters showed 82% agreement identifying unique and repeated ideas in the transcript.

Variety is a measure of the breadth of solution space covered by the ideas generated by the group. For this problem, we have developed a list of bins that describe the broad method of the proposed solution. Example bins are *cylindrical rollers*, *burn shells*, or *tumblers*. There are just over 40 bins in total. The more bins utilized by participants ideas the larger the variety score. This shows they have explored more of the solution space, which suggests more effective idea generation.

Novelty is a measure of how unique or unexpected the ideas in a set are. Novelty is calculated as a relative infrequency. Each idea receives a novelty score based on the bin that it falls in. The more ideas (of all ideas generated in the study) in a bin, the more frequent that bin is used, and therefore the less novel. After novelty is calculated for each idea, the groups average novelty is calculated as their novelty score.

The three measures used in this study describe unique aspects of idea generation effectiveness. Therefore, they will not be combined, but each one analyzed independently across the facilitator condition.

Questionnaire

The post-task questionnaire seeks to evaluate the workload experienced by participants as well as their perception of other aspects of the idea generation task (e.g., satisfaction with the results, enjoyment). The questionnaire was administered using the Qualtrics survey platform. Users were given a modified NASA-TLX Workload Assessment [32, 33] that uses a 8-point scale with 0 being Very Low and 7 being Very High. In addition to this, we asked three questions regarding the user's perception of the idea generation task to further enhance our ability to answer this research question. These were rated on a 7-point scale. All survey items are listed below.

1. How mentally demanding was the task? (Mental Demand)
2. How physically demanding was the task? (Physical Demand)
3. How hurried or rushed was the pace of the task? (Temporal Demand)
4. How successful were you in accomplishing what you were asked to do? (Performance)
5. How hard did you have to work to accomplish your level of performance? (Effort)
6. How insecure, discourage, irritated, stressed, and annoyed were you? (Frustration)
7. How satisfied are you with the ideas your team generated?
8. How satisfied are you with the ideas you generated?
9. Indicate how much you agree with the following statement: "I enjoyed the given task."

These questions will provide insight into the differences in participants perceptions of facilitated and unfacilitated groups. Participants will also be asked general demographic questions to examine if these factors predict any of the changes in their perceptions.

Results

This section first presents the results of the ideation effectiveness metrics followed by the results of the questionnaire. Participants in the individual condition were excluded from the ideation effectiveness metrics due to small sample size and difficulty with getting individuals to speak ideas aloud when generating ideas in isolation.

Ideation Effectiveness

Idea generation effectiveness was measured using three metrics—quantity, variety, and novelty as described in the methods section. The performance of the facilitated idea generating condition was compared to that of the unfacilitated condition on all three measures.

The quantity metric is a count of the number of unique ideas generated by each group. Therefore, we assumed that these data followed a Poisson distribution, which is typical for count data. The quantity scores of the two groups were compared using a Poisson test, a statistical test comparing means assuming a Poisson distribution. The mean number of ideas generated by the facilitated and unfacilitated groups are shown in Table 1. There was a significant difference between the two groups, $p < 0.05$. Figure 1 shows the comparison of the two groups.

Variety and novelty were analyzed using a t-test for independent samples. The means for variety and novelty for the two groups are also displayed in Table 1. There was not a significant difference between the two groups for either metric. For variety, $t = -0.14$, $p = 0.90$. For novelty, $t = 0.33$, $p = 0.77$.

Table 1 Mean Ideation Effectiveness Scores by Group

Mean Ideation Effectiveness Scores		
	Facilitated	Unfacilitated
Quantity	86.5	67
Variety	0.60	0.61
Novelty	0.95	0.95

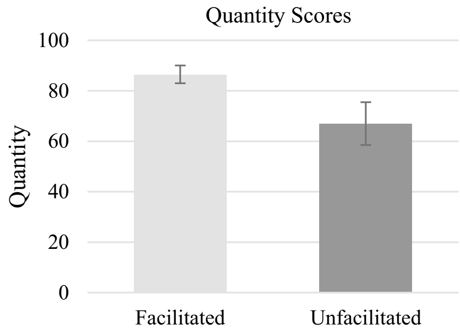


Fig. 1 Average Quantity by Condition

Survey Data

We utilize a post-task questionnaire to answer the second research sub question: *how does facilitation effect group members' perceptions of idea generation?*

NASA-TLX Workload Assessment

The averages for each group are shown for each item of the workload assessment in Fig. 2. We analyzed the comparison between groups for each item of the assessment using a one-way ANOVA with Tukey HSD post hoc tests where appropriate. Using a one-way ANOVA, we assume our data is normally distributed and verified this graphically through Q-Q plots of the data. Of the 6 items, 2 showed a significant difference between the groups—*temporal demand* ($F = 6.04$, $p = 0.010$), and *performance* ($F = 16.37$, $p < 0.001$). The temporal demand question asked participants how hurried or rushed the pace of the task was. The post hoc tests showed that the facilitated group reported significantly higher than the unfacilitated group. The performance question asked participants how successful they were in accomplishing what they were supposed to do. Post hoc tests showed that the facilitated group reported significantly higher for this measure than both the unfacilitated group and the individuals.

The total scores for the workload assessment were also calculated for each group by summing all items. These scores are shown in Fig. 3. Group performance on the total workload measure was also analyzed using an ANOVA with Tuckey HSD post hoc tests. We found a significant difference between groups ($F = 4.60$, $p = 0.025$). Post hoc tests showed that facilitated group members reported significantly higher overall workload than unfacilitated group members.

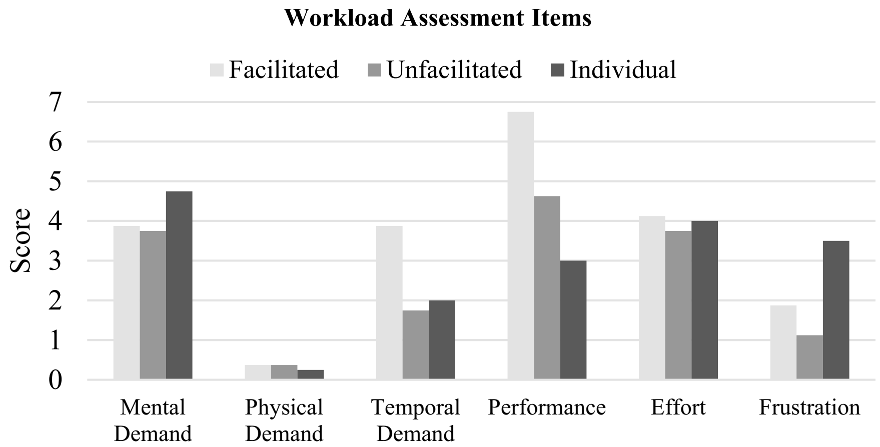
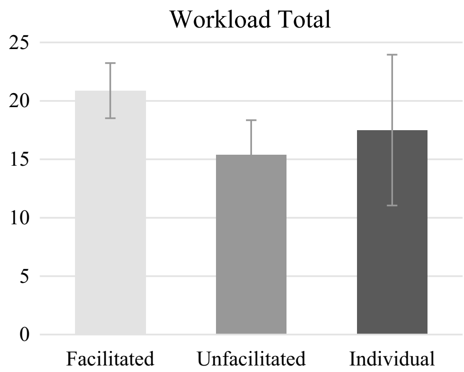


Fig. 2 A plot of the average rating for responses from the three tested groups (Facilitated, Individual, and Unfacilitated)

Fig. 3 The overall workload reported



Survey Questions

In addition to the NASA-TLX workload assessment, we asked three other post-task survey questions. These questions provide us with insight on how facilitation impacted the idea generation process. We asked about participants satisfaction with the ideas they generated and their enjoyment of the task they completed. We analyzed each of these questions using a Kruskal Wallis H Test for analyzing ordinal level data.

Figure 4 shows the distribution of responses to Q1. Users were able to answer from 7 different responses ranging from "Extremely Satisfied" to "Extremely Dissatisfied". This question related only to the two group conditions, facilitated and unfacilitated, because it asked about satisfaction with the ideas the group produced. We found a significant difference between groups on this question. Facilitated groups

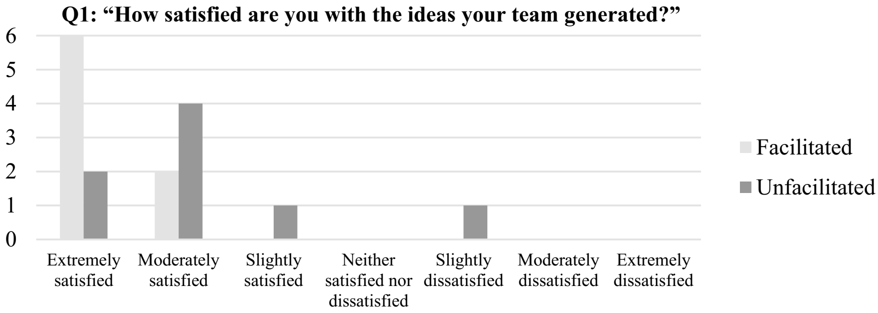


Fig. 4 Distribution of responses to Q1 by group

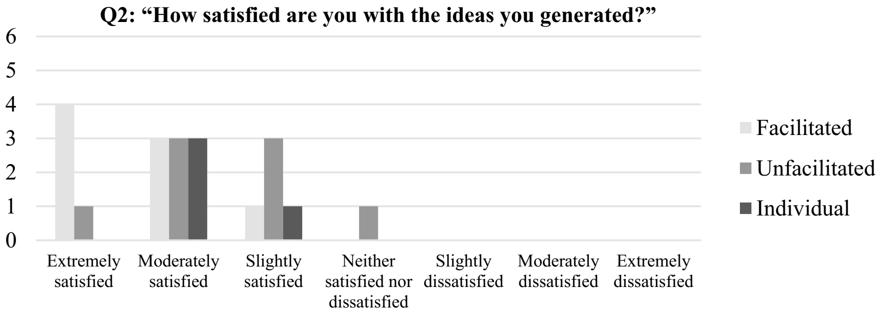


Fig. 5 Distribution of responses to Q2 by group

reported significantly higher satisfaction with the ideas their teams generated than the unfacilitated group, $H = 4.36$, $p = 0.037$

Figure 5 shows the distribution of responses to Q2. This question addressed participants satisfaction with the ideas they personally generated. We found no significant difference between groups on this item, $H = 4.36$, $p = 0.113$.

Figure 6 shows the distribution of responses to Q3. Users were able to answer from 7 different responses ranging from "Strongly Agree" to "Strongly Disagree". We found no significant difference between the three groups for this question either, $H = 0.218$, $p = 0.897$.

Discussion

In this paper, we ask the question, *how does facilitation affect idea generation for engineering design problems?* This overarching question is comprised of two sub-questions: (*a) How does facilitation influence the effectiveness of idea generation? (b) How does facilitation effect group members' perceptions of idea generation?* The first question we analyzed by comparing ideation effectiveness scores of facilitated

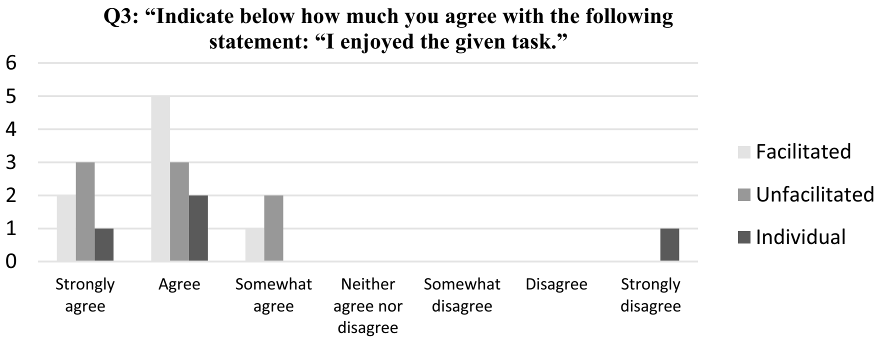


Fig. 6 Distribution of responses to Q3 by group

and unfacilitated idea generating groups. The second question we analyzed through a post-task questionnaire evaluating the groups and individuals' perceptions of their perceived workload, satisfaction, and enjoyment of the task.

We examined three ideation effectiveness metrics: Quantity, variety, and novelty. For both variety and novelty, the facilitated and unfacilitated groups scored almost identically on these measures. This could be in part due to the measurement technique. The bin scoring method is effective at producing rudimentary evaluations but may not pick up on minute differences. Quantity, however, showed a significant difference between the two groups. The facilitated groups generated more ideas on average than the unfacilitated groups, 87 and 67, respectively. This shows that facilitators may help groups generate more ideas than they would operating on their own. This increased efficiency could be largely due to any of the facilitation categories. Future work will explore which facilitator actions from the framework have the largest impact on idea generation.

The workload assessment indicated that members of facilitated groups perceived a higher overall workload than members of unfacilitated groups. This higher perceived workload coupled with the increase productivity indicates that while facilitation can help the idea generation process, individuals may find the process more mentally demanding or taxing than normal idea generation sessions. Specifically, we observed that facilitated groups felt a higher temporal demand than unfacilitated groups; they reported the pace of the task was more hurried or rushed. This could likely be due to the facilitator's goal setting constantly encouraging them to reach a lofty goal.

From the survey questions, we see a relation between facilitation and satisfaction with idea generation. Participants who performed in facilitated sessions reported a higher score for satisfaction of ideas generated when compared to unfacilitated groups. These preliminary results may indicate a larger trend given a more substantial sample size that can be explored further. Given these results, we find that while users find facilitated group idea sessions more workload intensive, they are more satisfied with the ideas they generated than those who are in unfacilitated idea generation sessions.

These results suggest that facilitators help groups to generate more ideas, have a higher satisfaction with the ideas they generate, and perceive a higher temporal demand and overall workload than unfacilitated groups. These three findings suggest that facilitators may enable participants to better apply themselves to the task of brainstorming. The facilitator seems to have a significant positive effect on the brainstorming task. Facilitators can be incorporated in practice with very little training. Future work will narrow down which aspects of the facilitator role are most impactful, so those can be prioritized in practice.

Limitations

The results presented in this paper are preliminary data to explore the effectiveness of the new approach of the facilitator. The small sample size drastically limits the statistical power of the study. These initial findings do suggest further exploration of the role of the facilitator would be productive. Another limitation of the study is that facilitation was done by a single trained facilitator implementing the new proposed approach. There are opportunities to expand findings by training other facilitators to validate the work.

In future work, collection and analysis of audio transcripts from the idea generation sessions provide an opportunity to explore how well the facilitator adheres to the facilitation guidelines. Through qualitative analysis, it could be determined how each of the four main describes factors (mediate, organize, motivate, guide) specifically impact the generation of ideas. For example, guide may more heavily impact the generation of novel concepts whereas motivate may lead to increased quantity of ideas. This work is planned as an expansion of the preliminary findings presented in this paper.

Conclusion

This paper explores a new approach and framework to facilitated idea generation and implements this in a group idea generation setting to determine its effectiveness. We found that facilitators increased the effectiveness of idea generating groups. The facilitated groups were more satisfied with the ideas they had generated, and the facilitated groups, felt that the idea generation task was more temporally demanding than unfacilitated groups. From these data, we conclude that the facilitator had an overall positive impact on idea generation in groups. However, these results are only preliminary because of the small sample size and more work should be done to further explore this idea generation intervention.

Future work will expand the sample size of this experiment to verify its results. We would also like to utilize a facilitator on different design problems to improve the external validity of these results. Future work will leverage the theoretical framework to explore specifically which aspects of facilitation are most influential on group performance through a factorial analysis leveraging the structure proposed in this paper.

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The Impact of Procedural Knowledge Retrieval on the Architectural Design Process in Parametric Design Environments

Thomas Dissaux and Sylvie Jancart

Given the rapid evolution of software, expertise has become increasingly transient forcing architects to keep learning after they have left educational institutions. Furthermore, complex tools such as parametric design environments (PDEs) are getting more popular. To mitigate the lack of expertise, architects can rely on information search systems. Even though, interactive information retrieval (IIR) has a rich literature, it is rarely addressed in architecture. This paper addresses knowledge retrieval and how it impacts the architectural design process in PDEs. Building on previous work on knowledge types in teaching parametric design, this article aims to bridge theory on IIR and searching as learning with architectural design through the Function Behavior Structure ontology. Data was collected through a long-term mixed approach of questionnaires and interviews during an elective course in computational design for graduate architecture students. Contrary to teaching, results show self-learning to rely mostly on procedural information which affects reformulation processes.

Introduction

Due to the rapid evolution of software, computational skills have become increasingly transient. Architects are put into a situation where they constantly must re-learn to master their tools, potentially during the design process. In order to address that situation, they rely on external information. Its rise in quantity, freedom of access and production has transformed human relationships with tools. Parametric design,

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which has become increasingly popular in architecture, is a prime example. The shift to process-based thinking where architects need to model functions and define relationships through parameters and functions brings a new kind of complexity [1]. Consequently, new tools such as visual programming interfaces have become unfamiliar and relying on external information turns into a necessity during practice. However, there is a lack of research in architecture and parametric design regarding information retrieval.

The paper presented addresses this empirical gap by proposing a theoretical base connecting interactive information retrieval and searching as learning to the function behavior structure (FBS) ontology. Novice designers were asked to complete 3 design tasks over multiple sessions and to report on their autonomous information search activity. A mixed approach combining questionnaires and semi-structured interviews was used to capture and discuss the data. Retrieval strategies are identified and finally their impact on the design process is discussed as well as perspectives fur further developments.

Background/Motivation

Parametric Design Environments

Parametric design in architecture describes a procedural process based on defined parameters that allows for automation and exploration. The designing takes place through a series of procedures translated into functions or components. It deals with form finding as well as managing all the metadata.

Visual programming tools like grasshopper have taken over as textual programming is quite unpopular among architects [2]. Visual programming is particularly interesting as complex forms can be described through a sequence of simple steps without the need for syntax. A specific geometry can therefore be captured through a series of components and relationships, then transcribed with other parameters to get variants of the original design (see Fig. 1). Those tools will be referred to as parametric design environments (PDEs). In terms of visual reasoning, information can potentially be as straightforward as a recipe compared to a more inspirational approach. Mental workload can therefore be reduced on both the tool and the design sides.

However, to go from a traditional representation tool to parametric design, architects need to translate the thought process into an algorithm. According to Woodbury, that kind of computational thinking requires new knowledge [3]. So, although working with PDEs can be seen as an epistemic action towards simplifying complexity, the tool itself is responsible for additional mental load leading to new cognitive investments and behaviors, themselves leading to other epistemic actions such as information retrieval during the design.

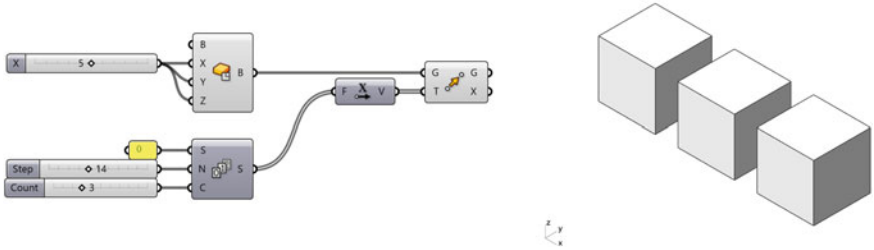


Fig. 1 Example of a visual script on Grasshopper, a popular visual scripting software

Function Behavior Structure Ontology

The function behavior structure (FBS) ontology [4] is a framework used to capture the design process and is one of the few popular cognitive models used in design and architecture.

In the original model, Gero defines 6 design issues: requirements, function, expected behavior, structural behavior, structure and documentation. Function (F) describes the designer's intentions, expected behavior (Be) is what is expected of the structure (S) and structural behavior (Bs) is the actual behavior of the structure put in place. Requirements (R) and documentation (D) are external issues triggering and ending a design episode. To transition from one issue to the other, Gero describes 8 cognitive processes: Formulation, synthesis, analysis, evaluation, documentation, and reformulation I (R1), II (R2) and III (R3). The 6 design issues and the 8 cognitive processes are presented in Fig. 2. According to Kan and Gero [5] reformulation processes are essential for innovation and creativity as they introduce new variables and/or directions.

Reformulation processes can be seen as follows. R1 is the reformulation of the structure within a defined design landscape and can be translated into an exploration through a given set of parameters. According to Erhan and colleagues [6] there is a risk of getting stuck into that process due to the sheer number of possibilities. R2 translates into the manipulation and addition of functions and their connections. The algorithm is modified and so is the expected behavior but always in line with the initial function. It triggers synthesis and possibly analysis and evaluation but can also induce subsequent R1s. In R3, the designer goes back to defining the problem space [7]. In addition to the formulation process, it might trigger the same processes as R2 and potentially other R2s and R1s. Formulation is determinant in PDEs. By setting up the algorithm or the necessary syntax to achieve the function, one formulates the boundaries of the design, or solution space. Eventually, exploring possible formulations leads to the selection of specific design spaces over others.

The FBS model has seen multiple improvements over the years as well as several superscripts' developments such as Yu and colleagues [8] which is concerned with PDEs. They distinguish 2 levels of design activities: The rule algorithm level and the design knowledge level. That study has provided a strong development basis for

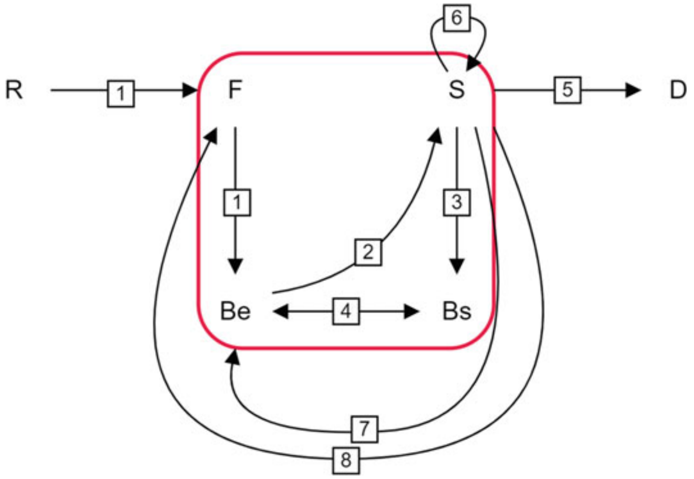


Fig. 2 FBS ontology based on the original model [4]. 1 = Formulation; 2 = Synthesis; 3 = Analysis; 4 = Evaluation; 5 = Documentation; 6 = Reformulation I (R1); 7 = Reformulation II (R2); 8 = Reformulation III (R3)

this research as it raised questions regarding the time constraints imposed by short protocols and consequently the lack of information retrieval possibilities. The FBS model informs on design cognitive pathways, but information retrieval has never to our knowledge been part of a study.

Therefore, this general model of design cognition seems like a strong basis. Given the very few papers specific to architecture, the model would enable to compare results with other design fields which is invaluable. Furthermore, the flexible nature of the model could potentially allow for a superscript taking information retrieval into account. Finally, using the FBS framework on PDE complements a growing basis of research for further development and discussion [8–11].

Knowledge in Interactive Information Retrieval

Interactive Information retrieval (IIR) is part of Human Computer Interaction (HCI) research and is concerned with the interaction between humans and information retrieval systems. Although we can trace back its history to more than 50 years, the term IIR only appeared in the 90 s with the advent of computational tools [12]. It revolves around the definition of information search tasks, but attention has been given to cognitive load and working memory because of the mental effort required to interact with search systems. There are many approaches to IIR, the one we are interested in is the characterization according to difficulty and complexity [13]. For this research we focus on Jansen's approach to searching as a learning (SAL) process that uses Krathwohl & Anderson (A&K) taxonomy of educational objectives to identify searchers' needs [14].

SAL is defined by the sense-making paradigm in IIR [15]. The term knowledge refers to information that is accessed via a storage medium and internalized. So, learning occurs in the searching process [16] and is conceptualized as a restructuring of one's knowledge. Consequently, accessing more information helps the stabilization process. Gero [4] describes designing as a goal-oriented constrained decision-making, exploration and learning activity. The learning aspect defined by Gero refers to the emergence of features in the design process. Because of the dynamic relationship designers have with retrieval systems, or more generally the Internet, emergence can also occur when searching for information.

The A&K taxonomy is a revision of Bloom's cognitive learning framework [17] and is widely used in pedagogy and learning design. It defines learning objectives through a 2-dimensional classification: The cognitive process and the knowledge type.

Cognitive processes are defined from least to most complex: remember, understand, apply, analyze, evaluate, and create. To each category correspond specific cognitive processes. For example, the "remember" category encompasses recognizing and recalling as specific cognitive processes. Based on A&K's revision, a design task would fall under "producing" within the "create" category. The latter is defined as "putting elements together to form a coherent or functional whole; reorganize elements into a pattern or structure". The "create" task is particular because it might require the learner to integrate the other cognitive processes [17]. As it corresponds well to the design task, this study naturally focuses on the "create" task.

Knowledge dimension is described through 4 types: Factual knowledge, procedural knowledge, conceptual knowledge, and metacognitive knowledge. Factual knowledge consists of the basic aspects a learner must know to be acquainted with one discipline. Procedural knowledge consists of methods on how to do something, and criteria for using skills. Conceptual knowledge is the ability to bring basic elements within a larger structure that enables them to function together. Finally, metacognitive knowledge is the awareness and knowledge of one's own cognition. Regarding the second dimension, few studies have been carried out [18] and none of them concerned with either design or architecture. For this paper, metacognitive knowledge will not be considered.

In a recent article, Vrouwe and colleagues [19] have conducted systematic research on "new knowledge" in parametric design and have described it as A&K's conceptual knowledge. That "new knowledge" is similar to what Yu and colleagues [8] describe as "rule algorithm level", which itself is based on Woodbury's definition of knowledge needs for computational thinking in PDEs [3]. Vrouwe and colleagues [19] have shown the consensus on the need for new knowledge and therefore identify conceptual knowledge as a learning objective for parametric design education. However there has not been any research on knowledge retrieval strategies adopted by architects or students while designing.

Urgo and colleagues [18] have recently reported conceptual knowledge retrieval task to be more prone to abandonment, to take a long time, to lead to less satisfactory results and to be perceived as more difficult than procedure-oriented knowledge retrieval tasks. Those results have yet to be applied in the architectural design field and in PDEs in particular. Empirical support from SAL in IIR tends to suggest that even though there is a consensus on conceptual knowledge to be the learning objective to aim for, the complexity of the design task might trigger other behaviors from autonomous learners.

Aims

The aim of this paper is to expose the information retrieval strategies of architecture students when dealing with PDEs and to explain how they affect the design process in the initial stages. The FBS ontology is used as a framework of reference for the definition of design. Our main hypothesis is that, given the complexity of parametric tools, novices will focus on procedural knowledge related to the tool, which will in turn guide subsequent design decisions by impacting design processes such as reformulation.

By adopting mental saving strategies, novices might be influenced by the information they consume to guide their design process. Eventually, this work should provide a basis for the refinement of the FBS model through the development of a potential superscript integrating IIR and SAL into the framework.

Significance

With the increasing transience of software, continuous self-learning through information retrieval has become common. In architecture, tools tend to be complex pieces of software, especially in PDEs which requires "new knowledge". This research is significant because it raises awareness concerning the impact of knowledge retrieval in the design process and is the first attempt at bridging IIR research with architectural design. The FBS ontology opens new perspectives for the development of a common framework to study that phenomenon. Given the quantity of information and the ease of access, raising awareness could be beneficial as there might be implications regarding the cognitive pathways used by architects to design and indirectly the final product. Therefore, the results of this study might prove useful for the architectural community dealing with new and complex tools, education, as well as provide foundation for further research.

Method

An elective class on computational design for graduate architecture students has been chosen. During one semester, students were given 3 design assignments, one every other week. The first assignment consisted in building a pedestrian bridge, the second assignment was to build a series of pavilions and for the last assignment, students were asked to design a multi-purpose high rise. They received basic constraints for each task, either related to the context or the function. Students worked in groups of 2 or 3 students. Eighteen students participated in the course, 17 of whom were surveyed as one was an exchange student and was not acquainted with the class language (French). The course was given on site at the faculty of architecture in accordance with the sanitary rules at that time.

The sample consisted of students with no experience in Grasshopper or PDEs in general. Given the elective status of the course, motivation levels were assumed to be similar across all students. During the in-class sessions, students were able to ask questions to the teacher/assistant, the student monitors, or the other students. There were 2 student monitors selected for their reliable knowledge of the parametric software used (Grasshopper) and they were asked not to intervene unless asked to do so by the students. The student monitors were also asked to keep an online conversation open in case students had issues outside of class.

A mixed approach was used to conduct this research. First, students were given 2 weekly pre/post task questionnaires. Then, based on the results, semi-structured individual interviews were conducted at the end of the semester.

Pre-task questionnaires were submitted right after the students received their assignments. The post-task questionnaires were submitted at the beginning of each session to reflect on the past working week. We collected a total of 3 pre-task questionnaires and 6 post-task questionnaires for both difficulty/knowledge and information sources. Students were given the questionnaires one week prior to the study on a sample assignment to get them acquainted with the format as well as the notion of knowledge type.

For pedagogical reasons, students were given theoretical sessions and hands-on exercises that were kept separated outside the scope of the 3 assignments (see Table 1). A typical lesson would last 4 h and be held as follows: First there was a presentation of each group work with feedback, then a theory session and the related hands-on practice task, finally the last 60 min were dedicated to the assignment. The collection of data started in week 2 as the first week was meant to get the participants familiar with the process. Week 5 was a holiday, which means that for the second assignment they had an additional week before the intermediary review. A global overview of the process can be seen in Table 1. All participants signed a use agreement regarding the use of the data collected.

The first pre/post task questionnaire followed a typical structure of pre/post task research in IIR. The goal was to collect quantitative information on the sources and the type of knowledge students would retrieve to complete their assignments.

Table 1 Semester course agenda

Week#	Course			Task#
1	Students ‘presentation	Theory	Hands-on exercises	Introductory task
2				Task 1
3				Task 1
4				Task 2
5				–
6				Task 2
7				Task 3
8				Task 3
9				–

In both questionnaires, a Likert scale was used to go from *not at all* (1) to *very much so* (5). The pre-task questionnaire consisted of 6 questions meant to measure perceived difficulty (2 questions), perceived need for factual knowledge (1 question), perceived need for procedural knowledge (1 question), perceived need for conceptual knowledge (1 question) and motivation (1 question). The post-task questionnaire was identical except for one additional question on the satisfaction level. For this paper, however, only the first 5 questions, which concerned difficulty and knowledge type, are considered. Those questions can be found in Table 2.

Table 2 Questions asked in the pre/post questionnaires right after students received the assignments, and after one and two weeks of working

Q#	Interest	Pre-task questionnaire	Post-task questionnaire
Q1	Task Difficulty	How difficult do you expect the task to be?	How difficult was it?
Q2	Tool Difficulty	How more difficult will the tool render the task?	How difficult did the tool render the task?
Q3	Factual Knowledge	How inclined are you to look for factual knowledge?	What is the effort put into searching for factual knowledge?
Q4	Procedural Knowledge	How inclined are you to look for procedural knowledge?	What is the effort put into searching for procedural knowledge?
Q5	Conceptual Knowledge	How inclined are you to look for conceptual knowledge?	What is the effort put into searching for conceptual knowledge?
Q6	Motivation	How motivated are you?	How motivated are you to continue?
Q7	Satisfaction	/	How satisfied are you with the results?

The second pre-post task questionnaire was introduced to students to collect data on information sources. Through multiple choice, participants were asked to choose what sources they were planning to use (pre-task questionnaire) and what sources they actually used (post-task questionnaire). The choices available were course material; assistant; monitor students; group members; videos; blogs and other sites; forums; and other. If they picked the last choice, they were able to specify other sources manually. Course material is represented by the theory given in class as well as the support for hands-on exercises. Although the material is indicative of the type of knowledge they retrieved, nuances had to be discovered through further investigations.

The second approach consisted of semi-structured retrospective interviews that used a mix of deductive and inductive coding. Codes from the first questionnaire were used as the premise for the structured part of the interview. The rest of the conversation served as inductive material to foster for emergence of unexpected data for later improvements of the method.

Fifteen out of the 17 students were interviewed individually for 20 to 30 min. The questions were based on questionnaire results and aimed to nuance the results as well as identify opportunities for future research. Finally, they provided the necessary information to translate research behaviors into the FBS ontology. Each interview was recorded via a two-way microphone and was held the week following their last course.

Results

This section is divided in 3 subsections: Questionnaire results, interviews results and the FBS interpretation. Difficulty of the task is presented first, followed by the type of knowledge. Sources are presented afterwards to build on previous results. Interviews are then discussed I regards to questionnaires. Finally, knowledge retrieval strategies are outlined and discussed in terms of FBS.

Questionnaires

Regarding difficulty (see Fig. 3), the results of the first questionnaires show how working with PDEs (Q2) can be perceived as difficult compared to the design task itself (Q1). This result is expected and can serve as a manipulation check. Indeed, it confirms that design tasks are in the higher spectrum of complexity, as defined by A&K's revision of Bloom's taxonomy. Like "create task", design problems are ill-defined and the most complex ones [20].

Concerning knowledge types (Q3, Q4, Q5), the results in Fig. 4 show a smaller investment into conceptual knowledge (Q5) than factual (Q3) and procedural knowledge (Q4), which is in line with our hypothesis. Furthermore, there is a tendency to overestimate the investment into conceptual knowledge retrieval. Those results

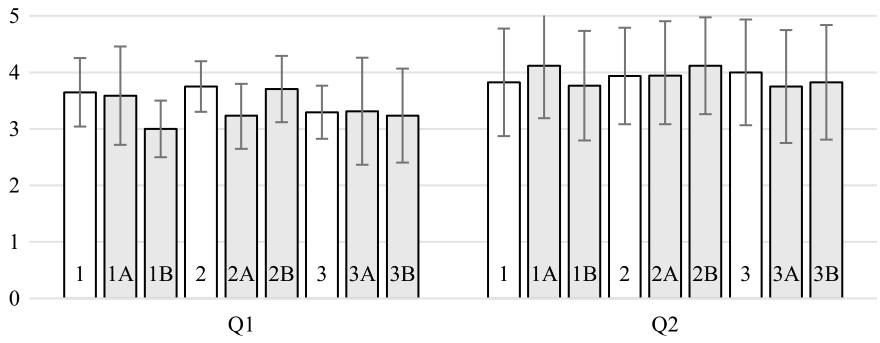


Fig. 3 Mean results for Q1 and Q2 for each step of each task

concur with research indicating that conceptual knowledge is more prone to lead to abandonment [18]. There is little difference between the investment in factual and procedural knowledge.

Results of the second pre/post questionnaires on sources are presented in Fig. 5. The first remark is that none of the participants picked the "other" option. The categories might either be sufficient or not detailed enough. During past semesters, books were sometimes used by students. This semester no one mentioned them even though they had a full library with a computational section at their disposal.

Video is clearly the preferred information source. If considered a source of procedural information, this is not consistent with the questionnaire results regarding the same investment into factual and procedural knowledge. Almost all students at every stage of every assignment used videos as source of information or had the intention to do so.

Student monitors were the second choice as a source of information. During the first week students did not rely too much on monitors, but the second week showed dependence. This tallies with former studies [21, 22] which concluded that the rise of complexity in a task tends to trigger people to rely more on people as source

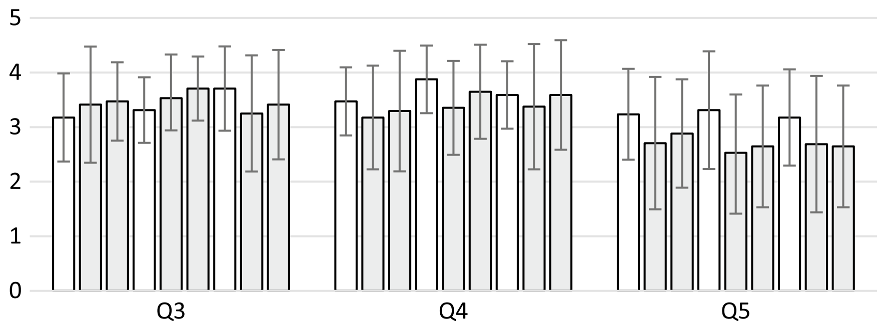


Fig. 4 Mean results for Q3, Q4, and Q5 for each step of each task

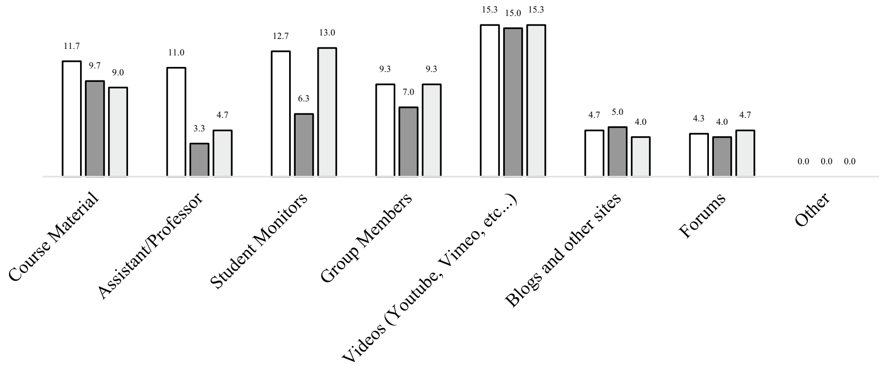


Fig. 5 Mean result for each step of the 3 tasks

of information. Although complexity does not increase throughout the assignments, students get eventually stuck, and complexity arises according to temporal pressure [22]. Another explanation is that formulating questions is not always easy and it might require some time before being comfortable enough with the material [16]. Finally, being stretched over a two-week period, students would rather try on their own during the first week before asking for help. Since monitors were available face to face during the course, students were able to explain their issues through sketching, gesture and talking while the rest of the week, they had to explain through written words and screenshots on the chat.

Course material was the third preferred source even though actual use dropped below group members after the first assignment. Given the lack of experience, it is not surprising that students rely on the little they know and get more autonomous as the course goes. However, those results do not convey the idea of autonomy as much as wanted for this research, but they are a good indicator for improvements in further developments.

Higher results regarding group members were expected as all students were all novices and working in groups would foster reliance on each other.

Assistants and professors were the last significant sources of information. Although expected use was quite high, actual use at the intermediate phase has the lowest average and the second lowest average for the second phase. Compared to monitors, the teachers were not in contact via chat during the week. Second, there might be potential fear of exposing weaknesses due to the fact that in this university context, students will eventually get graded for their work.

Finally blogs and forums were not used very much. As suspected, it is difficult to navigate those sources of information without prior knowledge.

All those observations served the structuring of the following interviews.

Additional Data from the Interview

Regarding difficulty (Q1, Q2), students expressed their effort towards the tools to be the center of their attention. At no point did any student mentioned difficulty concerning the design task. All groups referred to a similar strategy regarding their design process. First, they would generate ideas, and then they would look for adequate information to implement them in PDEs. Difficulty emerges first when translating an initial idea into a visual script. Students do not possess the adequate tool knowledge to do so. Moreover, they lack the conceptual knowledge required to do precise searches. Although it might be safe to think that this aspect would decrease along the 3 tasks, all members of one particular group explicitly mentioned the shift towards a more flexible approach to adapt to the material they would find more easily. This was in response to the struggle they faced during the first 2 exercises as they were trying to avoid reaching for external knowledge.

Regarding conceptual knowledge (Q3), interviews reveal that conceptual knowledge is indeed put to the side as students must deal with the new tool. It mainly concerns the design aspect of the task. Retrieval happened through image search but also through videos. A few students reported looking for references that seem programmable, even putting "parametric" as a keyword. One participant reported acting like that to legitimate the use of PDEs. Images were also mentioned to serve as visual support for the initial ideas or as references for creating them. Furthermore, students reported filtering images based on estimated feasibility rather than contextual value. It might be argued that the filtering of those reference images was based on the visual reasoning capabilities and computational knowledge of each student. Finally, several students mentioned looking at numerous videos unrelated to the design task to expand their tool related knowledge. Some of them mentioned however that this behavior eventually led to unexpected ideation. Eventually, students built conceptual knowledge through procedural knowledge.

For factual knowledge (Q5), student monitors are the preferred source of information. During the interviews, students mentioned how they wanted to tackle the design challenge themselves before relying on external help. Another aspect was that interactions outside the class varied between students. Formulating questions to the monitors was sometimes seen as an effort mitigated with time spent on the problem, which is in line with Li and colleagues' results [22]. This also explains why other resources such as forums, blogs or even the teacher were not exploited that much. Surprisingly, students also reported looking for factual information through video tutorials. When asked about the reason why they would adopt such a time-consuming strategy, they responded once again that formulating the search terms was difficult whereas searching through larger contexts was easier. Moreover, it was mentioned that video platforms such as YouTube provided visual cues, related content, as well as automatic translation of the titles from English into French. Those interviews revealed student's lack of skills when it comes to web searching. This was the conclusion of Rieh and colleagues' paper [23] that noticed: The struggle to find the right keywords, unsatisfying results not meeting needs and the reluctance to put efforts. Rieh and colleagues also observed that students tend to overestimate their search skills and effort put into it. Although the questionnaire results show a tendency to put effort into factual knowledge, the interviews reveal that it is marginal due to the difficulty experienced. By looking at videos, it might be argued students are not even looking for factual knowledge but rather procedural knowledge as the information is highly contextualized.

In terms of procedural knowledge (Q4), interviews revealed videos to be the main type of source. When asked to describe their design process, all participants mentioned "YouTube" as either the stage following the first concept ideas or a base for ideation. Monitors were also used as procedural knowledge sources. Some participants reported relying on the student monitors for procedural knowledge even outside the classroom. Later investigations revealed they had could physically meet and therefore did not have to rely on the chat discussion for support. Course material was mentioned as a source of procedural knowledge too. All students referred to the same video material that was part of a previous class and could be found online. Compared to the questionnaire results, this is more in line with our assumption of autonomy. Surprisingly, 3 students reported looking for images of visual scripts. A reference that would have required visual reasoning in more traditional means was delivered as visual step by step information. Images were not part of information sources as we did not consider them to be relevant in retrieving tool-related knowledge. However, they should be investigated in the future.

Relying on other students depended on the group dynamic and whether they were working together, which allowed for a collective memory [24] and all three types of knowledge.

The interviews revealed videos to be the main source for all types of knowledge. Assistants were also considered as sources of all knowledge but the interactions appeared less dynamic as students had to wait and potentially get no answer. Also, it came at the end of the design process as deadlines approached. Images were seen as conceptual knowledge sources although the filtering happened in order to serve either internal knowledge or the induction of video queries. In general, factual knowledge and conceptual knowledge served the building of queries for procedural knowledge found in video searching platforms, most likely YouTube. That nuance was not observable in the questionnaire results. Images should also have been considered independently.

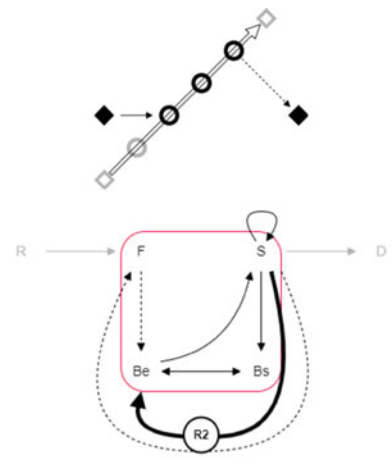
FBS Interpretation

With interviews data integrated, interpretation based on the FBS model is provided regarding the impact of procedural knowledge (Pk) on the design process. Students exposed 2 specific strategies regarding interaction with procedural information during their design process.

The first strategy consists of searching for Pk and integrating it into a larger conceptual knowledge scheme (see Fig. 6a, b). It can be time consuming and would potentially require considerable effort from the student [25]. Time constraint has been mentioned as schedules vastly varied between students. Two outcomes were observed. The first one integrates Pk to produce a structure without reconsidering formulation (see Fig. 6a). However, staying true to that initial formulation proved to be challenging and often forced students to rely on monitors. Finding adequate Pk required the retrieval from multiple sources. The more information was retrieved, the more conceptual knowledge grew as well as the ability to make queries for missing pieces of factual knowledge. However, time constraints limited retrieval. Synthesis of expected behaviors is therefore restricted to the retrieved knowledge. That would suggest an additional layer to Yu's superscript where a synthesis process (BeR > S) could be based either on external or internal knowledge. In terms of cognitive effort, Pk contains a free underlying synthesis process by providing the syntax for the algorithm. Analysis can also be free given the necessary information is supplied. Evaluation dictates whether the initial expected behavior is met or not and potentially leads to a subsequent R2 process. Therefore, the impact of displacement on the design process is mitigated by the amount of Pk retrieved. However, the lack of search effort after the initial formulation can lead to more displacement (see Fig. 6b). If the right information is given, Pk offers all the following processes for free: Formulation, synthesis and evaluation. Compared to R2 it also offers the formulation process for free. R3 can thus be triggered by the mental ease of Pk retrieval. Therefore, there could be an increase in the risk of displacement with the initial function.

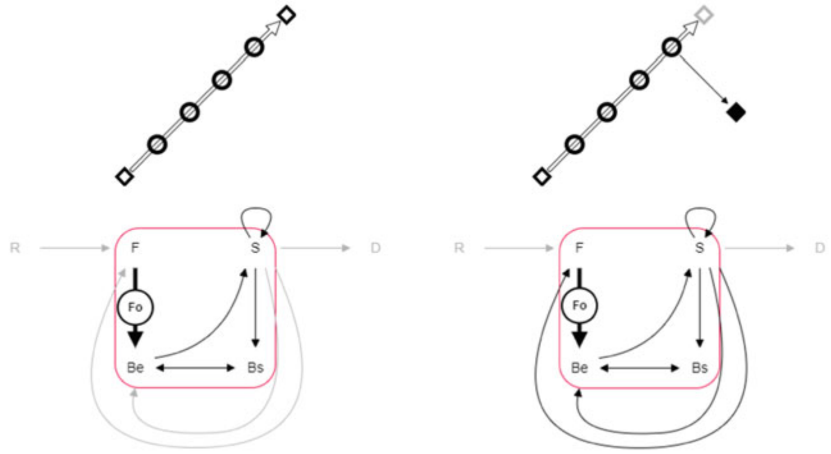
The second strategy relates to information-based ideation and affects the formulation process directly (see Fig. 6c, d). Ideation happens through the retrieved Pk without concerns for a more global conceptual knowledge to save effort and time. That Pk becomes a cognitive distribution device with the risk of architects falling into fixation and potential design displacement through what is called the worked example effect [26;27]. Even though there are advantages in education, the design of good, worked examples is challenging. Indeed, it requires the learner to put effort into integrating the knowledge rather than applying it directly as a completion problem (see Fig. 6c). This would shift the learning objective from "create" to "apply", which is described as a less complex task. Indeed, it is easier in terms of mental effort and therefore more prone to happen when saving mental load. Regarding FBS, this would translate into a cognitive free design process. Formulation as well as all subsequent processes would be integrated into the procedure and given the nature of PDEs, R1 would offer the possibility of design appropriation and thus the other reformulation processes wouldn't be considered. The other outcome would be to use Pk as a starting point and evolve from there either internally or using the first strategy of retrieval (see Fig. 6d). That behavior would be similar but would integrate further R2s and R3s. Either way, time constraint is the major factor for using the second strategy and would suggest integrating temporal pressure as a parameter in future studies.

Those strategies are not exclusive. There has been reconsideration across the different tasks but also during a single task. Taking the 1st strategy for example, the lack of information or experience in query can lead to mental overload and the adoption of strategy 2 without further reformulation. Moreover, flexible approaches to formulation have been mentioned to better accommodate the integration of retrieved



(a) Pk triggers R2. The initial function persists.

(b) Pk triggers R3. Function is influenced by the retrieved Pk



(c) Formulation and subsequent processes align with Pk

(d) Formulation aligns with Pk but reformulation 2 and 3 are still possible

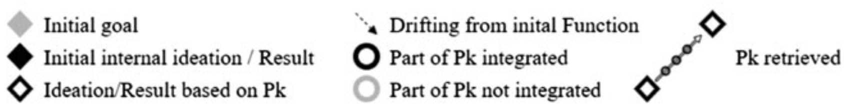


Fig. 6 Behaviors displayed in information retrieval strategy 1 (a, b) and retrieval strategy 2 (c, d)

Pk. This would indicate an initial loose formulation process to accommodate further R3. In that case only strategy one should be considered. Furthermore, retrieval can only happen if a query is made which would imply an initial formulation.

Conclusion and Further Research

Considering how fast software tools evolve and are created nowadays, architects are bound to rely on external information to keep up with their expertise. This phenomenon is accentuated in new complex computational tools such as parametric design environments. This paper proposes to integrate IIR and SAL into the FBS framework to study the impact of knowledge retrieval on the design process. To do so, we used a mixed approach using questionnaires and interviews to expose information retrieval strategies of graduate students in architecture. The participants had no previous experience with PDEs which fostered retrieval. The impact of procedural knowledge was of particular interest.

The paper shows that in a situation of autonomy, procedural knowledge is the preferred type of knowledge to search for learning while designing. The questionnaires and interviews suggest 2 strategies for knowledge retrieval: ideation support; and information-based ideation. The transcription of those results into the FBS model reveals procedural knowledge to have an impact on reformulation processes 2 and 3, commonly considered as triggers of innovation and creativity.

In summary, findings show that the retrieval of procedural knowledge can have a major impact on the design process. Methodology regarding quantitatively capturing behaviors should be investigated to support those results. The preliminary results also suggest the potential development of a superscript for the FBS model that would integrate IIR and SAL as part of the design process. There is an interest to further pursue that research into other digital tools for comparison and eventually in professional settings. In the future, we plan to implement theory on cognitive load and self-directed learning and to focus on video as a source as it was clearly demonstrated to be the preferred one.

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Evolutionary Optimization of Benchmarks: Parametric Typologies for Generating Typical Designs

Likai Wang, Patrick Janssen, and Kian Wee Chen

Abstract Benchmark designs can play a critical role in giving performative feedback to the design exploration process. This paper explores the idea of using computational design optimization as a way of generating such site-specific benchmark designs. A case study of the proposed benchmarking approach is presented focusing on public residential precinct design in Singapore. A key feature of this approach is a parametric typology that can generate designs that vary significantly in their overall configuration while at the same time remaining feasible and valid. In addition, an evolutionary optimization system is then used to evolve a set of high-performing site-specific benchmark designs. The case study successfully demonstrates how these benchmarks can be used to give performative feedback to the design exploration process.

Benchmark designs can play a critical role in giving performative feedback to architectural and urban design exploration processes. The problem is that there are often significant differences between the benchmark design and the proposed design. These differences can undermine the relevance of any performative comparisons that are made. In order to address this mismatch, approaches need to be developed for creating customized site-specific benchmarks. This paper explores the idea of using computational design optimization as a way of generating such site-specific benchmark designs. A case study of the proposed benchmarking approach is presented focusing on public residential precinct design in Singapore. Two existing public housing projects are selected with typical high-rise residential typologies that are common in Singapore. The selected projects are analyzed and the underlying design logic is

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abstracted and encoded as a parametric typology. A key feature of this parametric typology is the ability to generate designs that vary significantly in their overall configuration while at the same time remaining feasible and valid. An evolutionary optimization system is then used to evolve a set of high-performing site-specific benchmark designs. The case study demonstrates how these benchmarks can be used to give performative feedback to the design exploration process.

Introduction

Design precedents are often used as benchmarks against which design proposals can be compared. Such benchmarks will typically have a conventional type of design that is familiar and well-established. For the designer, the benchmark is not used for design inspiration, but rather as a way of checking various performance metrics for their proposed design options. The designer may explore design options that may differ radically from the benchmark, incorporating novelty and innovation. But for each option, performance can be evaluated and compared against the benchmarks.

For such benchmarks, existing designs are typically selected that have a similar typology to the proposed designs. The problem is that there will often be significant differences between the benchmark design and the proposed design. Such differences can undermine the relevance of any performative comparisons that are made. Firstly, the benchmark design will generally be located on a different site, with surrounding contexts that may be very dissimilar. Secondly, the benchmark design may differ in the overall scale of the project. Thirdly, the benchmark design may have a program that does not match the design brief. These differences can significantly affect the performance metrics being analyzed.

An alternative approach is to create highly simplified massing models, with the correct site, scale, and program. In order to save time, the designer will often define such a benchmark as a simplified rectangular box, sometimes referred to as a "shoebox model". The problem with this approach is that the simplified massing will again introduce significant differences in the performance metrics being analyzed.

In order to address the mismatch between benchmark designs and the proposed designs, approaches need to be developed for creating customized site-specific benchmarks. On the one hand, the benchmark needs to be based on typical typologies that are well-established. On the other hand, the benchmark needs to be adapted to the site context, and have the correct scale and program. Furthermore, to make the benchmark to be challenging, care needs to be taken to create high-performing design configurations. While theoretically such benchmarks could be created manually by the designer, in practice designers would be reluctant to spend time on this.

Site-Specific Benchmarks

In this research, we propose computational design optimization as an effective method for generating site-specific high-performing benchmarks. These benchmarks can be based on typical typologies. The optimization process will ensure that the benchmark will be adapted to the site context and will achieve good performance for selected performance metrics.

Computational design optimization has been considered a powerful tool for architects and planners to address complex performance challenges in designing a sustainable and livable built environment [1–3]. The design optimization process generates and evaluates a large number of design variants and identifies high-performing solutions for the selected performance criteria. Recently, researchers and designers have increasingly been highlighting the potential of computational design optimization in early-stage design exploration for conceptual development and ideation [4, 5].

With the proposed approach, we focus on the urban design process, specifically the design of residential precincts consisting of multiple high-rise residential towers. The designer would start a new project by automatically generating a set of optimized site-specific benchmarks. The designer would then creatively explore novel and innovative design solutions by following their usual design process. However, during this process, design decisions could now be informed by the performative feedback offered by the site-specific benchmarks. The designer would be able to directly compare the performance scores of each design option to the performance scores achieved by the benchmarks. The designer would likely be motivated to achieve scores that would be at least as good as those achieved by the automated process.

Parametric Typologies

In order to be applicable in practice, the process of generating site-specific benchmarks should be highly automated, requiring minimal manual work from the designer. Ideally, a library of predefined parametric models would be created for various typical urban typologies, applicable to a wide range of different sites. We refer to these models as "parametric typologies". The designer would then be able to select a desired parametric typology, specify some global parameters, and then generate a set of optimized site-specific benchmark designs. The resulting benchmarks would then represent high-performing configurations of well-established typical design solutions.

A major challenge is the creation of a library of parametric typologies with sufficient flexibility to be able to adapt to different site shapes and contexts [6]. The parametric schemas underlying these models need to be able to generate sufficient variability while at the same time ensuring that validity is maintained. Variability refers to the ability to generate design variants that differ significantly from one another in their overall configuration. Validity refers to the ability to generate designs that are coherent and that adhere to the logic of the typology.

At the building scale, an example of a parametric typology is the EvoMass [7]. EvoMass provides two flexible parametric typologies for generating building massings, both of which can be applied to a wide variety of sites. The parametric typologies are able to generate highly varied configurations, while at the same time implementing various constraints in order to maintain validity. The EvoMass parametric typologies can be used to evolve site-specific benchmarks, which can then provide performative feedback to the design process [8, 9].

At the urban scale, researchers have been exploring various approaches to the parametric generation of building layouts. In many cases, the parametric models that are created are highly site-specific and unique. Two examples are the Kartal Masterplan in Istanbul and the One North Masterplan in Singapore. In these projects, the aesthetic qualities typically play a significant role in the decision making which can undermine their use as performative benchmarks.

More recently, several studies have been conducted using computational design optimization for urban design focusing on various performative aspects [1, 2, 10]. In these studies, standardized urban design typologies are adopted and encoded as a parametric schema that can be potentially applied to different sites. However, these schemas tend to be over-constrained and therefore lack the ability to generate significant design variability.

A commonly used approach for generating urban layouts is the use of predefined urban patterns. In some cases, buildings are placed on a predefined grid that is usually orthogonal [2, 11]. In other cases, an urban street pattern is predefined [12]. With such approaches, design variability becomes limited to the changes in building orientation and height, while the overall configuration of building layouts remains constant. This approach is likely popular because it is relatively easy to encode as a parametric schema. Nevertheless, due to its inability to achieve sufficient design variability, the corresponding design optimization often fails to produce high-performing solutions that respond to the site conditions.

To address these issues, a critical step is to develop parametric schemas that are capable of generating urban layouts with appropriate variability while maintaining validity.

Designing Public Housing Precincts

As a demonstration of the proposed benchmarking approach, this research focuses on public residential precinct design in Singapore. Public housing accommodates over 80% of the resident population in Singapore [13]. The application of the proposed benchmarking approach can potentially have a significant impact and practical value.

In Singapore, the designs for public housing precincts tend to adopt very similar housing typologies to promote design and construction standardization. The underlying design logic embedded within these existing designs is abstracted and encoded as parametric typologies. Several previous studies have attempted to apply computational design optimization to Singapore residential housing [11, 14, 15]. However, the parametric schemas developed in these studies do not meet the criteria required for the benchmarking approach. This research proposes a method for developing parametric typologies that can achieve both high variability and high validity.

The developed parametric typology is then integrated into an evolutionary optimization system that allows designers to generate high-performing site-specific benchmarks. These benchmarks are then analyzed to give performative feedback to the design exploration process.

Paper Overview

Following this section, the paper starts with an analysis of two selected residential projects in Singapore, where the spatial structure is extracted. With the analysis, we elaborate on a parametric typology that can capture the underlying logic of these projects. Afterward, a parametric schema is described, which realizes the selected parametric typology, and is demonstrated in a case-study optimization. Finally, we conclude the paper by discussing the relevance of the application of parametric typologies to research and practice.

Methodology for Creating Parametric Typologies

In order to achieve both design variability and design validity, the underlying logic embedded within the urban typologies needs to be analyzed and encoded. With this in mind, we propose the following methodology for developing parametric typologies for building layout generation:

- First, select existing projects that are representative of the urban typology that needs to be generated and evolved.
- Second, create an organizational diagram and identify the underlying dependencies between the design elements.
- Third, define a sequence of steps for generating designs where the steps mirror the dependency relationships between the design elements.
- Fourth, encode the sequential process as a parametric schema.

Representative Projects

To extract the design logic, we investigate several recent and ongoing housing development projects and select two representative projects for further analysis. These two projects, Tampines GreenGlen and Punggol Northshore Edge, respectively consist

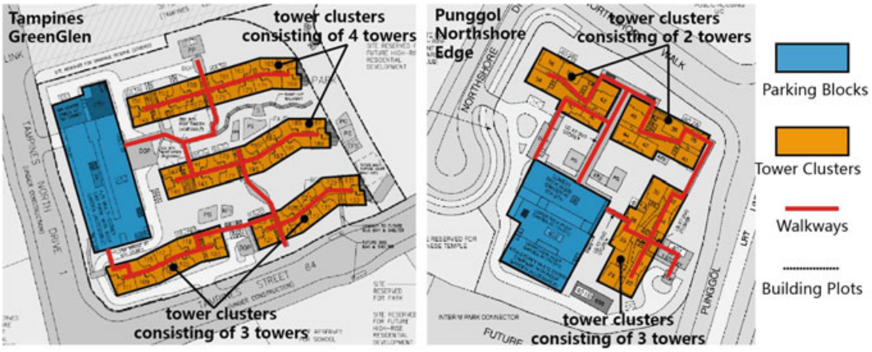

Fig. 1 Selected projects

of 649 units and 388 units (Fig. 1). In addition, the highest floors for both projects are 16 levels (Tampines GreenGlen) and 22 levels (Punggol Northshore Edge).

With a clear spatial structure of precinct configurations, these two projects are ideal for the initial implementation of parametric typologies. Furthermore, their commonality to other projects will facilitate the developed parametric typology to be further upgraded to adapt to other large-scale precinct designs.

Underlying Dependencies of Design Elements

Based on the two selected projects, a hierarchical dependency among different elements that constitute the precinct design can be identified (Fig. 2). First, as shown in Fig. 1, the parking block is a dominant element in both projects. The parking block functionally connects the exterior city road network to the interior circulation system of the precinct, which, as a result, defines the main entrance of the precinct. Hence, the parking block is always alongside the boundary but not in the center of the building plot. Beyond its functional role, the parking block also directly affects the arrangement of tower clusters regarding the orientation and length/size.

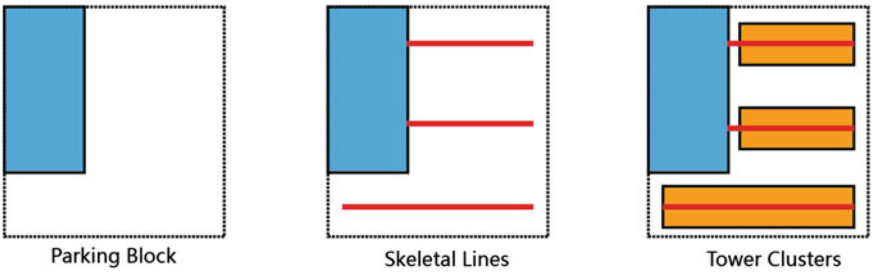

Fig. 2 The dependency relationship between different design elements

Fig. 3 The walkway segments serve as the axis of tower clusters

The second-level element defining the precinct configuration is a set of organizational lines that determine the overall spatial structure within the site. These lines connect the parking block and tower clusters and coincide with the walkways and air bridges. These lines also serve as the connection between different adjacent tower clusters as well as the internal link among the buildings in one cluster. Thus, in the selected parametric typology, these 'skeletal lines' are used as the primary organizational device for generating the building layout.

The orientation and length of skeletal lines are related to the precinct configuration. For the orientation, all the skeletal lines are roughly parallel or perpendicular to the edge of the parking block, while the skeletal line segments also serve as the axis to create tower clusters. For the length, the length of the segment defines the number of towers in the cluster (Fig. 3). Moreover, skeletal lines can include small turnings, which can help to accommodate more towers or prevent the end tower from being too close or crossing the boundary of the site.

The last level of elements is tower clusters. As mentioned above, the number of towers in each cluster is defined by the length of the corresponding walkway segment. In each tower cluster, there can be two to four towers according to the length of the walkway segment. With different numbers of towers, the floor plan of each tower also changes in terms of the number and the configuration of apartment units. As shown in Fig. 3, one or two corners of the tower can be replaced by a void to allow two towers to sit closer to each other (Fig. 4). Moreover, vertical circulation cores (elevators and fire escape stairs) are shared by the towers in the same cluster. Constrained by the fire evacuation requirements, the number of towers in each cluster is limited to a maximum of four.

While the parking block is the first-level design element, the second-level element of walkways plays a more decisive role in defining the building layout as all buildings are aligned to the walkways. From the urban design point of view, these walkways determine the orientation of the towers in each cluster, as well as the overall building density and accessibility of the precinct.

In this regard, the walkways can be perceived as the skeleton that principally defines the spatial structure of the precinct. Thus, we define walkways as 'skeletal

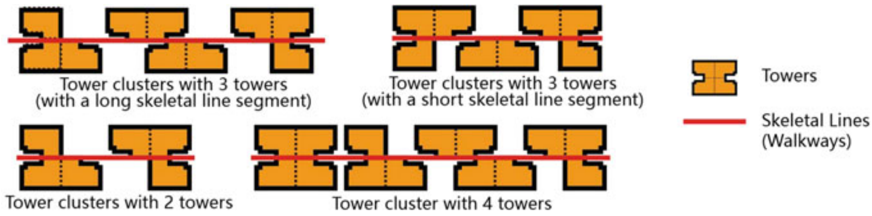

Fig. 4 Tower floor plan patterns for different numbers of towers in the cluster

lines' in the parametric typology and consider these lines an organizing principle for generating major elements constituting the design such as tower clusters and walkways. The positions and orientations of the skeletal lines can be defined in relation to the parking block and the tower clusters.

Generative Steps

Based on the hierarchical dependencies among the design elements identified in the previous stage, six steps are defined, as shown in Fig. 5.

- Step 1: Generate the parking block at one of the corner points along the plot boundary. The parking block will have two inner edges that are straight and that meet at a right-angle corner.
- Step 2: Generate a set of skeletal axes orientated parallel or perpendicular to the two inner edges of the parking block. The spacing of the skeletal axes is configurable based on a user-defined parameter.

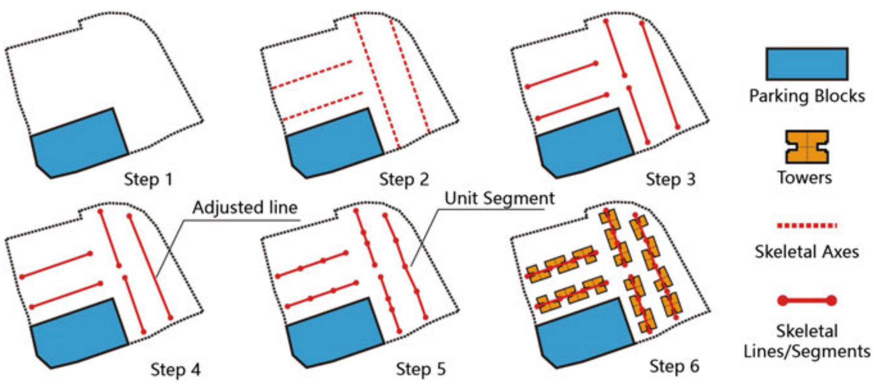

Fig. 5 Six generative steps

- Step 3: Generate a set of skeletal lines along each skeletal axis. The length of the skeletal line will be adjusted to ensure that each line can host one cluster of towers.
- Step 4: Adjust the positions and orientations of the skeletal lines in response to the plot boundary.
- Step 5: Subdivide the skeletal lines into smaller segments, where each segment will host one tower.
- Step 6: Generate tower clusters along each skeletal line. The floor plan of each tower is created according to the pre-defined solid-void pattern.

Example Parametric Schema

Based on the generative steps, we encode these steps into a skeletal parametric schema with four algorithms [16]. The four algorithms generate 1) the parking block, 2) the skeletal axes, 3) the skeletal lines, and 4) the tower clusters. These four algorithms are executed as a sequence of steps. The output of each algorithm will serve as the input for the next algorithm.

Algorithm for Parking Block Generation

The execution of the first algorithm defined the parking block (Fig. 5 -Step 1). The algorithm starts by selecting a base point on the boundary of the site (Fig. 6). The orientation of the parking block rectangle is set to be parallel to the line segment found at the selected base point. The width and length of the rectangle are also set according to the base point and are automatically adjusted to achieve the area required for the parking capacity.

To ensure that the algorithm can handle different boundaries, the base point is selected using a continuous parameter in a 0.0-to-1.0 range. A value of 0 maps to a point at the start of the boundary polyline, while a value of 1 map to a point at the

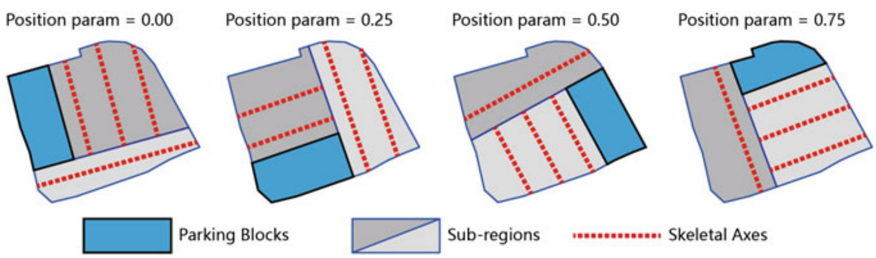

Fig. 6 The parameter controlling the parking block position and the subdivision of sub-regions

end. In addition, in order to further constrain the position of the parking block, the user can exclude certain segments from the boundary polyline.

Algorithm for Skeletal Axis Generation

Once the parking block is defined, the second algorithm is executed to create skeletal axes (Fig. 5 -Step 2). The algorithm first uses the inner corner point of the parking block to further divide the building plot into two sub-regions as displayed in Fig. 6. For each sub-region, one parameter is used to define whether the direction of the inside skeletal axes is parallel or perpendicular to its adjacent edge to the parking block. The selected direction will further determine the orientation of buildings in this sub-region. Based on the selected direction, the sub-region is filled with skeletal axes, where the density of the skeletal axes is determined by a spacing parameter defined by users. Lastly, when several skeletal axes from different sub-regions are found to be co-linear, these axes will be joined and merged.

Algorithm for Skeletal Line Generation

The third algorithm covers the generative steps 3 to 5 in Fig. 5, including transforming the skeletal axes into skeletal lines and adjusting the skeletal lines according to certain local conditions. First, for those skeletal axes with appropriate length to host one tower cluster, the axis will be directly transformed into a skeletal line. Second, for those axes exceeding the maximum length for hosting four towers, these axes will be subdivided into two segments and, thereafter, transformed into two skeletal lines (Fig. 5—step 3). The resulting skeletal lines will then be further truncated and shortened to satisfy the spacing requirement to the plot boundary or adjacent skeletal lines.

Next, skeletal lines are adjusted with respect to the plot boundary using various tweaking operations. For skeletal lines close to the boundary, the lines are adjusted to make them more parallel to the boundary (Fig. 5—step 4). At the same time, for skeletal lines that are very close to the boundary, the lines will be moved backward to satisfy a setback requirement. After these operations, the adjusted skeletal lines will be sent to the next algorithm to generate tower clusters.

Algorithm for Tower Cluster Generation

The last algorithm generates the tower cluster. The algorithm first calculates the number of towers in the cluster according to the length of the skeletal lines and subdivides the skeletal line into smaller unit segments. In most cases, these unit

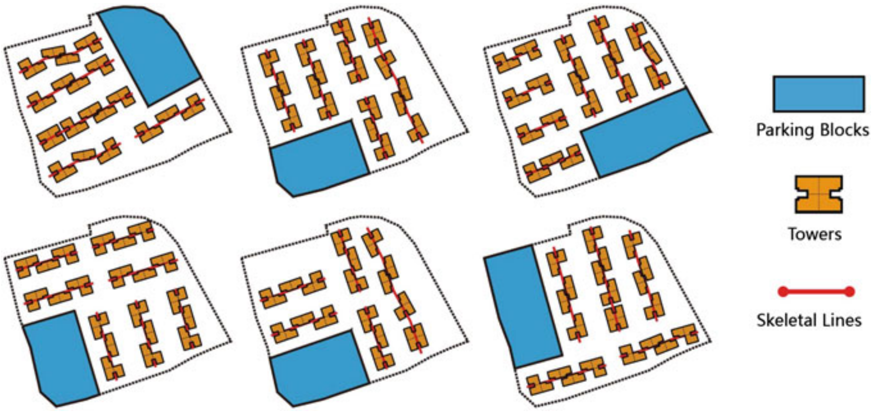

Fig. 7 Random sampling building layout designs

segments are co-linear. However, if a skeletal line has been rotated with respect to the plot boundary, each unit segment may have been adjusted, resulting in unit segments that are not co-linear (Fig. 5—step 5). Twoer floor plans are then generated for each unit segment. These floor plans are generated according to a pre-defined solid-void pattern (Fig. 5—step 6).

Figure 7 displays a random sampling of generated building layouts based on the skeletal parametric schema. It can be seen that the generated design variants show significant design variability in terms of building layouts. At the same time, in terms of design validity, the design variants all adhere to the existing housing typology and remain feasible. The tweaking operations allow building layouts to adapt to different parking block locations and plot boundaries.

Case Study

In order to test the efficacy of the selected parametric typology, a case-study optimization is carried out using the skeletal parametric schema. In the case study, building layout designs are evolved for a residential precinct based on Tampines GreenGlen. Three evaluation metrics are considered: Solar heat gain, accessibility, and economic feasibility.

Evaluation Metrics

As the paper primarily focuses on design generation, issues related to rigorous performance evaluation for realistic urban design concerns or housing development projects are beyond the scope of this study. As a result, the case-study optimization of this study is relatively simplified and only includes three commonly-adopted performance and functional evaluations, which might be insufficient for real-world design scenarios. Nevertheless, the proposed design optimization system is extendable to other performance criteria in typical housing development projects such as views, thermal comfort, and cost/budget.

Solar Radiation Metric

The main evaluation objective is to minimize the annual solar radiation (RA) on the facade surface of all residential buildings. RA is an important performance factor for housing design in Singapore [11]. As Singapore has a typically tropical climate, designers often manipulate urban forms to shield buildings from RA for reducing overheating and cooling load. For this evaluation, Ladybug is used for the RA simulation.

Accessibility Metric

For residential precincts, accessibility is a critical functional requirement. It has been widely adopted by many relevant studies for urban design optimization [17–19]. Accessibility is evaluated by calculating the efficiency of the circulation network in the design. The optimization objective is set to minimize this length.

To evaluate the accessibility metric, a circulation (walkway) system needs to be established first, and the skeletal lines can be used as the basis to establish such a system. The skeletal lines, i.e., the walkway segments, generated by the skeletal parametric schema are isolated. By connecting the skeletal lines into a circulation network, we are able to calculate the distance of each tower cluster to an assigned destination. In this study, we assigned the parking block as the destination because it serves as an entrance and a vehicle drop-off point for the precinct. Most people need to pass the parking block before reaching the tower where they live. Thus, the distance between the entrance and the tower is critical to accessibility.

Based on the above consideration, the algorithm first creates a circulation network by generating connections between adjacent but disconnected skeletal lines (Fig. 8). This algorithm uses various heuristic rules to create reasonable connections. For example, connection lines that cross other lines are prohibited and connection lines that are roughly parallel or perpendicular to the parking block are given preference. Once the circulation network is generated, the accessibility metric can be evaluated by calculating the sum of the distances of all the tower clusters to the parking block. Note that the algorithm can include other destinations in addition to the parking block, such as bus stops or footbridges. However, for this case study, just a single destination was used.

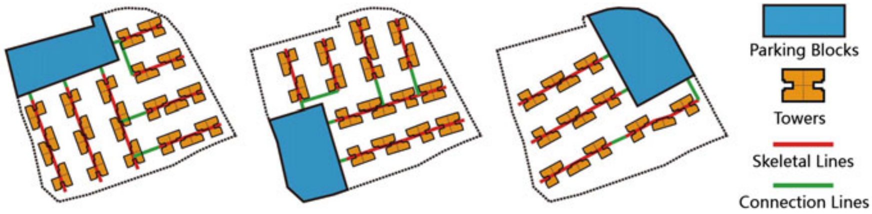

Fig. 8 Examples of the generation of connection lines between skeletal lines or the parking block

Economic Feasibility Metric

Finally, land-use efficiency is also important for residential precincts [12, 20]. The total gross floor area of the design is typically required to maximize the plot ratio defined by the urban design code. Considering this requirement, we develop an algorithm to generate towers with varying numbers of floors. When generating the towers, two constraints are applied. First, the heights of the towers are constrained to a minimum and a maximum number of floors. Second, the total floor area is constrained to not exceed the target area defined by the plot ratio. In this case study, we set a plot ratio of 2.0 and a height limit of 50 m (or 16 floors with a 3-m floor height). For the optimization, the gross area is set as a soft constraint to punish those design solutions failing to provide enough floor area.

Design Optimization System

For the design optimization system, a hybrid algorithm, called Steady-State Island Evolutionary Algorithm (SSIEA) [21], is used as the optimization solver to evolve the design population. Figure 9 illustrates the design optimization system built on the selected parametric typology and fitness evaluations. Note that the system is extendable to other performance factors by including additional performance evaluation algorithms or simulation tools, such as greenery, daylighting, and views. The three evaluation metrics are formulated into one single-objective fitness evaluation function.

Regarding the search difficulty, the skeletal parametric schema requires 13 parameters to control the design generation as mentioned above.

- One parameter is required for selecting the parking block position
- Two parameters are required for setting the orientation of skeletal lines in each of the sub-regions.
- Ten parameters are required to set the number of floors for each cluster.

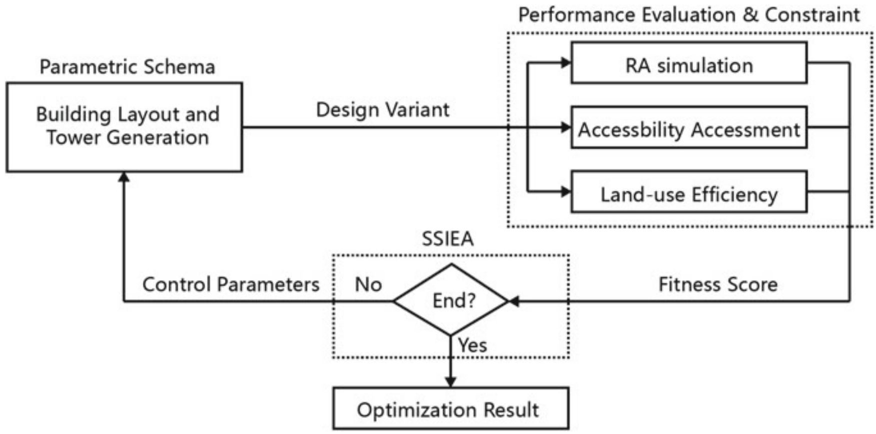

Fig. 9 The design optimization system

It is noted that in most cases, the number of tower clusters will not reach 10. In such situations, some of the parameters used for setting tower heights may be redundant and remain unused.

The relatively small number of parameters allows us to apply a short optimization run, evolving a total of 2000 design variants. The result indicates that the evolutionary process reached convergence after about 1000 iterations. With the optimization and simulation setup, the optimization process is completed in one night using a laptop with an i7 processor. This time frame for optimization renders this optimization system a higher utility to real-world design tasks.

Optimization Results

In the case study, SSIEA was used to evolve eight subpopulations. The subpopulations increase diversity in the optimization results. Further details on the SSIEA algorithm can be found in the previous study [21]. Figure 10 shows five selected design options from the final design population. As shown by these options, the encoding of the underlying building layout logic ensures that the evolved design variants all share desirable traits with the existing as-built building layout, as illustrated at the right-bottom in Fig. 10. This guarantees the design validity. The evolved design variants are all feasible and can provide designers with examples of design options that perform better than the existing design. At the same time, the design variability is also significant. The parametric schema allows the optimization process to evolve the design variants with building layouts that differ significantly from one another.

The five designs exhibit different alternative building layouts, each having distinct advantages and/or disadvantages. Options 1 and 2 have a lower RA (solar heat gain)

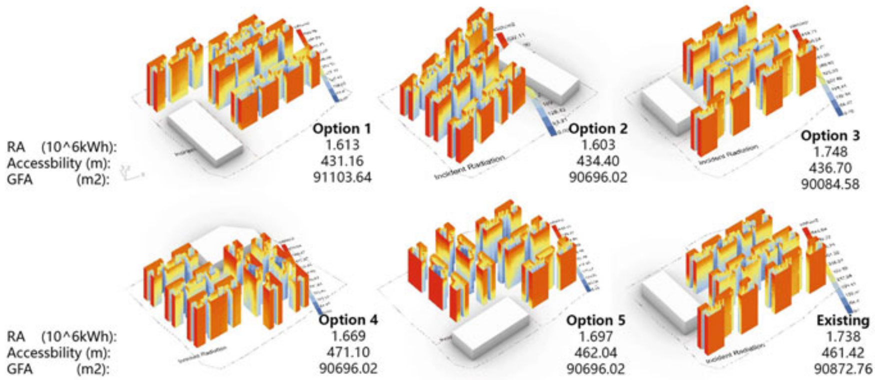

Fig. 10 Optimization result

and better accessibility than the other three designs. In these two designs, all the tower clusters face south, and the major difference between them is the location of the parking block. In contrast, option 3 has the highest RA among the five design options, while its accessibility is better than that of options 4 and 5. In addition, its overall building layout is also similar to that of the existing one. Lastly, for options 4 and 5, these two designs have a lower RA than option 3 does, but their accessibility significantly underperforms the other three designs.

To validate the optimization effectiveness, we also evaluate the performance of the existing building layout and compare it with the selected design variants (the bottom-right design in Fig. 10). The existing design has a higher RA than all of the selected design options except for option 3. Options 1 and 2 outperform the existing design both in solar heat reduction and accessibility. Option 3 shares a similar building layout with the existing design but further improves the accessibility. However, option 3 is weaker in solar heat reduction than the existing one. Options 4 and 5 surpass the existing design in terms of solar heat reduction, while it comes with a drawback in regards to accessibility.

Discussion

The design optimization results show that the case-study design optimization can discover high-performing designs that perform better than the existing designs. This also demonstrates that design optimization is able to provide designers with high-performing site-specific benchmarks. In addition, the design variability in the optimization result also allows designers to better understand the trade-offs between different precinct layouts in terms of the strengths and weaknesses in performance. Such information can further help designers conceive promising directions for subsequent design exploration and ideation.

The case study demonstrates that the skeletal parametric schema provides a viable and promising approach for achieving both design variability and design validity. The wide variation of skeletal line configurations offers sufficient variability in building layout configurations, while also maintaining a coherent spatial order. Thus, by capturing the hierarchical and dynamic dependency relationships among different design elements, the skeletal parametric schema can effectively represent the underlying spatial structure underpinning the selected projects and urban typology.

Optimization in Design

The benchmarking approach proposed in this paper differs from previous research in the role that is envisioned for the optimization process. In this research, the optimization process is envisioned as a way of optimizing typical typologies based on existing case studies. The resulting benchmark designs are expected to achieve high performance, but there is little expectation for novelty or innovation. In most previous research, the optimization process is envisioned as a way of discovering design solutions that themselves embody significant novelty and innovation. This may raise questions as to why the optimization process is being limited to such a routine design task.

Over the past decade, the increasing prevalence of design optimization in architectural and urban design may have raised expectations. In many cases, designers in practice may feel that the use of optimization algorithms to evolve novel and innovative design solutions should be possible. However, in reality, it is generally very difficult to use optimization to discover designs that are truly novel.

In the previous research, three key approaches can be identified. In the first approach, designers hard-code the novelty in the parametric model. In such cases, designers will create bespoke parametric models specific to one project and site [4, 22, 23]. When optimized, this can result in novel and innovative designs being generated. However, in such cases, the novelty is not discovered by the optimization system. Instead, the designer predetermines a novel design concept by hardcoding it in the parametric model. Furthermore, this approach has the drawback that the hard-coded novelty may actually be detrimental to performance. Using such parametric models can therefore increase the bias towards a specific design concept and hinder broader reflection.

A second alternative approach is for the designer to create multiple bespoke parametric models, each representing different design ideas or concepts [24–27]. These parametric models can be used to optimize multiple solutions, which can then be compared against one another. In this case, the novelty is still predetermined by the designer. But the possibility to compare the performance of multiple competing designs significantly reduces the bias. Nevertheless, from the designer's point of view, a downside is the need to create multiple parametric models.

The third approach is for the designer to create a parametric model that has sufficient variability to allow truly unexpected and innovative designs to emerge. In theory, the optimization system can then discover high-performing designs that could possibly also be highly novel. However, in practice, creating such a parametric model is very difficult. In general, any attempt at significantly increasing variability will be detrimental to maintaining viability. In such cases, the majority of designs generated by the parametric model may end up being infeasible or unrealistic, which can undermine the whole optimization process.

This research proposes a fourth approach to apply optimization in the design process. In this approach, the computer performs the more mundane task of optimizing typical well-established design typologies. The designer, on the other hand, performs the more creative task of generating design options embodying novelty and innovation. It is expected that most designers would be receptive to such a division of labor. In general, designers prefer to spend as little time as possible developing benchmarks and to spend as much time as possible focusing on novelty and innovation. Furthermore, with our approach, the designer is not required to build any parametric models. For many designers that are less computationally inclined, this may be a relief.

Conclusion

Benchmarks can play a critical role in giving performative feedback to the design exploration process. This research proposes a method for generating high-performing and site-specific benchmarks. With this method, a library of predefined parametric typologies is created that can then be used to develop optimized benchmarks. The parametric typologies are created based on typical well-established design typologies reflecting existing design solutions. An evolutionary optimization process is then used to evolve these parametric typologies in order to generate a set of high-performing site-specific benchmarks.

A demonstration was presented, focusing on public housing precincts in Singapore. A parametric typology was developed based on two existing case-study residential projects. For the parametric typology, a skeletal schema was developed that was able to generate significant design variability while maintaining validity. A set of high-performing and site-specific benchmarks were then evolved. Finally, these benchmarks were used as a basis for extracting performative feedback.

The benchmarking approach developed in this research represents a new way of using computation optimization to support the design exploration process. The proposed approach could be of interest to practice, as designers are not required to create their own parametric models. Instead, they can evolve high–performing benchmark designs based on predefined parametric typologies using a highly automated process. Future research will focus on expanding the library of parametric typologies and on developing additional demonstration projects.

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Imager, Interpreter, Aesthete: Roles Played by Design Students in Graphic Design Ideation

Vimalkrishnan Rangarajan, Prasad S. Onkar, Alison De Kruiff, and Deirdre Barron

In conceptual design, the designers' 'visual and cognitive aspects of engaging with visual inspirational materials and ideating have been studied. However, in domains like graphic design, designers ideate to develop rhetorical artefacts like posters or advertisements which convey certain affective qualities to an audience. This study takes an interpretive phenomenological approach to understand the graphic design ideation experience of seven design students' after they were exposed to various visual inspirational materials. The results show that while the 'imager' and 'interpreter' role respectively correspond to 'visualizing' and cognitive processes like 'semantic processing', students take on a distinct aesthete role to ideate based on perceived 'affective qualities' of inspirational materials which have the capacity to persuade the feelings of potential viewers. Students in turn incorporate such visual elements and 'affective qualities' into their ideations. The relevance of these findings for graphic design ideation and the broader area of design ideation is discussed.

Introduction

Traditional paradigms of design describe designers as 'rational problem solvers' [1]. Existing studies of inspiration-based design ideation focus largely on cognitive and visual faculties of designers. However, in graphic design, the dynamic roles played by designers, especially those involving aspects of 'emotion' leading to idea generation are not explored. In the rhetorical view of design, especially graphic design, designers are not merely problem-solvers. They are individual 'authors', who have the agency

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to shape the content of their designed messages, whether initiated by themselves or by clients [2]. For example, designing a poster to promote ‘industrial safety’ can be perceived and solved by graphic designers in multiple ways. While one designer could perceive the task as requiring an appeal to reason or logic, another designer could perceive it as requiring an appeal to ‘emotions’ [3]. These authorial positions will in turn determine how designers would perceive inspirational material and how they would ideate. Depending on the authorial position, the visual design of the poster could have information displayed in a clear, hierarchical order to appeal to the logic of viewers. The visual design could also have elements like compelling visual imagery to appeal to the ‘emotion’ of viewers [3]. Buchanan’s [4] rhetorical view of design also describes designers as speakers who ‘fashion worlds’. Designers actively advocate arguments about ‘how people should live’ and are not mere ‘problem solvers’ [5]. While the traditional ‘problem solving’ paradigm of design emphasizes the designers’ dominant reliance on ‘cognitive’ and ‘visual’ faculties, the rhetorical paradigm of graphic design implies that designers also rely on their ‘emotional’ faculty when they embed various arguments into artefacts like posters and advertisements to shape beliefs of an audience [6]. In other words, agents like professional designers or design students would assume various roles for the ‘invention’ and ‘disposition’ of their arguments through graphic design ideas, specifically roles which involve distinct aspects of ‘emotion’ apart from roles involving ‘cognition’ and ‘visualization’.

By adopting an interpretive phenomenological approach, this paper studies the various roles assumed by design students in their experience of ideating for a graphic design task. The paper shows that graphic design ideation emerges from the dynamic interplay of roles involving cognition, visualization, and an aspect of emotion.

Background

Various scholars have studied the cognitive and visual aspects of how designers search and use information to solve problems, but the emotional aspects have not been explored in detail. Riding and Cheema [7] note that designers are ‘imagers’ and ‘verbalizers’ which denotes the tendency to use images and words to search and represent information. This is comparable to Medinick’s [8] distinction between ‘visualizers’ and ‘verbalisers’. Focusing on the professional identities of designers, Kunrath, Cash and Kleinsmann [9] note that cognitive abilities and cognitive strategies are important constituents making up designers’ professional identity. Cognitive abilities include designers’ ability to understand the design problem, abstract thinking, reflective abilities, and analogical reasoning. Cognitive strategies include factors such as decision-making heuristics, technical competence, domain knowledge and the like. Technical competence could also denote visualizing abilities. The visual and cognitive aspects of design ideation are discussed in another study [10] where it is noted that designers ideate by adopting graphic and mental approaches which include aspects like sketching and mental imagery processing, a distinct cognitive process through which designers visualize ideas in their minds. The perception that designing is a process which predominantly involves the cognitive faculties is evident from studies which focus on the various 'cognitive' styles of designers. According to Kim and Kim [11] there are four cognitive styles in idea generation emerging from precedents or sources of inspiration. These are 'focused probers', 'treasure hunters', 'selectors', and 'explorers.' Focused probers tend to retrieve a select few concepts from inspiration sources and develop a few ideas in detail. Treasure hunters explore a diverse range of precedents while developing a few ideas. Both selectors and explorers explore a wide range of precedents. However, while selectors go on to make a primary development of the idea, explorers don't develop their ideas. The linkage of cognition and the visual aspects of design thinking is further explored by Brescani [12] by developing a framework to profile various visualisations of designers. 'Structural restrictiveness' denotes the ability of the visualization to guide or constrain the design process. 'Content modifiability' denotes the extent to which the elements of visualisations such as text, lines, shapes etc. can be modified. 'Directed focus' denotes how designers visually emphasize certain aspects of their ideas. 'Perceived finishedness' is the extent to which a visualized idea or concept appears finished, inviting or hindering further elaboration. In the domain of graphic and visual communication design, Schenk [13] notes that visual literacy is a crucial quality that designers should nurture to generate ideas from inspiration sources. Meggs [14] uses the term 'ocular reconnaissance' denoting graphic designers' tendency to visually scan their environments for inspiration.

While this literature establishes the cognitive and visual aspects of designers' ideation, less work has focussed on aspects of emotion. Even in design students' own critical reflections of their ideation process, very little attention is paid to their emotions [15] One reason for this could be the predominance of the problem-solving paradigm of design, where both design researchers and design students subconsciously believe that the process of design is a largely cognitive and visual. This study explores whether aspects of emotion shape the ideation process especially in rhetorical graphic design tasks. Such tasks demand that designers perceive aspects of emotion in their inspirational material and embed such aspects of emotion into their design ideas. This is known as 'pathos' in the rhetorical framework of graphic design [3]. In other words, designers not only have to play roles as visualizers and cognitive thinkers, but also play roles which involve sensitivity to aspects of emotion in the perceived inspirational material and their ideations. To delineate this more clearly in a design context, this paper adopts the concept of 'perception of affective quality' from Russel's Core Affect Model of emotion [16]. Perception of affective quality indicates the capacity of various objects [for example a 'beautiful' flower, a 'terrifying' snake] to persuade how people 'feel' at any given moment. Affective quality of various objects is a blend of two dimensions namely valence and arousal. While valence denotes positive–negative aspects like how attractive or repelling an object is, arousal relates to aspects of intensity like strength-weakness, where it denotes how strongly or weakly a person can be attracted to or repelled by an object. For example, the affective quality 'exciting' is a blend of positive valence and high arousal whereas the affective quality of dullness is a blend of negative valence and low arousal. This is a distinct mode of perception which makes up the phenomenology of contact with the external world and influences various decisions [16].

Methodology

This paper adopts the Interpretive Phenomenological Approach [IPA] to study the ideation experience of design students. IPA is part of the broader domain of phenomenological psychology. Phenomenological psychology investigates how people subjectively make sense of their experiences in various situations and contexts [17]. For instance, the image of a dove might imply just a bird to one designer, whereas for others it could imply a bird and an affective symbol of peace. Phenomenology rejects the subject-object dualism of positivist paradigms which imply that phenomena could have an existence independent of perception. On the contrary, phenomenology suggests that people and objects are in a bi-directional and holistic relationship. The mind reaches out from the individual and the phenomena reach out from the object and meaning is generated in this interaction [18]. IPA interprets the experiential lifeworld of the participants and situates it in specific contextual frameworks [19]. In this study, IPA revealed how the design students related to and made sense of their graphic design ideation after they perceived various visual inspirational material. There are two steps in IPA. The first step is to produce a description of the lifeworld of the participants as interpreted by them getting as close as possible to their views. In the next step, the researchers further interpret and contextualize this lifeworld within wider socio-cultural and theoretical contexts [20]. This dual interpretation of the lifeworld: First by the participants and then by researchers' further interpretations of the participants' views constitutes what is known as a double hermeneutic [21].

The participants in the study [n = 7] were master level design students who have received some training in the discipline of communication/graphic design. The sample met the criteria of being purposive and homogenous to the extent that all the students had been trained to think like designers and they had received some training in communication design and were familiar with the use of inspirational material and sketching for ideation. This aligns with interpretive phenomenological analysis which seeks to make interpretive claims about the specific experience of a specific group of people who share that experience [19, 21]. However. The participants also represented different cultures and nationalities, some of whom were familiar with the native cultural context of the inspirational materials used in the study. The phenomenological method also prescribes smaller sample sizes: 'around five or six or sometimes fewer participants for most research conducted individually due to the time-consuming nature of the analytical process' [19]. Small sample sizes are used as phenomenological psychology is idiographic and does not attempt to make general claims about large populations [19].

This study employed a process isolation design strategy by using a sample design task [22]. This strategy is suitable for studies which observe the cognitive and

Fig. 1 The study setup

emotional aspects of designing in specific phases of design. Process isolation involves the use of “controlled miniaturizations” of design problems. The process isolation strategy is mainly used to explain ‘design behaviour’ [22]. First, the participants were given a practice design brief. The practice task involved generating ideas for a logo of a sky diving club after watching sample inspirational material. This helped the participants to become familiar with the digital sketching tool, the software interface, and the study setup in general (Fig. 1).

The participants were given the task of developing conceptual design outcomes for a graphic design problem which was rhetorical in nature: “to develop conceptual ideas for a landscape poster to be used in web/digital platforms to promote the ponds of Kerala as a national/international tourist attraction.” The brief also contained some general instructions and background information about the South Indian state of Kerala and its other tourist attractions. After reading the design brief, the participants were shown various sets of related visual inspirational material and they were asked to think aloud as they saw the material. The inspirational materials were grouped into various categories based on the literature on images commonly used by graphic designers [23]. These included:

(a) cognitive aids (Fig. 2), which included a set of photographs of pond architecture, a set of photographs showing fine details such as texture of laterite bricks, relief sculptures, vegetation etc. These images were compiled by the first author before the study, by taking field trips.

(b) Aesthetic of the Market (Fig. 3): Images of example solutions related to Kerala tourism such as posters and web collateral, videos related to Kerala tourism promotion. These were compiled from open access online databases and search engines. These inspirational materials were cued as slideshows on a laptop monitor. Each set

Fig. 2 Cognitive aids: Pond architecture and texture of laterite bricks

of images and videos was preceded by a blank grey screen for ten seconds which helped the participants to relax and be ready to take in the images.

Participants viewed cognitive aid and aesthetic of the market images for 12 min. These were presented as timed slideshows on a laptop monitor. During sketching, the participants could refer to printed images of these inspirational materials. In addition to these standard inspirational materials, a virtual reality [VR] simulation of a temple pond of Kerala was designed for use as an inspirational material (Fig. 4).

Fig. 3 Aesthetic of the Market. Reproduction of Kerala Tourism Logo

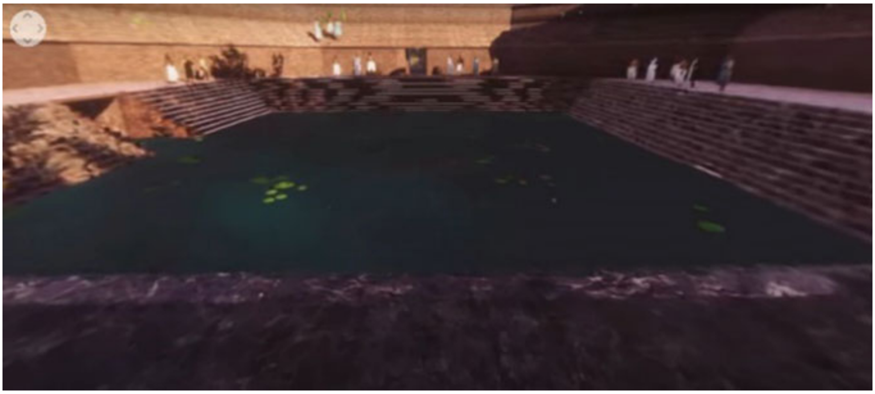

Fig. 4 Screenshot of VR simulation

This simulation was shown to the participants (two minutes and 30 s) through an Oculus Go VR headset. Participants were instructed to close their eyes and relax for 10 s before the simulation was played using the hand controller. The relaxation time helped the participants to be primed and be ready for viewing the VR simulation. All seven participants were shown all sets of inspirational material including the VR simulation. The exposure to the inspirational material (68 images, 2 videos, and 1 VR simulation) lasted for around 15 min.

Following the inspiration stage, the participants were given 30 min to sketch and ideate on the digital sketching platform to produce conceptual design ideas in response to the design brief. During sketching, participants had access to all the static inspirational material in the form of printed collages. Their sketching activity was screen captured using a screen recorder software. Following the sketching activity, a short break was given to the participants. During this time, the sketch recording video file was rendered. After the break, the participants' sketching video files were played back to them. As they watched the sketching activity, they produced retrospective verbal descriptions of how they formed and shaped their design arguments and ideations. After this step, through a semi-structured interview (Table 1) which is a standard data collection method in the IPA framework [19], more details related to the experience of engaging with the inspirational material and ideating were elicited. The following question alternatives were asked based on the responses of the participants.

Data Analysis

In IPA, thematic analysis is the main method used to analyse transcripts. To derive themes, a four-stage analysis was undertaken [19] on the post-sketching transcripts which contained the retrospective accounts of the participants and their responses to the questions in the semi-structured interview. The first stage involves reading

Table 1 Sample questions in Post-Sketching Semi-Structured interview

Topic	Sample Questions
Role of inspirational material in design ideation	In the context of the design problem, can you describe how you felt before, during, and after seeing the inspirational material? Can you describe how the inspirational material influenced your work?
Affective qualities of inspirational material—Arousal Dimension	Are there components in the inspirational material that made a strong/weak impression on your mind?/Why did specific components make a strong/weak impression on you? Did such components influence your design?
Affective qualities of inspirational material—Valence Dimension	Are there any components in the inspirational material that you like/dislike? Why did you find certain components to be attractive/unattractive? Did such components influence your design?

and re-reading the transcripts to get an overview while comments and notes are made on the left-hand margin. Staying close to the text, the comments simply state what is happening in the text without interpretation. Comments were made about participants' descriptions of iterations, decisions related to the design argument, ideations emerging from the inspirational materials, evaluations of iterations and so on. In the next stage, the notes were synthesised into broader themes and meanings corresponding to specific sections of the transcripts (Table 2). In this stage, the initial themes were formed by using psychological definitions of semantic processing [24] and the definition of perception of affective quality [16]. In the next stage, the themes were listed separately and interpreted further by the researcher. The themes were identified for links and commonalities. While some themes were clustered, others were broken up further and in this way superordinate and subordinate themes were formed. The final themes were further named and listed. Representative quotes were linked to each subordinate theme by forming a master table of superordinate and subordinate themes [21] and corresponding quotes by the participants.

Table 2 Sample of interpretive phenomenological analysis

Notes	Transcript	Emerging theme
Attempts an iteration because participant likes a specific visual element: Seeing the pond through a tunnel	P1: and then I started playing with different perspectives…umm… I quite liked the idea of seeing the pond through a tunnel	Perceived affective quality becoming the basis of a visual idea: [liking of the tunnel vision translated to perspective, movement, Dominance etc. which are design principles of organisation]

Results

This section presents results of the IPA on post-sketching transcripts. During conceptual design sketching, the students spontaneously switched between three roles—interpreter, aesthete, and imager—to derive design ideas from their engagement with the visual inspirational materials. These roles are explained below. The roles are illustrated through representative quotes and the related design outcomes of the participants.

Interpreter Role

Participants adopted the interpreter role as they shaped the semantics of their design argument. Here, the ideation intentions of the participants were shaped by their concerns with meaning and logic. The interpreter role is mainly characterised by ideations based on the meanings interpreted from the inspirational material through the cognitive process of semantic processing. Such interpretations of meaning were translated into visual design aspects like compositions and formal organisation of visual elements. Decisions to include or exclude certain visual elements were also based on aspects of meaning such as relevance. Participants also attempted to embed meaning and connotations into their design arguments to convey their intentions to a potential audience. Also, evaluations of ideations were done through justifications and logical arguments. Table 3 shows a representative quote and corresponding design ideation by P3 which captures the interpreter role.

Imager Role

Owing to their training in design, participants naturally took on the role of 'imagers' as well. This primarily encompassed visual aspects such as planning and configuring the composition, generating iterations based on certain visual patterns, detailing and refining the quality of the iteration, and revisiting recurring patterns and motifs which were noted when the participants engaged with visual inspirational material during the inspiration stage. Table 4 illustrates the imager role through a representative quote and design iteration by P1.

Aesthete Role

When the participants took on the role of an aesthete, their ideation intentions were shaped mainly by their perception of affective qualities of inspirational material.

Table 3 Representative quote and corresponding design outcome of P3

Quote	Iteration in design argument, design outcome
P3: I kept looking around and I could see trees and I could see the skyline going down and so that was….one like I would say that was one of the influences…the other one was the motto…God's own country …so …So like these two things combined …gave me that idea of you know like going to a place to an entity like ascend to an entity … P3: So then the second thing like..it was obviously like Kerala so…ehh…in Kerala like everyone puts like…coconut is like a secret ingredient for every recipe…for everything and they are like tall so. you know, they stand like a sky scraper…like you know…above all that skyline…you can see like coconut trees coming out ….and …Like there is a..there is a different Coastal….kind of vibe with the coconut tree… Like generally because it is found in the [unclear]…coastal area…so …so I was trying to get that.ehh…feature.	(Fig. 5)

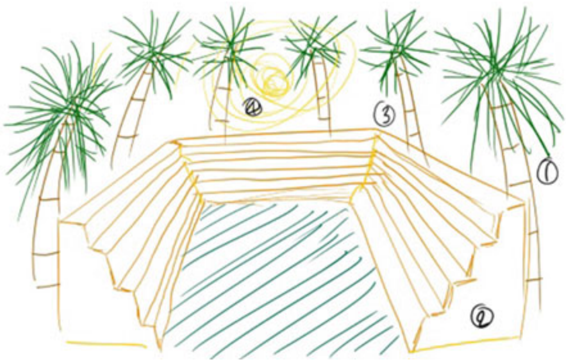

Fig. 5 Iteration of P3 based on Interpreter Role

Table 4 Representative quote and corresponding design outcome of P1, P2

Quote	Iteration in design argument, design outcome
P1: So I was playing with that so square inside a square inside a square and	(Fig. 6)
P2: So when I started I was trying to draw the the pond and the wall surrounded umm cos I wanted to umm my eh the image in my head is the the pond basically I see every picture and apparently you guys try to promote is that ponds so I want to the pond of definitely seeing the picture	(Fig. 7)

Fig. 6 Iteration of P1 based on Imager Role

Fig. 7 Iteration of P2 based on Imager Role

Participants translated their perceptions of affective qualities of inspirational material into design iterations. This was done through decisions to include or exclude specific visual elements, choice of compositional and visual organization principles to achieve harmony or emphasize an aspect through variety, and choice of specific formal elements such as colors and shapes. The participants also attempted to embed affective qualities and even a feeling of embodiment into their design arguments and outcomes, so that potential viewers may perceive such affective qualities and be persuaded. Finally, the participants evaluated their ideations through subjective values such as good and bad and also by personally relating to the ideations through like—dislike frameworks (Table 5).

Discussion

In the area of design ideation, the role of affect, which includes aspects like perception of affective quality, is discussed mainly in the evaluation of design ideas stage. Suwa, Purcell, and Gero [25] term this as 'e-action' where designers preferentially and aesthetically evaluate their ideas and iterations, through valence dimensions such as 'good-bad', 'beautiful-ugly' or personal values such as 'like-dislike.' Kim and Ryu [26] note that experts frequently use 'affective evaluations' to evaluate their ideas and make design decisions. However, this study shows that aspects like perception of affective qualities not only serve the function of evaluating ideas, but also drive design iterations. If certain visual elements in the inspirational material are found

Table 5 Representative quote and corresponding design outcome of P6

Quote	Iteration in design argument, design outcome
P6: So first idea was…just …what it would feel like to get inside one of the ponds…the feeling of the water as it touches your skin for the first time… P6: I really liked that imagery of…especially the animals and the birds…and the bird song was playing in the VR …so that was like very immersive like…I felt like I had to be there where the birds are… P6: Ahhmm…Mostly I could say like…obviously…it is the ripples in the water…because you can only have ripples in calm water…otherwise…so it is very…its its…you immediately know…as soon as you see it that it is peaceful…incorporated it… P6: As soon as you see the picture and the colour and the coolness…. like it should be…you should feel cold looking at it…not cold essentially…but calm	(Fig. 8)

Fig. 8 Iteration of P6 based on Aesthete Role

to have certain specific affective qualities, such elements are incorporated into the design iteration. Perception of affective qualities is translated visually as elements of composition, in visual organization and, visual emphasis. Design ideation should therefore be understood as emerging from the interaction of cognition, visualization, and emotion.

This study advances new perspectives into the role of sketching and ideation, particularly in a type of sketch called 'thinking sketch.' Sketching is one of the main external representational modalities in design ideation [27]. Fergusson [28] classifies sketches into four types: 'rapid sketch', 'prescriptive sketch', 'talking sketch', 'thinking sketch'. Designers use thinking sketches to offload the nebulous ideas in their working memory. Through thinking sketches, designers have a conversation with themselves and refine their ideas. As shown by the results of this study, design students sketch to embed the affective qualities that they perceive in the inspirational material. This gives more details about the 'thinking sketch'. Designers could make thinking sketches to refine depiction of affective qualities, to refine semantics, or to refine visual properties. This delineation within the thinking sketch type is necessary to further improve sketch support tools and the design ideation process.

Furthermore, existing studies on designer's professional identity include aspects of 'emotion' as a personal attribute [9] which defines the personality and characteristic of a designer. However, this study shows that aspects of emotion such as perception of affective quality can be included as a 'design skill' constituting designers' professional identity. Design skills denote the skills needed to execute design tasks and are not related to the personalities of designers. Design skills include cognitive, technical, and behavioral characteristics related to the practice of design and these skills can be acquired through training, education, and practice [9]. This study shows that the ability to perceive affective qualities and ideate based on such perceived affective qualities are significant, especially in domains like graphic design which involves a range of rhetorical problems. Therefore, the sensitivity to perceive affective qualities should be recognized as a 'design skill' constituting professional design identity.

The results of this study also add new insights into the 'design as rhetoric' paradigm. According to Ehses [3], a rhetorical argument in the form of a design artefact is produced when designers with specific 'intentions' develop a speech artefact or a graphic design artefact. This study shows that the intentions of the designers could be shaped by the dominance of the interpreter, imager, or aesthete role. Furthermore, there are various steps in the creation of the graphic design artefact which can be mapped to these three roles. The first three steps are called 'inventio', 'dispositio', and 'elocutio.' 'Inventio' denotes finding what to communicate through a graphic design artefact. This involves engaging with inspirational materials and developing the graphic design argument. 'Dispositio' denotes the structuring and ordering of the message. In the framework of graphic design, this denotes aspects like planning a composition, layout design, deciding on the dimensions of the graphic design artefact and so on. In the 'elocutio' stage, more layers such as the style, clarity, and ornamentation of the message is decided. This would involve aspects like choice of colors, choice of font sizes and weights, visual style and so on. This study shows that the 'inventio' phase is determined largely by the roles played designers in terms of interpreters and aesthetes. While the interpreter role would lead to formation of a graphic design argument which is predominant in terms of logic and meaning ['logos'], the aesthete role would lead to the formation of a graphic design argument which would be predominant in terms of affective qualities ['pathos']. The 'imager' role would be predominant in the 'dispositio' and 'elecutio' phase in the production of the graphic design artefact as these stages involve the visualization of the graphic design argument. These insights help to more consciously brief designers in such a way as to what roles they should play in a rhetorical design context.

Conclusion

This paper identifies the various roles played by design students in graphic design ideation. While existing studies focus more on the cognitive and visual faculties of designers and design students during ideation, this study widens the ambit of this focus by showing that design students also play the role of 'aesthetes' where design ideation is driven by aspects of emotion such as 'perception of affective quality.' In a rhetorical graphic design context, this study shows how the roles of interpreter, imager, and aesthete interact to shape design ideation and outcomes. Therefore, design ideation is not only cognitive and visual but also emotional. To arrive at these results, the study adopted the interpretive phenomenological approach to gather subjective accounts of design students' ideation experience. This qualitative approach can complement existing quantitative approaches to the study of design ideation using methods like protocol studies and sketching analysis. The personal account given by the design students is a more direct description of the ideation experience which can be further explored. By delineating the specific role of 'aesthetes', this study contributes to the design ideation literature by showing that ideation involves the rich interplay of cognition and emotion and the visual faculties of designers. However, in future, other studies can explore these roles with a larger sample size. The study can also be expanded to professional designers working in real world settings. Furthermore, while this study used graphic design as a context, future studies can involve designers from other domains such as architecture and industrial design.

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Research Questions in Applying Quantum Computing to Systems Design

James Gopsill, Oliver Schiffmann, and Ben Hicks

Model-Based Systems Engineering and our ability to computationally model all manner of design feature is pushing Systems Design into new and exciting areas. Design spaces are becoming increasingly hyper-dimensional featuring a vast set of design options and constraints. This vastness is often a challenge for classical computation resulting in numerous techniques to efficiently explore the design space. However, these introduce uncertainty concerning the derived solution as the design space is not evaluated in its entirety. In this paper, we perform an empirical study applying Grover's quantum computing algorithm for unstructured search was applied to an 8×8 tiling problem. Achieving this evidenced quantum computing's application for Systems Design problems and the computational gains it can bring. In addition, nine research questions in applying quantum computation to Systems Design were elicited. Answering these research questions will step us towards quantum-enabled Systems Design.

Introduction

Systems Design is the science of configuring a system to optimally meet the needs of its stakeholders [1]. The associated design space of a Systems Design problem is typically hyper-dimensional requiring the validation and subsequent scoring of a vast number of design options against an equally vast number of criteria. The validation and score are then used by engineers to review and select a design.

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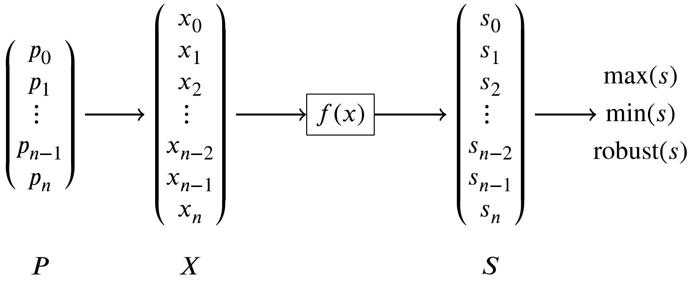


Fig. 1 An abstraction of the Systems Design problem

Typical systems range from gearboxes, multi-bar mechanisms and pipe networks through to production lines, nuclear power stations, aircraft, automobiles, skyscrapers, satellites, and space stations. Notable examples include the development of the B2-bomber, Boeing 787 Dreamliner, and re-configuration of the ExCeL center as the NHS Nightingale hospital to respond to COVID-19. In these cases, both researchers and practitioners have concluded that they could not have developed an optimal solution without taking a Systems Design approach [2–4].

A Systems Design problem can be defined abstractly as an evolving design parameter set, P, that combine to create a set of design options, X (Fig. 1). This is referred to herein as the design space. The design options are subsequently passed through a function, $f(x)$, which features the constraints and performance assessments for a design option. The result is a set of scores, S. Design options that do not meet the constraints often either exit $f(x)$ with a 'False' value or fixed negative score beyond that which can be attained from $f(x)$. The role of the individual(s) is to configure the computer to navigate the design space with the objective of identifying optimal and/or robust solutions.

While the premise is straightforward, the scale of modern-day systems means that for reasons of time and resources, the full design space is rarely computed. For example, consider a 3-stage gearbox and motor system with the objective of finding an optimal configuration. A typical set of design parameters, P, may consist of:

- 17 gear options for the 6 gears;
- 5 materials for the 4 shafts;
- 9 bearing options for the 8 bearings; and,
- 8 electric motors for the motor.

To evaluate an option, $f(x)$ would often evaluate the performance, check for potential clashes, preferred (bounded) gear ratios, overall reliability and efficiency and peak stresses.

The set of design parameters generates a design space comprising 5.18×10^{18} design options. To evaluate all solutions, assuming that a design option can be evaluated ($f(x)$ calculated) in one clock cycle on a 1 GHz processor, would take 164 years.

Although small in terms of design parameters, this problem demonstrates the computationally intensive nature of Systems Design, which is driven by the size of the design space and computational complexity of calculating $f(x)$.

To solve Systems Design problems, methods, such as evolutionary algorithms, and gradient descent, have been developed and employed alongside Model-Based Systems Engineering (MBSE) approaches. These both add structure to the exploration of the design space and optimize the execution of $f(x)$ with constraints and performance assessments being run in parallel as well as being ordered by computational complexity [5–7]. However, such methods still fall foul of issues such as:

- local maxima and minima;
- the ability to navigate across disjoint design spaces; and,
- limited by the computational time and resource available.

Thus, there will always exist a degree of uncertainty in the results.

Quantum Computing provides a new method by which we can interrogate design spaces [8]. The mechanisms of superposition and entanglement enable us to define the design space as an ensemble of quantum states and manipulate this ensemble as one. Over the years, mathematicians have developed algorithms that exploit the features of quantum computing to provide a computational advantage over classical computation.

One such example is Grover's algorithm for quantum search [9]. This has been shown to offer a $\sqrt{n}$ performance compared to $n/2$ for unstructured search. If we were to exploit this quadratic speed-up, engineers would have the potential to canvas the entire design space overcoming the uncertainty present in current approaches. They would also be able to explore design spaces of a size that would not be practical for classical computation.

To examine this further, this paper reports on the application of Grover's algorithm to a Systems Design problem. Through this study, we elicit the research questions that need to be addressed in order for Systems Design to take advantage of Quantum Computation.

Grover's Algorithm for Unstructured Search

Grover's algorithm identifies the subset of options that meet our constraints and can achieve this with a quadratic speed up when compared to unstructured search [10]. It achieves this by employing amplitude amplification.

A general implementation of the algorithm is depicted in Fig. 2 and features four steps, Initialisation, Oracle (U_f), Diffuser (U_s), and Measurement, and features four bit registers—a variable qubit register (v_{reg}), clause qubit register (c_{reg}), single validation qubit (v) and classical qubit register (c_{bits}).

The variable qubit register is used to represent all the options we wish to search through and often acts as an index that can be later unpacked to describe an option.

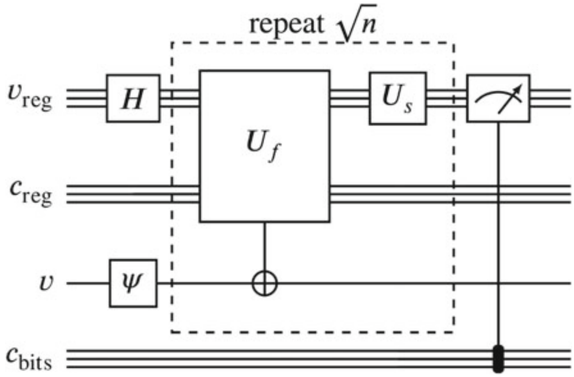


Fig. 2 Grover's algorithm

The clause register is used to reason about our options and performs the checks as to whether an indexed option is valid for our problem. The validation qubit is used to indicate which options are valid and invalid to our problem. The classical bit register is used to store the outcome from the computation.

First, we initialise our circuit. The variable qubit register typically has Hadamard gates applied to the qubits to form a uniform superposition of the option indices. This enables 2^n options to be represented with n being the number of qubits in the register. The clause register is typically set to |0 > in preparation for being used to validate the set of options using a, to be defined, series of quantum gates. The valid qubit is set to |- > and enables us to perform amplitude amplification on our set of options. The classical bit register is the same length as the variable qubit register and are also set to 0 and await the outcome of our computation.

Second, we create an oracle, U_f, that evaluates the ensemble of options using the clause register. If an option is deemed valid, it flips the valid qubit. As the valid qubit is of a different phase, the act of flipping the valid qubit introduces phase kickback making the entire option shift in phase. The result is that all the valid options feature a different phase to the invalid options. Achieving this phase difference sets the problem in a manner where amplitude amplification can be exploited.

Third, we apply the diffuser, U_s, which performs the amplitude amplification that results in a considerably heightened probability of retrieving a valid option while lowering the probability of retrieving invalid options. Steps two and three are repeated with $\sqrt{n}$ times providing near certainty of retrieving our valid option.

Four, we measure the quantum computer, which takes it out of its quantum state and returns a single option as the result. Our manipulation of the quantum state ensures that it returns an option that is valid to our problem.

Applying Grover's Algorithm to a Systems Design Problem

To explore the potential of quantum computing for Systems Design, we performed an empirical study in applying Grover's algorithm to a configuration design problem. Building on the work of [8], who examined a 2 × 2 tiling problem and demonstrated how one can add design constraints such as no-overlap and none permitted locations (Fig. 3), we sought to tackle a 8 × 8 tiling (configuration) problem.

The problem features two tiles that need to be placed in an 8 × 8 room and adjacent to the eastern wall (Fig. 4). In addition, the two tiles cannot be positioned in the same location. This gives us a Systems Design problem with 4096 design options with 56 valid solutions.

To solve this problem, we had to define an index strategy for the potential tile locations across the 8 × 8 grid. This was achieved using three qubits to represent the locations along a dimension giving us twelve qubits—six for each tile (Fig. 5i). This formed our variable qubit register, which we will refer to as our design option

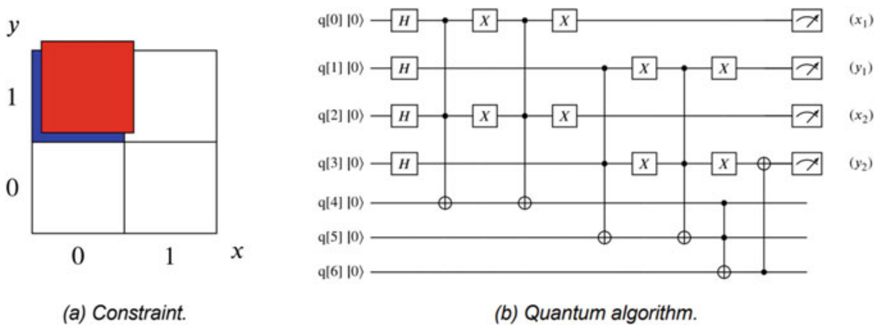
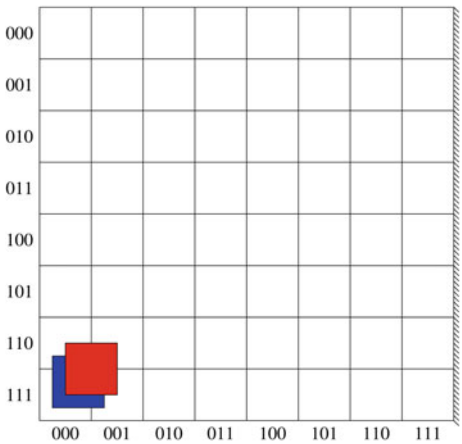


Fig. 3 Applying constraints to a 2 × 2 tiling problem [8]

Fig. 4 8 × 8 Tiling problem



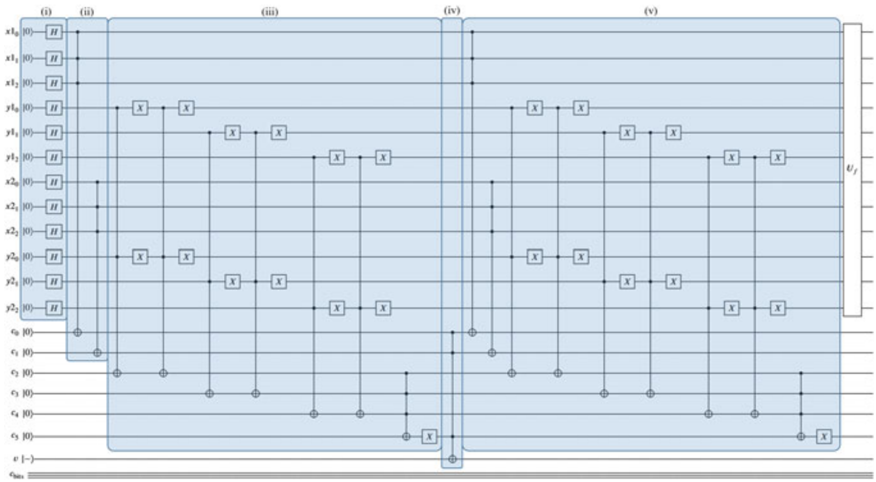


Fig. 5 The quantum circuit

register herein. Setting the register into superposition forms the design space of 4096 options that we wish to explore.

With the design option register configured, the next step required the creation of an oracle that could evaluate the constraints and check whether an option is valid for our configuration problem. The first constraint to check was the adjacency check with the eastern wall (Fig. 5ii).

A multi-control Toffoli gate connected to the three qubits representing the *x* dimension for both tiles and individual clause qubits—c_0 and c_1—would flip the clause bit if all dimension qubits were 1—i.e., the option is along the east wall. This check is performed for both tiles.

The second constraint required us to check whether the tiles are in the same location (Fig. 5iii). This is achieved via bit comparison between the qubits used to represent each tile. The y-dimension qubits between the two tiles were compared using a Toffoli gate, which flips the clause qubit to 1 if both the options qubits are 1. A Pauli X gate is then applied to each qubit and the process is repeated to capture states where they are both 0. We use the Pauli X gate to temporarily flip the qubit and after another Toffoli gate, we apply another Pauli X to return the qubit to its original state. A multi-control Toffoli is then applied across the three clause qubits—c_2, c_3 and c_4—and causes c_5 to flip if all are 1, which indicates the tiles are in the same location. We then apply a Pauli X gate to flip the c_5 as we want to identify the solutions that do not meet this criterion.

We now have a set of clause qubits—c_0, c_1 and c_5—that will be 1 if the design option has satisfied them and we use a multi-controlled Toffoli gate to flip the valid qubit if that is the case (Fig. 5iv). This introduces the phase kickback to the valid design options.

The last element of the oracle is to return the clause qubits back to their original values so the oracle can be re-used (Fig. 5v). This is achieved by repeating the constraint check computation and is referred to as 'uncompute'.

The next element is to add the diffuser, U_s, which uses the implementation described in [10]. This performs the amplitude amplification providing the quantum advantage in promoting the valid options as more likely to be retrieved when the quantum computer is measured. These steps were then repeated to heighten the probability of valid solutions being returned through measurement.

The circuit was then implemented on a classical computing quantum simulator using Qiskit[1] that simulated a perfect quantum computer. The simulation was performed on a 24-core 256 GB workstation PC. The number of Grover iterations set to 16 with 200 runs of the algorithm. Figure 6 shows the results with the circuit achieving amplitude amplification with almost all results returned being valid solutions to the design problem.

Comparing with Classical Unstructured Search

Having demonstrated that we can derive a solution to the problem using Grover's algorithm, we can perform a brief comparison of the computational requirements and compare this to an unstructured classical approach.

Starting with a classical unstructured search. Assuming we know, or have an approximation of, the number of solutions we're looking for, s (56 in this case). The probability of returning s within measures, m, for a classical search of our design space, n, can be described as follows. First, we first determine m's k-permutations, $m!$. Now we say that $s!$ must reside in m's k-permutations. We then need to then determine the k-combinations that exist to fill the remaining slots in the m permutation to accompany s—$C(n\text{-}s,\ m\text{-}s)$. Multiplying the two together gives the number of sequences of m that feature n. This is then divided by the k-permutations of n in m, $P(n,\ m)$.

The result is:

$$c_c = \frac{m!C(n-s, m-s)}{P(n, m)}$$

where $n \geq m \geq s$.

For our quantum algorithm as-is, we could simply repeatedly measure with an equal chance of selecting one of the valid options. The confidence, c_q, in retrieving s within m measures is given by the number of permutations of s, $s!$ multiplied by the Stirling number of the second kind and divided by the number of possible returned sequences, s^m.

[1] https://qiskit.org/.

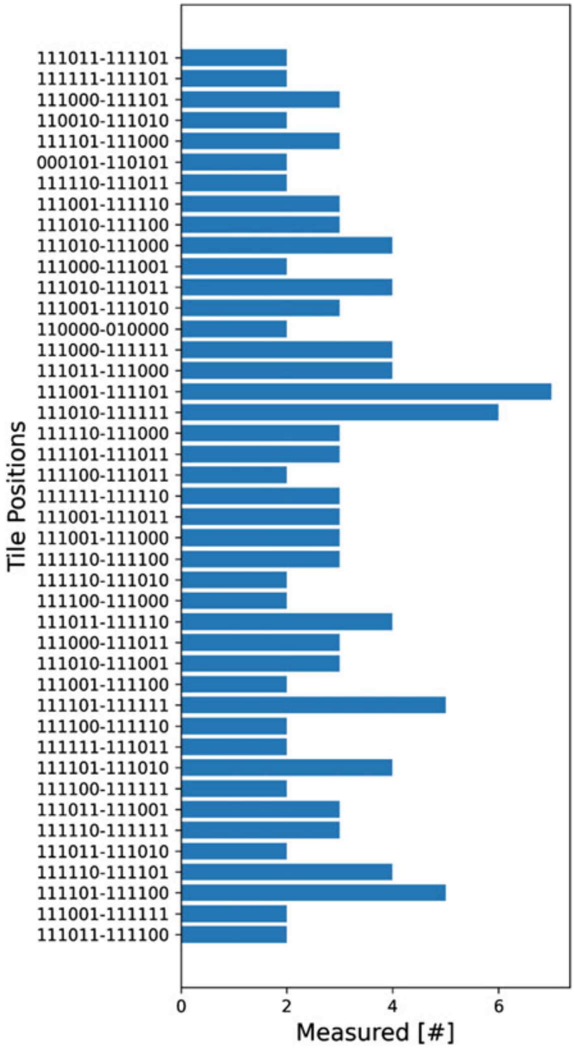
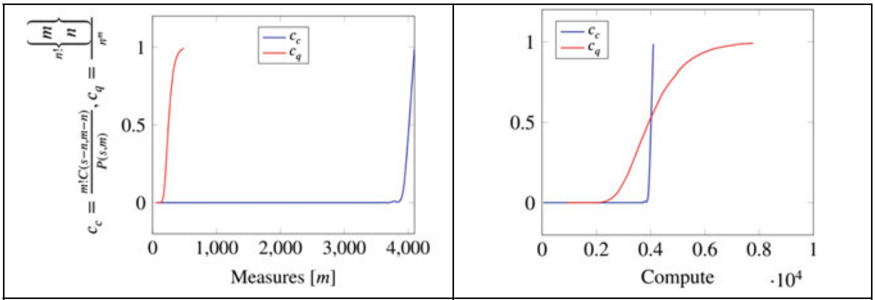


Fig. 6 Demonstration of Grover's algorithm being applied to a 8 × 8 tiling problem

$$c_q = \frac{s!\left\{ \begin{matrix} m \\ s \end{matrix} \right\}}{s^m}$$

Figure 7 reveals the confidence that we have in retrieving s in a fixed number of measures (7a) as well as equating for the level of computation required (7b). This was achieved by taking the unit of computation as a single evaluation of a design option in a classical computer compared with a single iteration of Grover's algorithm. Thus, for a classical computer, there is a one-to-one mapping within 4096 compute cycles needing to be performed to be confident in returning the solutions. In the case



(a) Measures | (b) Compute requirements

Fig. 7 Confidence in retrieving all solutions in m measures

of using the quantum algorithm as is and set at 16 iterations per measure, we get ~ 7000. This could be improved by reducing the number of iterations.

Also, we could also adapt the quantum algorithm to check for existing ‘known’ valid solution and add a clause to make the invalid for the future runs. This would remove the element of chance of retrieving an existing known solution with little additional computational complexity. At best then, we could achieve all the results in 56 runs of the quantum algorithm. For an algorithm that includes a clause to negate the known solutions, we get $56 \times 16 = 896$—a 4.5 times performance increase. So even for this illustrative example, we can observe the potential of quantum computing for systems design. And the scaling behaviour of quantum over classical will increase this performance differential further.

Discussion and Research Questions

While building the algorithm, several research questions arose. The first is defining the methods by which we index our design space. In the example, we used qubits to represent our spatial dimensions. But as we build out more complex systems, we will need methods that can take an index and unpack it to describe all the features of a potential design.

The second concerns the constraint applied to our Systems Design problems and related to question one, is there a set of generic primitives that we can use across our Systems Design problems? If we are able to develop such a toolbox, then this would support the application of quantum computing across the discipline.

The third then looks at the practicality of real-world quantum computing. The simulation of this illustrative problem took a reasonably powerful workstation, and the modelling of larger quantum computing system is challengeing for classical computers. Real-world quantum computers are beginning to emerge with 50 qubits but there is the question as to what size of quantum computer do we need in order to move beyond our current practice and explore real-world design spaces [11].

Four, we have been working on the premise of a 'perfect' quantum computer, but current technologies feature noise, which limits the depth of quantum circuits. Thus, there is also a question as to the different types of constraint operations and which ones are likely to be included in algorithms in the near and far term.

Five, we also posited that it would be relatively simple to include known results in a clause check for a quantum algorithm to further help reduce the search space as we measure results from the quantum computer. However, this still needs to be verified as well as determining whether there is a standard form this should take so that a standard practice can be put in place in solving Systems Design problems using QC.

Six, is the role of both classical and quantum computing to work together in solving our systems design problems. A classical computer could be used to verify results from a quantum computer as well as the quantum computer acting as a 'spotter' of areas potential solutions in our hyper-dimensional design space. A classical computer could then perform a more focused search on these areas.

Seven, is in exploring how can consider scoring solutions alongside constraint satisfaction so we are able to identify the optimal design options given an objective. We have also only examined Grover's algorithm and research needs to consider how other quantum algorithms could be deployed to support us in solving Systems Design problems—Eight.

Nine, the current oracle applies classical methods to check the constraints on a design option and their may be constraints that could also take advantage of quantum algorithms providing further speed-ups in a design options evaluation.

In summary, 9 research questions were elicited from the practical development and implementation of a quantum algorithm to solve a systems design problem:

1. How to map/index a set of design options to a set of qubits set in superposition?
2. Are there some standard building blocks for building out systems design problems in a quantum computer?
3. What are the quantum compute requirements to solve typical constraints and performance criteria?
4. What sets of constraints are achievable in the Noisy Intermediate-Scale Quantum (NISQ) era?
5. Is there a systematic method of removing a known solutions from the valid solution set once it has been returned by the quantum computer?
6. Hybrid computation using quantum computing as a 'spotter' for areas in the design space for classical computing to evaluate around
7. How do we move from constraint satisfaction to scoring?
8. How can other quantum algorithms support Systems Design?
9. Are there any speed up within the checking algorithm itself?

Conclusion

System's Design problems are inherently challenging for classical computers to solve and has resulted in an entire discipline in how to conduct design space exploration in an efficient and optimal manner. However, an uncertainty will remain as the design space is never fully evaluated. Quantum computing has the potential to provide quadratic speed-ups in the exploration of the design space and enables us to reason across the entire design space. This could eliminate the uncertainty we have in reasoning about our current design spaces as well be able to explore increasingly large design spaces.

This paper has demonstrated how quantum computing, and more specifically Grover's algorithm, can be deployed to reason about a design space. Through the practical implementation of a quantum circuit to solve a Systems Design problem, we elicited 9 research questions that need answering to bridge the gap between the disciplines.

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Human Behavior

"Like a Moodboard, But More Interactive": The Role of Expertise in Designers' Mental Models and Speculations on an Intelligent Design Assistant

Vivek Rao, Elisa Kwon, and Kosa Goucher-Lambert

The successful adoption of artificial intelligence (AI)-enabled tools in engineering design requires an understanding of designers' mental models of such tools. This work explores how professional and student engineering designers (1) develop mental models of a novel AI-driven engineering design tool and (2) speculate AI-enabled functionalities that can aid them. Student (N = 7) and professional (N = 8) designers completed a task using an AI-enabled tool, and were interviewed to uncover their mental model of the tool and speculations on future AI-enabled functionalities. Both professional and student designers developed accurate mental models of the AI tool, and speculated functionalities that were similarly "near" and "far" in terms of analogical distance from the AI tool's functionality. These findings suggest that mental models and cross-application of AI tool functionality are readily accessible to designers, offering several implications for widespread adoption of AI-enabled design tools.

Introduction

Teaming between humans and artificial intelligence (AI) has been widely explored in engineering design research [1]. Studies have described how AI can learn from human designer behavior [2], how human designers' performance improves with the assistance of AI [3], and the negative impacts of poorly-contextualized AI assistance on human design teams [4]. Common across these studies is the fact that, when applied carefully, AI systems create the most value when partnered with humans in teams [5]. This value is not limited to the team itself: human-AI teaming broadly promises to enhance the value and impact of design in *organizations* as well [6].

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To unlock the power of human-AI teams, however, human team members must first willingly adopt and integrate AI into their work, requisite for broader integration of new technologies into organizations' practices [7].

Critical to effective adoption of AI tools are the *mental models* a designer has of what an AI tool is and does [8]. Norman, exploring end-user interaction with products, defined a mental model, or conceptual model, as an individual's "explanation of how something works" that is "often inferred from the device itself" [9]. Individuals with 'sound' mental models of an intelligent tool appear to achieve more better outcomes from it [10].

Engineering designers, however, must not only *adopt* AI, but *adapt* it to the kinds of complex and uncertain challenges they encounter in their work. From this perspective, two cognitive strategies outlined by Ball and Christensen are relevant: *analogical reasoning,* which describes "transferring previously acquired knowledge … to support current problem solving" and *mental simulation*, which describes a designer's use of imagination "to test out ideas and validate solution concepts" [11]. Here, we combine our examination of both analogical reasoning and mental simulation under the umbrella of *speculation* about AI tools, to reflect our focus on understanding novel applications of AI that may emerge in engineering design contexts. In this work, *speculation* describes a designer's ideation and narration of how AI-enabled functionalities could address current challenges or opportunities the designer faces, combining elements of analogical reasoning and mental simulation.

Despite their importance, few studies have examined how engineering designers develop mental models about AI tools, or how they speculate AI applications in their domain of practice. Similarly, while mental models, analogical reasoning, and mental simulation have shown to depend on a designer's expertise [12]–[15], little is known about how expertise informs these behaviors in the context of intelligent design tools. Addressing these knowledge gaps is essential to ensure researchers and leaders can best support designers in adopting and adapting AI tools as they further permeate engineering design practice.

In this work, we seek to develop a preliminary understanding of designers' mental models of AI-enabled design tools, designers' speculations on AI-enabled functionalities, and the relationship of both to designers' expertise. We present insights from semi-structured interviews with student (N = 7) and professional (N = 8) designers following their completion of a task involving a novel AI-enabled design tool developed by our team. We address two research questions, each of which we examine and understand with a specific consideration of designers' expertise:

1. What mental models do engineering designers develop of a novel AI-enabled engineering design tool?
2. What speculations about AI functionalities in their own domain do designers envision?

The main contributions of this study are twofold. First, we describe mental models and speculation immediately following engineering designers' engagement with intelligent tools. Second, we explore preliminary evidence of similarities and distinctions in the mental models and speculations that novice and professional designers develop.

Related Work

In this section, we briefly review five relevant areas of engineering design research to contextualize our work. First, we consider foundational and recent examples of AI-enabled functionalities in engineering design. Second, we consider relevant work on human-AI teaming. Third, we explore literature describing users' mental models of intelligent agents. Fourth, we briefly describe relevant work on analogical reasoning and speculation in engineering design. Finally, we briefly describe pertinent findings related to the distinctions between novice and expert designers regarding mental models and analogical reasoning.

AI-Enabled Functionalities in Engineering Design

AI methods have increasingly been used to assist humans with engineering design. In early considerations of the role of AI in supporting creativity, Boden described AI as potentially useful for novel combinations of familiar ideas (i.e., analogies) and exploration and transformation of the conceptual design space [16]. Recent work in engineering design has used AI to advance engineering design capability by enhancing conceptual design, accelerating design processes, and reducing and eliminating iterative design processes [1]; AI has been shown to be effective at various stages of the design process. Understanding user needs can be accomplished by AI through natural language processing (NLP) on product reviews [17]. AI can additionally use NLP to facilitate concept selection and evaluation based on user product reviews [18] or machine-learned ratings of design concepts [19]. Various AI-driven approaches utilizing NLP or latent semantic analysis (LSA) are useful for retrieving and representing design ideas from large datasets of text-based stimuli such as patents [20, 21], or crowd-sourced designs [22]; more general semantic networks, e.g. TechNet, broadly support engineering design activities [23]. Beyond sourcing design ideas from text-based data, deep-learning, neural-network-based approaches can be leveraged to also extract visual information from design examples from e.g., sketches, patent databases, or 3D-model data [24].

Our work extends on the AI design-support tool developed by Kwon et. al [24], but rather than present the design outcomes achieved when interacting with this system, we consider how AI is used and understood by designers. Accordingly, our contribution aims to improve how we can support the adoption and adaption of future AI-enabled engineering design tools.

Human-AI and Human–Machine Teaming in Engineering Design

Models of how humans and AI or machines should 'team' to achieve desirable design goals are widespread [25]. Recent research by Zhang et al. memorably highlighted that humans expected AI teammates to be an "ideal human" [26]. However, many AI systems function more as 'tools' rather than 'teammates,' a distinction that can be often arbitrarily perceived by the end-user interacting with the agent. In a large-scale study, Lyons et al. discovered that more than two-thirds of over 600 surveyed workers viewed intelligent systems they interacted with to be tools, rather than teammates, because the workers perceived a lack of decision authority and richness of communication [27]. Despite the heavy influence of perception on the distinction between teammate and tool, frameworks such as *autonomous agent teammate-likeness* establish guidelines for various types of representation of team members [28]. However, as software systems shape new workflows for the individuals using them [29], so does the introduction of AI tools. Describing the first CAD tools, and how such tools transformed designers' workflows, Ozkaya argues: "We will likely observe similar task shifts… through the development and use of AI-enabled systems" [30].

In this work, we present a relatively tool-like AI assistant into an open-ended task in a workflow familiar to engineering designers: 3D CAD design. Extending from Ozkaya's framing, we seek to understand how the functionality enabled by AI in our assistant invites different workflows for our participants, and connect such workflows to the mental models participants develop about our tools. We explore how an AI tool may—or may not—inspire designers' envisioning of new functionalities enabled by AI.

Mental Models in Engineering Tasks Related to AI

Mental models are how individuals make sense of systems they interact with: they are an individual's beliefs about a system and represent functionalities of the system perceived by them [9, 31]. Mental models can be inaccurate, and inaccurate mental models may lead to the *gulf of execution,* or a mismatch between the user's expectation of a system's function and its actual function [32], which may lead to poor adoption and less effective use of such systems. We note that in design research discourse, a *mental model* can be thought of as somewhat distinct from a *shared mental model* or a *team mental model;* these latter constructs describe a team's convergence on shared understanding and knowledge in their work [33] and have also been used to describe engineering design team behavior [34].

Several studies have explored how end-users develop mental models of AI while executing complex tasks, like design. These are primarily focused on how a user develops a mental model of trusting AI [35]. Tenhundfled et al. identified that users developed no consistent mental model of voice-controlled personal assistants despite similar interactions [36]. Tomsett et al. argued that rather than an immersive experience with an AI tool, users could create a mental model quickly if the systems offered interpretability and estimates of uncertainty [37]. Riveiro and Thill critically identified the importance of a user's *expectations* of an AI system in shaping their mental model, alongside the functional output of such a system [38]. Most pertinently among recent studies is Bansal et al.'s work examining the mental models that users of AI-based systems create while interacting with a decision-recommendation AI tool [8]. The authors focused on a specific dimension of the user's mental model, that is, the user's perception of the likelihood of error of the AI agent, the error boundary, in an experimental study of how users engage with an intelligent agent. Finally, as Wang et al. illustrated, users' mental models of AI assistants evolve over a period of usage and exposure, suggesting that mental models are not just experiential, but temporal, as well [39].

In this work, we extend on the idea of ascertaining a user's mental model of an AI system to understand *what* beliefs end-users hold about an AI system in a complex design task. While many of the leading studies such as Bansal et al.'s have focused on mental models grounded in error and trust, we focus on surfacing users' mental models related to the AI system's purpose, leveraging the Function-Behavior-Structure (FBS) framework [40]. Furthermore, we explore questions of mental models in AI systems in an engineering design CAD context, not an HCI context. We note that this work considers mental models at a single instant—immediately after interaction—as our interest is in *perception and adoption* of AI systems, rather than longitudinal evolution, which would invite further study.

Analogical Reasoning and Speculation in Engineering Design

Analogical reasoning, mental simulation, and their relation to design cognition and metacognition have been reviewed elsewhere [41]. Here, our review focuses on relevant background in *spontaneous*, *self-generated* analogizing pertaining to transfer *within* and *between* domains in engineering design. Then, we review mental simulation in engineering design.

Self-generated analogies are a crucial component of the design process. Christensen and Schunn [42] revealed that 'near' analogies—those that are *within* the domain of the target—were more frequently employed to identify a problem in design, but 'far' analogies—those that connect *between* an outside domain and the target domain—were more frequent during explanation in design. Further work by Ball and Christensen, and later Wiltsching et al., suggested that self-generated analogies reduce subjective uncertainty in design [11, 43]. Mental simulation is a "cognitive mechanism that enables reasoning about how physical systems might behave without the need actually to construct such systems" [44, 45]. Mental simulation allows designers to envision, explore, and evaluate possible concepts or solutions, and has been shown, like self-generated analogy, to play a key role in reducing uncertainty in the design process [11, 42].

In this work, we extend on previous work in analogical distance and mental simulation to examine (1) what types of analogies engineering designers employ when explaining an intelligent agent and (2) how mental simulation affords designers' speculation on AI functionalities, and the relationship of speculated functionalities to the intelligent agent they engaged with. In this study, elements of analogical reasoning and mental simulation are described by *speculation* in the context of designers' ideation of AI functionalities applied to next engineering design contexts.

Experience in Designers' Mental Models and Speculation

We focus our review on observed differences in mental models and analogical reasoning based on designers' experience. Only one study examining the differences in designers' mental models based on experience could be found. Fish et. al, in studying the differences in mental models of products (a hair dryer, leaf blower, and clothes dryer) between sophomore and senior engineering design students, found no significant difference between mental models despite a difference in experience [15]. The authors ascribed this to differences in curricula the students were exposed to.

Several studies have explored differences in analogical reasoning in engineering design based on experience. Ahmed et al. found that novice engineering designers tended to develop analogies based on explicit geometric information in a given part, while experienced designers used analogy for more abstract tasks of problem identification and problem solving [13, 14]. Studying architectural designers, Ozkan and Dogan found that experts made analogical 'mental hops,' connections to near-source domains. 'Hops' were typically grounded in structural similarity and led to incremental innovation. In contrast, first-year students made 'mental leaps,' connections to distant domains. 'Leaps' were typically grounded in surface similarity and led to more original solutions [12].

In this work, we extend Fish's work to explicitly explore the role of experience in mental models of AI agents. Rather than take a quantitative approach, we use interviews to ascertain users' perceptions of the AI tool's FBS to deconstruct their mental model of it. We similarly build on Ahmed and Ozkan and Dogan's results, by seeking to understand how the experience level shapes users' ability to speculate and transfer their experience with AI into novel domains.

Methods

In this section, we present background on the research study methodology: participants, the engineering design tool and task we developed, and the interview study. An overview of the methodology employed is in Fig. 1.

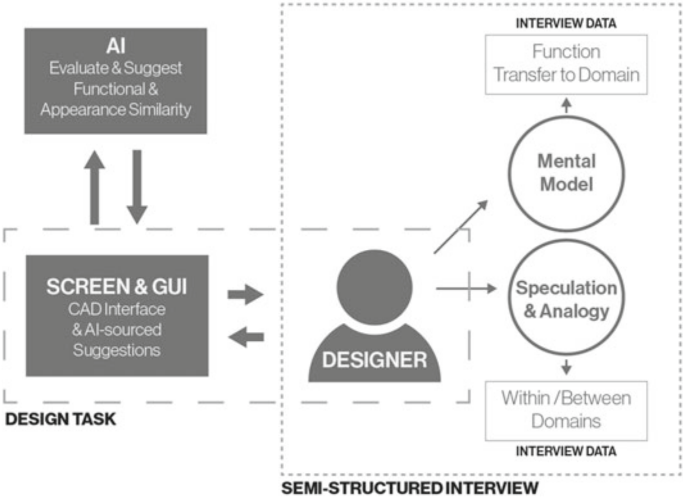

Fig. 1 Overview of methodology. A CAD interface is coupled to an AI backend, providing suggestions of 3D models that are similar to user-selected parts. After a 30-min design task, a 30-min semi-structured interview, the focus of this paper, elucidates the designer's mental model and speculation on future AI tools. Interviews are examined based on FBS and analogical reasoning frameworks

Participant Information

Participants were recruited via email solicitation among graduate students at the University of California, Berkeley, and professional networks in industry. All participants were required to meet the minimum eligibility of having at least 1 year Computer-aided design (CAD) experience. Fifteen participants volunteered for the study, including eight professionals (Table 1) and seven students. Students (3 males and 4 females) had self-reported experience with CAD tools ranging from <1 year to 9 years, and professionals (7 male and 1 female) had 3 to >10 years of professional design experience, also self-reported. Participants were offered $20 compensation for their participation in the 1-h study. Interviews were conducted via Zoom, using screenshare and audio transcription. This study was approved by the university's institutional review board.

Engineering Design Tool and Design Task

In this study, engineering designers completed an approximately 30-min design task using an AI-enabled tool we developed for multi-modal search for 3D parts. The objective of the design task was to use the tool to search for 3D parts to inspire solutions to a given design challenge. Our design tool relies on a deep-learning approach to efficiently retrieve relevant 3D-model parts based on the user's input

Table 1 Details on professional participants

Identifier	Role	Engineering design experience	Size of organization
P-1	Designer	10+ Years	>10,000
P-2	Designer	6–9 Years	>10,000
P-3	Designer	10+ Years	>10,000
P-4	Engineer	6–9 Years	>10,000
P-5	Designer	10+ Years	>10,000
P-6	Engineer	3–5 Years	<10
P-7	Designer	3–5 Years	1000–10,000
P-8	Engineer	6–9 Years	>10,000

query. Deep neural networks are used to model similarities between various 3D-model parts from the PartNet dataset, consisting of 24 object categories and 26,671 3D-model assemblies. The tool is further described in Kwon et al. [24] (Fig. 2).

The study objective presented to designers was to use the AI-enabled search interface to conduct multi-modal searches for 3D parts as they sought to design a compartmentalized waste bin. To search for parts, the available input modalities include (1) by text-based query, (2) based on another 3D-model part, and (3) based on the user's current 3D-modeling workspace, composed of previously retrieved parts. In the second and third search modalities, sliders in the user interface could also

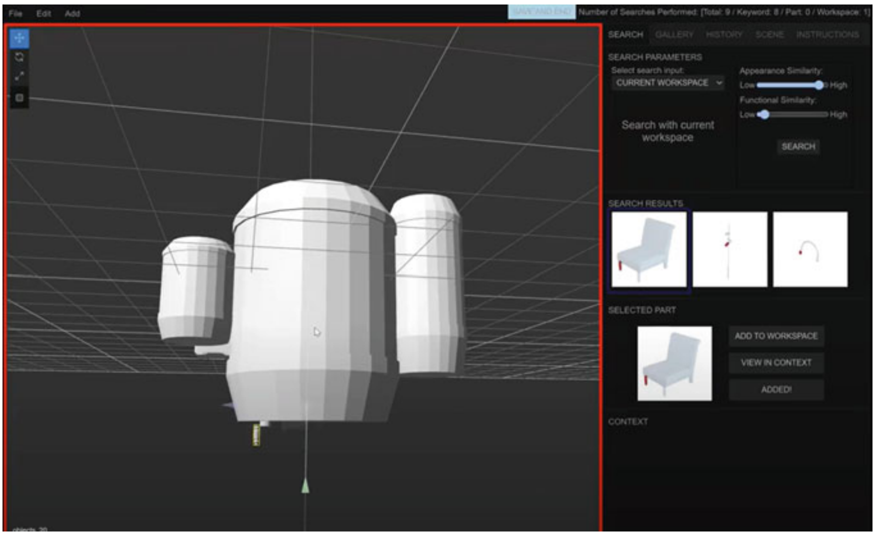

Fig. 2 Design task in progress, with functionality allowing the user to search with the AI-enabled tool. Here, three results have been returned from the workspace-based search input for parts with high appearance similarity. The selected chair leg result has been added to the developing design in the user's workspace

specify how similar the desired results were from the selected part and workspace inputs, respectively, by visual and functional similarity. For each search made, three parts are retrieved and shown in the user interface. Results of the design task are not explicitly discussed in this paper; our focus is on the mental models and speculations that designers expressed following the design task.

Interview Study Protocol and Analysis

Immediately following the completion of the design task, participants were engaged in a semi-structured interview. Questions explored the key themes of the interview study: mental models of the AI tool engaged with in the design task, and speculation and analogy around future AI functionalities (Table 2). Interviews were recorded and de-identified. Two researchers with at least two years of design research experience and two peer-reviewed papers authored proceeded to double-code various portions of the interview, resolving disagreements to reach a 100% inter-rater agreement. A single coder tabulated analogies and named systems.

First, participant-reported assessments of the tool's function (question F1) were coded for the level of abstraction. Level of abstraction was described as whether the function described was *abstract* (meaning the described function was generalizable to many design activities and tasks); *concrete* (meaning the described function was specific to the particular use-case illustrated in the AI design tool); or *hybrid abstract-concrete* (meaning the described function included elements that were both generalizable and specific). This set of codes highlights whether the participant's mental model was tied to the use case illustrated by the tool or not. Given the scope of this exploratory work, we do not consider *behavior* and *structure* in the FBS construct, instead exclusively focusing on *function.* Second, transfer of the illustrated AI functionality to the participant's own domain (question F2) was reviewed

Table 2 Interview protocol: exploration topics, themes, and questions

Exploration	Theme	Question
Mental model of the encountered AI tool	Function	**(F1)** How would you describe what the tool you just worked with does, or, in other words, the tool's function? Why? **(F2)** How important is this function in your work?
Analogical reasoning and speculation about AI functionalities	Key Functionalities	**(K1)** How would you like AI to support you in engineering design? What would the specific functionalities be? **(K2)** How would they help you in your work?

and coded for whether the designer was able to articulate why, or why not, the illustrated functionality was relevant to their work. *Successful transfer* was indicated by a clear and specific rationale for why (or why not) the illustrated functionality could support the type of work the individual pursues. *Unsuccessful transfer* was indicated by a poor or non-specific rationale for why (or why not) the illustrated functionality could support the type of work the individual pursues. Third, participant speculation on AI functionalities was reviewed (question K1 & K2) and coded for whether the proposed functionalities were, relative to the original AI search tool, *within-domain* or *between-domain,* drawing on Christensen and Schunn's work [42]. Coders determined whether the speculated application was 'within' the domain of the original functionality of a search design task, or 'between' the original functionality and another, very different functionality. Fourth, a single researcher identified (1) analogies and (2) named systems from a designer's experience and practice that were important to their mental model of the AI tool or their speculation on future functionalities.

Results & Discussion

Mental Models and Perceived Function of AI Tools

We first describe the mental models participants developed of the AI tool by examining the level of abstraction of the *function* they described. Nearly all participants were able to clearly articulate the function of the tool they engaged with (question F1). In many cases, these assessments were quite close to the actual purpose of the tool as defined by the researchers. Participant responses varied in terms of the level of abstraction, that is, whether they concretized the purpose in a specific function, or abstracted it to a more generally applicable statement of function (Table 3).

These results suggest that both students and professional designers are able to construct mental models that soundly represent the function of the AI tool. This is promising for future AI tools in design, as designers are able to quickly grasp the function of an intelligent tool, a prerequisite to *adoption* of such tools. In terms of ability to construct these mental models, there appears to be no meaningful difference between the two groups, reinforcing Fish et al.'s findings [15]. Further research could explore the apparent result, although not significant, that professionals more often interpreted the functionality of the tool abstractly than students did. This suggests a greater readiness to transfer the tool's functionality and principle to another context than that presented, which will be discussed in the next section.

Table 3 Mental model level of abstraction examples

Mental model level of abstraction	# of responses		Example quote	Participant code
	P	S		
Abstract	4	3	*“Quickly visualize a form or function, not in detail not in nuance, but enough to capture the functionality of what I’m trying to do.”*	P-2
Concrete	4	4	*“… develop simplified 3D CAD files. I like the functionality that allowed us to search for pieces that might not normally come up in mind.”*	*S-1*
Hybrid Abstract-Concrete	1	0	*“[the tool’s function is to] … help me find mechanical components that might be relevant to my design either for inspiration or directly incorporating into the design, or a small part that could be reused.”*	*P-8*

Transfer to the Participant’s Domain

Next, we examine if participants were able to transfer the perceived function of the AI tool into their own domain of expertise. All participants, regardless of experience level, demonstrated successful transfer, even if that transfer meant no fruitful application (question F2). A professional described process-oriented benefits of the tool:

> *[It] helps me get through my thinking faster. Simplifies my thought process on where to start .. to think about what to type to search it helps me think about the bigger picture of where my product is going.* **(P-3)**

A student, not finding a functional benefit for their own work, said:

> *In my work I don’t have liberties to make changes. But it makes me inspired, I really like that the search function didn’t give me what I was expecting.* **(S-8)**

These findings suggest that participants of all experience levels could transfer the principles and functionalities illustrated in the design task to their own responsibilities. This is a promising finding for design researchers exploring AI tools, as it underlines designers’ ability to take a specific example of an AI tool and *adapt* it to their work, essential for wider application of AI tools in design and the discovery of new applications.

Analogy and Connections to Named Tools

Next, we examine the analogies and named systems participants invoked in their description of the AI tool to understand differing conceptualizations of the tool. We observed that professionals and students appeared to differ in the number of analogies and references to specific, named design tools they invoked. In responses to questions F1, F2, K1, and K2, professional designers used a total of nine analogies and seven named tools. Student designers, in contrast, used a total of one analogy and eighteen named tools.

One professional analogized the function of the AI tool to a moodboard:

> *Like a moodboard, but more interactive than a moodboard ... you can immediately see your design in 3D, scale it, etc.* **(P-6)**

One example of an invocation of a 'named tool' was this professional designer, who referenced McMaster-Carr when describing a future functionality they envisioned based on AI tools:

> *... [I] go to McMaster and see what's out there. It's nice being able to quickly find the components, using McMaster's search tool and working through catalog pages and stuff.* **(P-8)**

Despite the apparent difference in the usage of analogies and named tools, Wilcoxon Signed-rank tests examining the differences between the number of student and professional *analogies* ($W = 42.5$, $p = 0.0646$) and the differences between the number of student and professional *references to named systems* ($W = 15$, $p = 0.1147$) revealed no significant difference between the groups. We do note that both differences are nearly significant at a confidence level of $p < 0.10$, suggesting that further studies with larger sample sizes could statistically reinforce these findings.

Examining analogies (Table 4), we observe the one student analogy, 'toolbox,' is invoked by professionals. Examining the most frequently named systems (Table 5), three of the systems most frequently named by students are CAD tools. In contrast, none of the professionals named CAD tools during the specified questions, but frequently invoked McMaster-Carr, a popular catalog of components used in engineering design.

Nonetheless, professionals' apparently greater use of analogies points to relatively immediate and specific contextualization of an AI tool into their context. Professionals appear to be able to analogize to a range of concepts, from film ('Mad Max') to anthropomorphic interactions ('Smart Assistant'), than students do. We note

Table 4 Analogies invoked by participants

	Analogy	% of Total
Professional (7 total)	Personal Assistant (1), Lego (1), Database (1), Smart Assistant (1), Library (1), Moodboard (1), Toolbox (1), Mad Max (1)	14 (each)
Student (1 total)	Toolbox (1)	100

Table 5 Top Three most frequent named systems invoked by participants

Professional (9 total)		Student (18 total)	
Named system	*% of total*	*Named system*	*% of total*
McMaster-Carr (6)	67	Solidworks (8)	44
Google (1) Amazon (1) Netflix (1)	11 (each)	Google (4)	22
–	–	AutoCAD (2) Fusion360 (2)	11 (each)

that these analogies were self-generated and explanatory analogies. Students, on the other hand, may have less design practice experience to readily generate analogies, and instead appear to more readily reference specific named systems, particularly CAD tools, in order to articulate their ideas about AI-based tools in design. This is striking as the AI example may evoke the need to ground in well-understood *tools* for description. In contrast, professionals' use of named systems centers on engineering *resources*. This suggests that less experienced designers may look for direct tool analogues in establishing mental models and speculations about AI tools, whereas professionals may be able more immediately envision how AI tools relate to their existing workflows. We caveat this result by acknowledging that these results are not specific AI tools, and may apply to differences between professional and notice designers generally.

Speculation and Exploration of AI Functionalities in Design

Lastly, we examine the AI-enabled functionalities each participant speculated, and evaluated if these functionalities were 'within' or 'between' the functional domain of the presented tool. We found that when asked to speculate on AI functionalities (question K1 & K2), professionals and students were indistinguishable by whether their functionalities were determined to be 'within' the functional domain of the example AI system—retrieving 3D parts—or 'between' functional domains –beyond search and retrieval. Professionals reported four functionalities that were 'between,' with four 'within.' Students reported four functionalities that were 'between,' with three 'within.' One professional described an envisioned functionality, considered 'between' from the example functionality and another domain:

> *In the library if you ran FEA on each component—and then you applied that to the disposal unit. Having known what the loading capacity is, it could understand the context supporting whatever you were trying to do. It might ask you to expand the scale of the foot, or to match the simulation.* **(P-4)**

Another professional described a functionality that was considered within the example functionality's domain:

[there is a] difference between appearance and functional similarity … here, I didn't really care what the part was. The AI could make it much faster. **(P-1)**

These findings suggest that when pursuing mental simulation and speculating on future AI tools, student and professional designers leverage similar modes of analogical reasoning. This finding is in contrast with Ozkan and Dogan's findings that expert designers often executed 'mental hops' in analogical reasoning, or 'within' analogical reasoning, resulting in incremental innovation, while student designers executed 'mental leaps,' or 'between' analogical reasoning, resulting in more originality [12]. We believe this finding offers an extension upon the previous work: that experience plays less of a distinguishing role when it comes to analogical reasoning during speculation. In design problem-solving, there may exist a difference between experienced and novice designers; however, in the differing cognitive mode of constrained speculation on emerging technologies, analogical reasoning that distinguishes less based on experience could occur.

Implications for Design Research and Practice

These findings present two points of departure for design research and practice. For design researchers, this work offers three areas for further investigation. First, our finding that professional and student designers pursue 'between' and 'within' speculation at similar rates could extend on Ozkan and Dogan's findings on the effect of experience on mental "hops" and "leaps" in design [12]. Notably, while their work studied architects in design problem-solving, our work examines engineering designers in speculating on future applications, suggesting that Ozkan and Dogan's conclusions about design cognition may invite nuance in different design problem-solving modes. Further research is necessary to explore *why* professionals and students both pursue similar patterns of speculation in our context—rather than associated with a design task, after all, participant replies came in the context of pure speculation. Second, this work explores the concept of mental models in the context of engineering designers' engagement with AI tools. Subsequent research is needed to explore how to further reconcile behavior and structure from the FBS framework with mental models in the context of AI tools, as this work was only able to examine function. Finally, this work hints at a high level of mental model soundness achieved in a short trial of an AI tool. Further exploration into the nexus between human-AI teaming, mental models, and experiential encounters are necessary to elucidate their interplay in engineering design.

For design practitioners and managers, this work provides preliminary indications of how to best strategize and rollout new AI functionalities into design teams. Perhaps most encouraging is the suggestion that professional designers are adept at *adapting* and *generalizing* a new tool to their work, and are readily able to envision somewhat related functionalities. This latter quality is promising to facilitate high-impact opportunities for AI tools within engineering design and design-driven organizations: it appears design professionals are particularly prepared to help realize this.

Limitations

This work had several key limitations that invite further study. First, the statistical power of our findings was limited by a small sample size, ultimately limiting the generalizability of our findings. Second, ascertaining mental models is a well-known challenge in design research, and use of FBS and our corresponding interview questions warrants further validation and study. In particular, we do not consider *behavior* and *structure* among the FBS construct, which invites further research. Third, our focus on self-generated, spontaneous analogies and named references means that participants predisposed to using analogies and references may have a large influence on our findings.

Conclusions

In this work, we examined how professional (N = 8) and student designers (N = 7) perceived the function of an AI-enabled tool they interacted with, and what kinds of future AI-enabled functionalities they could envision. Three key preliminary findings emerged. First, designers, regardless of experience, were able to construct relatively sound mental models of the AI-enabled tool that represented the function of the tool, and could transfer its functionality to their work responsibilities. Second, professional designers appeared to speculate on AI functionalities 'within' the example AI tool's functionality, while student designers speculated on functionalities that were 'between' from the tool's functionality and other domains. Lastly, professional designers appeared to more often draw analogies in describing the AI tool than students, while students invoked specific design tools than professionals in their descriptions of the AI tool.

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How Long Until We Are (Psychologically) Safe? A Longitudinal Investigation of Psychological Safety in Virtual Engineering Design Teams in Education

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This paper investigates team psychological safety (N = 34 teams) in a synchronous online engineering design class spanning 4 weeks. While work in this field has suggested that psychological safety in virtual teams can facilitate knowledge-sharing, trust among teams, and overall performance, there have been limited investigations of the longitudinal trajectory of psychological safety, when the construct stabilizes in a virtual environment, and what factors impact the building of psychological safety in virtual teams. The results of this study identified that the construct of psychological safety took more time to become a reliable construct in virtual design teams, but once it stabilized, it did not change. Additionally, qualitative findings point to issues with communication and conflict across various stages of the design process in the development of psychological safety. Finally, we identify potential interventions to enhance team mental model development in the early phases of virtual teaming to support team psychological safety.

Introduction

What helps teams to remain effective during a worldwide pandemic? The COVID-19 pandemic has forced us to explore this question as education had to shift to remote formats, relying on conference call applications for events from classroom lectures to proctored exams [1]. Mixed-methods research has shown that this adjustment to online learning has negatively impacted students due to increased stress that can harm class performance [2] and induce hesitance when using tools for conveying social cues [3]. While online learning is not a new concept, e.g., Massive Open Online Courses (MOOCs) that have been in use for several years [4], prior work showed

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that student-to-student interaction in these methods of online learning is typically low [5]. These reduced interactions are especially problematic when it comes to project-based courses that require greater student interaction, such as in engineering design classes. This could in turn prevent the development of team psychological safety, or the "shared belief that the team is safe for interpersonal risk taking" ([6], p. 123). This paper uses a mixed-methods approach to illustrate a framework for measuring psychological safety and analyzing qualitative data to understand how psychological safety influences team interactions in online project-based courses like engineering design. We focus our analysis on (1) understanding when psychological safety becomes reliable and established as a measure, (2) how psychological safety varies between virtual and traditional teams, and (3) the factors that teams perceive to influence the building or waning of psychological safety.

Measuring and Validating Psychological Safety in Teams Research

Psychological safety plays a critical role in how teams coordinate and carry out tasks. Specifically, research has shown that this "safety" in teams is established through deep interactions and conversations that facilitate how team members feel treated and viewed by others [7], building from perceptions at the individual level, and then emerging as a collective team phenomenon [8, 9]. These feelings of psychological safety have also been shown to build and wane over time [10], and have been shown to translate to online contexts [11–13]. However, there are several challenges to supporting psychological safety in teams, including identifying when a shared understanding of team psychological safety is established and how it is affected over the course of a team's lifecycle. Measuring this establishment can show *to what extent* team members can converge to a strong Team Mental Model (TMM), i.e., a measure of how similar team members' organized knowledge representations are with each other [14]. Because psychological safety is dependent on whether team members are in agreement about how they feel about their team [6, 10], the effects of a stronger TMM demonstrate the potential for high psychological safety to drive team performance.

The first challenge of supporting psychological safety is understanding if there is a shared understanding of psychological safety in a team. This shared understanding is important because psychological safety is a *team-level* construct [6], referring to a *shared* belief that a team is safe for interpersonal risk taking. As such, the first step in computing psychological safety is justifying aggregations of individual team members' ratings of psychological safety to the team level and validating the team construct. This justification is established via two methods: (1) calculating interrater reliability (IRR, using Cronbach's alpha), which indicates when perceptions of psychological safety are established, and (2) computing interrater agreement indices

(r_{wg} and ICCs), which justifies aggregating the scale to the team-level [15]. Cronbach's alphas that do not meet the acceptable threshold ($\alpha > 0.70$) may occur due to poor inter-relatedness between items or because heterogeneous constructs are present in the scale [16]. In addition, meta-analysis has shown that greater social presence, such as projecting one's self and the ability to perceive one another in an online environment [17], is related to greater persistence, retention, motivation, and success in an online course [18]. These factors could impact how participants complete course requirements, such as the psychological safety surveys. Therefore, understanding these aspects can help with understanding the challenges of extracting such team-level metrics, especially when some team members do not engage in the course. In contrast with interrater reliability, agreement indices (such as r_{wg}) and team member consistency measures (such as ICC, or intraclass correlation coefficient) allow us to investigate Team Mental Models (TMMs) [19]. Low ICC or r_{wg} values would bring to concern the validity of the TMM, indicating a lack of team consensus on team perceptions of psychological safety [6], and thus raise concern for aggregating team member responses to the team level [20].

The second challenge in supporting psychological safety is understanding when a shared perception of psychological safety is established in a team. While psychological safety has been shown to be a consistent, generalizable, and multilevel predictor of numerous outcomes important to individuals, teams, and organizations [10], these studies tend to implement "snap-shot" methods that capture the psychological safety of a team at the *end* of a project rather than over the course of a project. This is problematic because while these studies show that psychological safety is important factor in a team's performance, we do not know *when* to intervene, or *what type* of intervention would promote psychological safety. While recent research has shown that the TMM on psychological safety may stabilize early on in a team's life cycle in traditional teams [21, 22], psychological safety may be more difficult to establish in virtual teams as task interdependence increases [23]. This can arise from barriers in sensing team members' contexts and motives [24], lack of social and visual cues [25], and social loafing [26]. Furthermore, such obstacles can impact team performance negatively if individuals are "not on the same page" [27]. Thus, the first step is to understand the establishment of psychological safety in the environment that most students and schools can access.

Potential Differences with Virtual Teams in the Engineering Design Process

This section highlights why there may be differences in psychological safety between traditional (in-person) and virtual teams' engineering design processes and how we might be able to foster psychological safety during these stages. Particularly, meta-analytic evidence has shown that psychological safety influences tasks that are complex, knowledge-intensive, and involve creativity and sense-making [28]. These tasks make up the engineering design process [21, 22]. However, moving engineering design to an online environment may negatively impact team psychological safety because engineering teams rely on *knowledge-sharing* [21] to develop design solutions, which can suffer in an online environment [11]. Even more problematic, psychological safety is typically measured using snapshot methods where only one measure is obtained [29], emphasizing the importance of questioning if psychological safety manifests itself differently throughout the engineering design process [22]. However, there has been limited evidence exploring the role of psychological safety throughout the engineering design process, particularly in a virtual setting. While the design process is categorized into three phases including generation, evaluation, and communication [30, 31], the cornerstone of this process is team formation.

The beginning of most engineering design projects begins with team formation, where teams first meet and establish team culture. This early engagement is critical to the establishment psychological safety in a team, but research on traditional teams has shown that teams often vary in terms of formation, leadership, culture, norms, and accountability [32, 33] and that developing *trust* is a critical component of psychological safety [34]. This is further complicated in virtual teams where a lack of trust and free-riding team members is more prevalent, decreasing the likelihood of knowledge-sharing between individuals [11, 25, 35, 36]. In addition, trust can be harder to establish in virtual teams due to lower social presence and slower communication, which can disrupt performance outputs [27], as well as a lack of social cues in the online environment [12, 24] which can limit a teams' abilities to communicate naturally [13, 37]. Leadership is also related to trust such that team leaders can set the tone to create a psychologically safe environment [10, 28]. In online environments, leaders can build trust through "technological cues," such as performing kind gestures and maintaining constant team communication [38]. Stemming from a lack of trust, meta-analytic evidence has shown that the more virtual the team, the greater the opportunity for conflict over tasks [27]. However, conflict is not inherently bad [39], as psychological safety can allow teams to leverage conflict by encouraging team members to speak up and problem-solve through the issue [6, 10]. Otherwise, failing to control conflict can threaten team effectiveness and increase time for task completion [40]. To address trust issues, prior work used icebreakers and social games as interventions to build trust, which have been successful [41]. Additionally, structuring distributed synchronous peer-learning interactions improved performance and participation [42]. However, how we could even begin to apply such tools to foster team psychological safety at the start requires further preliminary work.

Branching after the start of a project, the concept generation stage of the design process relies on teams to develop creative ideas to be evaluated at subsequent stages [43]. Psychological safety is important during this process because low psychological safety can impair the ability to communicate ideas and knowledge [11, 44], as well as provide teams with the freedom to take risks by offering creative solutions [6]. Psychological safety also plays a vital role in concept screening when teams make go/no-go decisions when moving forward with concepts, as teams with high levels of psychological safety are more likely to be open to providing feedback can benefit teams and feeling safe for risk-taking [6], particularly when selecting creative ideas.

Additionally, leader agreeableness can promote psychological safety [45], helping teams to engage in the aforementioned behaviors. During prototyping, students try to convey their designs [46]. In the final stage of the design process, teams compile their work during the final deliverables stage. This stage can be affected by poor communication, which can promote interpersonal tension [10], and lack of time management [22]. In the case of low psychological safety, such issues can fester if team members do not feel safe to question the status quo [6]. This implies that low psychological safety can promote insufficiencies in coordinating together, substantiating its importance until a project's end.

Across the engineering design stages, other factors can also play a role in the development of psychological safety. For example, The Nine Critical Considerations of Teamwork (9 C's) [47] (adapted to the Seven Critical Considerations of Engineering Design (7 C's) in [48]), contain factors highlighted in meta-analytic research [10, 28]. In virtual teams, such issues can be amplified due to reliance on technology, which could limit the ability to communicate and coordinate work [12]. Therefore, how such factors relate to psychological safety should be investigated as well.

Research Design and Methodology

Based on the previous literature, the goal of this work was to investigate the role of psychological safety in virtual engineering design teams. Specifically, this paper was developed to answer the following research questions:

- **RQ1**: How long does it take teams' psychological safety to become a reliable and established measure in virtual teams? Once established, how does psychological safety change over the design process?
- **RQ2**: To what extent is team psychological safety different between in-person (traditional) and virtual teams throughout the design process?
- **RQ3**: What factors impact team psychological safety in virtual engineering design teams throughout the course of a design project?

To answer the research questions presented above, an empirical study was conducted at a large northeastern university in the US during the first project of a cornerstone engineering design course over the Summer 2020 semester. The course provides students with the opportunity to go through an in-depth 4-week design project. The time points in this study represent the milestones in the engineering design process for a team [30] (see Fig. 1).

Participants

Thirty-four engineering design student teams across six sections (i.e., classrooms) composed of 127 participants (93 males and 34 females) participated in the study.

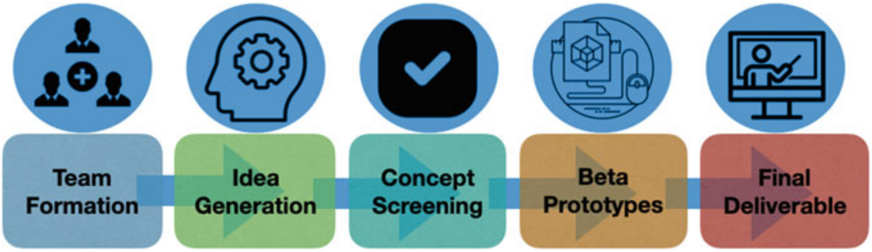

Fig. 1 Study timeline—psychological safety was captured at the end of each design stage, lasting approximately 3 h each (total time period: 4 weeks)

All participants were enrolled in a first-year engineering design course at a large northeastern university. The study was integrated into the curriculum through a series of surveys at the end of stages to represent the time points, where Miller et al.'s [22] work looked at traditional teams in engineering design. However, the current investigation examines six sections of a first-year engineering design course, and both studies occurred as a condensed summer session course. The traditional teams focused on designing for the developing world, and the virtual teams focused on designing for the developed world. Students were graded based on their participation.

Procedure

The online course followed a course schedule similar to the in-person study [22], where the psychological safety of the teams was analyzed over the same five time points (see Fig. 1). Each design stage at their respective time point lasted approximately three hours, with approximately five days to a week in between each stage, and teams were grouped together for about half the time. In the online course, Zoom was used to conduct all lectures, which were broadcasted as live PowerPoint presentations. All students were able to use webcams and microphones to interact within the class, both in the main "classroom" with everyone present, and in breakout rooms. Importantly, at the end of each design stage, students completed an electronically distributed seven-question psychological safety survey developed by Edmondson [6], which is computed as an average of team members' scores for the team measure. These survey questions investigate important aspects of a team's relationship, such as team members feeling comfortable making mistakes without criticism, bringing up issues to overcome obstacles, and feeling valued as a team member [6]. At the end of each design milestone, students completed the psychological safety survey (five times). Participants were also required to provide positive and negative comments to support their rating in the psychological safety survey.

All participants consented at the beginning of the study based on the Institutional Review Board guidelines established at the university. Table 1 shows a summary of

Table 1 Descriptions of design challenges based on instructor and semester

Project	Team type	Semester	Instructor	Number of teams	Number of students
Tackle food insecurity in developing countries as a result of climate, conflict, unstable markets, food waste, and lack of investment in agriculture	Traditional [22]	SU 2018	A	12	46
Based on the changes to the shopping experience imposed by COVID-19 restrictions, address the needs of grocery store shoppers for the world of today and tomorrow	Virtual	SU 2020	B	12	46
			C	11	40
			D	6	23
			E	5	18

the number of participants, their instructors, and the design tasks in this study, along with the sample from [22].

At the ***team formation*** stage, instructors grouped students into teams of 3 and 4 people randomly. Next, students were presented with a design challenge which varied depending on the section and instructor of the course. The teams then conducted in-depth context research on their design challenge, which guided their focus for their design project.

During the ***concept generation*** stage, students attended a lecture delivered via Zoom on customer needs and developed their problem statements within their teams in breakout rooms. After this, an innovation lesson that focused on the importance of creativity in engineering design was conducted. Next, the participants were guided through a series of idea generation exercises where they were asked to individually sketch as many ideas as possible in a 15-min session in nominal brainstorming groups. After generating ideas, students shared them on Stormboard; a web-based application for sharing sketches of ideas.

During the ***concept screening*** stage, participants were led through a concept screening activity where they individually assessed all the ideas generated by their design team and rated them as "Consider" or "Do Not Consider." This was conducted in the main Zoom "classroom" to limit teams from interacting. Ideas in the "Consider" category were concepts that the participant felt would most likely fulfill the goals for their design challenge, while ideas in the "Do Not Consider" category were concepts

Fig. 2 Example of CAD rendering from one of the virtual teams—this represents a cart that travels to customers and stores refrigerated and unrefrigerated groceries

that the participants felt were not satisfactory for achieving their goals for the design challenge. This was continued until all ideas from the group were assessed. The students then discussed the ideas they screened and formed two piles as a group—"Consider" and "Do Not Consider." They were tasked with picking out four distinct ideas to prototype in the next design stage.

During the ***beta prototypes*** stage, instructors held a lecture on prototyping methods, discussing the benefits of creating physical and virtual prototypes, as well as mockups of user experiences. From there, the students were placed in their breakout rooms to discuss the best prototyping options (at least 2 different methods) for their beta prototypes, depending on the information they were seeking from testing with users. From there, they started working on their prototypes as a team.

The project ended at the ***final deliverables*** stage, in which the final deliverables were completed including a formal PowerPoint presentation, a final design report, and a high-fidelity prototype including a CAD rendering of the design; an example is shown in Fig. 2.

Results

Our results are presented in this section with relation to our research question. The statistical data were analyzed via the SPSS v.26. A value of $p < 0.05$ was used to define statistical significance. For all research questions, Cronbach's alpha and ICCs were used to establish reliability, whereas team psychological safety measures were used as a dependent variable.

Our first research question was developed to investigate how long it takes for psychological safety to become established as a reliable measure and whether the reliability changes over the course of the project. Our hypothesis was that psychological safety would not become a reliable measure until at least the idea generation stage due to a lack of social cues [12, 24] and social loafing while online [26]. Furthermore, lack of social presence can cause issues with motivation to complete tasks [18], therefore we hypothesized there may be decreased scale validity in the online environment. Finally, we hypothesized that ICC(1) and ICC(2) would tend to be lower in virtual teams, demonstrating lack of homogeneity in individuals' TMMs.

The results of our analysis reveal that the scale did not meet this internal reliability threshold during *team formation* and *idea generation*, shown in Fig. 3. The results of this part of the research question support our hypothesis such that individuals' perceptions of psychological safety may take longer to become established in virtual teams measured based on the scale's reliability score, because team members may not have a sufficient understanding of their psychological safety. This could be attributed to participants having interpreted the scale items as heterogeneous and thus they rated each item differently [16]. Importantly, when we compare these findings to those captured during in-person instruction [22], we see that the construct of psychological safety is developed only after substantial time spent in the team setting, see Fig. 3. This may be because the online environment makes it more difficult for team members to converge to a similar team mental model, due to lack of social cues [12, 24] that may limit teams' abilities to communicate naturally [13, 37]. This in turn can lead to a breakdown in coordination and trust [12], ultimately hurting team performance in multiple facets, such as biased interpretations of team members' behaviors.

To identify when the construct of psychological safety was established in the teams, the consistency of scores among team members was analyzed. In other words, team members must have a shared agreement regarding the overall level of psychological safety of the team [6] at each design stage because psychological safety describes the team rather than individual perceptions. As such, if there were disagreements between team members about the level of psychological safety at any design stage it would mean the team did not have a shared view of this construct and thus it would not be considered a shared team level construct [15]. The results revealed that the mean $r_{wg}(j)$ for remaining valid design stages ranged from 0.85 to 0.91,

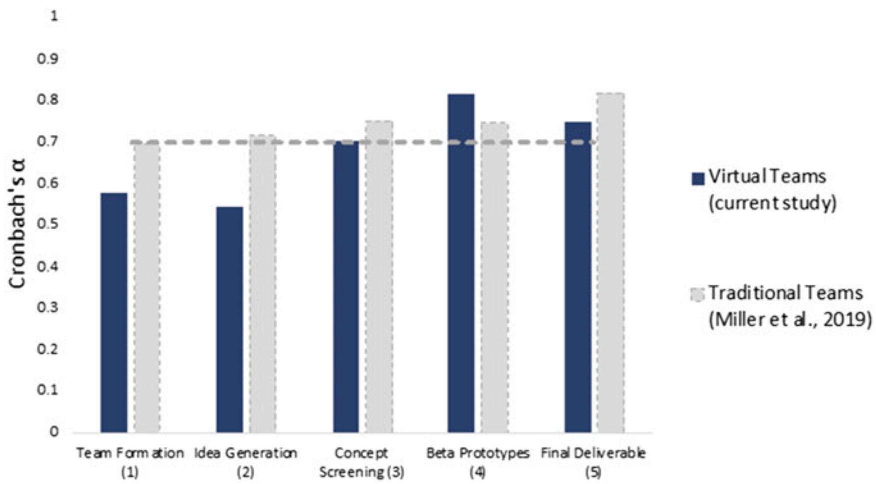

Fig. 3 The internal consistency of the psychological safety scale over the five design stages as measured by Cronbach's alpha (α) between traditional [22] and virtual engineering design student teams. The dashed line shows the acceptable level reliability (0.7)

indicating acceptable agreement on psychological safety level within teams. Interestingly, these measures were not drastically different from the traditional teams, as mean r_{wg}(j) values were between 0.86 and 0.92 [22]. Similar findings were reflected in ICC values, where ICC(1) was highest for final deliverables in the traditional teams (0.32) [22], and highest for beta prototypes in the virtual teams (0.34). It was also lowest at concept screening in both team types. Additionally, ICC(1)s revealed a range of variance in psychological safety due to team membership, ranging from 9% (small effect) to 34% (large effect) [15]. The larger value at beta prototypes reflects greater team interaction compared to concept screening and final deliverables. ICC(2) values followed a similar trend, indicating greater reliability of group mean ratings of psychological safety over time [15].

Finally, results from the one-way repeated measures ANOVA failed to show any statistically significant changes in psychological safety, over time, $F(1.591, 38.183) = 2.046$, $p = 0.151$. These findings support our hypothesis, as prior research in engineering design teams showed that the trajectory of psychological safety varied by team [22]. This implies that it is not the design activity that contributes to any rises or dips in psychological safety, but rather the interpersonal interactions that occur within each team. This can be generalized to various fields where teamwork is necessary, particularly in an online setting. Importantly, psychological safety may not change much across all teams within an organization until a significant amount of time passes, allowing the construct to manifest [10]. This effect of limited time spent as a team is evident in these results, see Table 2.

While the first RQ looked at how psychological safety did not become a reliable measure across teams until concept screening and there was not a significant difference across the design stage that were valid for analysis, the second RQ looked at how psychological safety compares between virtual and traditional teams throughout the design process. The data from the 12 teams in [22] were obtained from the authors and included in this analysis. Our hypothesis was that psychological safety would be lower in virtual teams, particularly during the earlier stages (e.g., team formation and concept generation) of the design project. The results show that at and beyond the concept screening stage in an engineering design project, differences in team psychological safety do not vary significantly between traditional and virtual teams (Table 3). These findings refute our hypothesis somewhat, as we would expect differences to be more prominent towards the beginning of the project, as prior research

Table 2 Average team psychological safety descriptive statistics and psychometric properties across time

Design stage	Mean	SD	α	Mean r_{wg}(j)	Median r_{wg}(j)	ICC(1)	ICC(2)
Concept screening	6.04	0.517	0.70	0.91	0.92	0.09	0.26
Beta prototypes	6.22	0.651	0.82	0.90	0.95	0.34	0.64
Final deliverables	6.17	0.565	0.75	0.85	0.94	0.18	0.42

Table 3 Independent t-test results from the virtual and traditional teams [22]

Design stage	Mean (virtual teams)	Mean (traditional teams)	SD (virtual teams)	SD (traditional teams)	t-statistic	p-value
Concept screening	6.04	5.96	0.517	0.563	$t(43) = -0.574$	0.569
Beta prototypes	6.22	6.11	0.651	0.587	$t(38) = -0.509$	0.614
Final deliverables	6.17	6.18	0.565	0.668	$t(41) = 0.031$	0.975

shows that it can be more difficult to foster psychological safety in online settings due to lack of social interactions that help form relationships and build trust [12, 35, 36]. These results imply that psychological safety does not vary between team types when comparing teams at each one of the design stages analyzed. However, results also point to something deeper occurring within the team.

While RQ1 and RQ2 established when psychological safety was established in design teams and how psychological safety varied between traditional and virtual teams, the goal of RQ3 was to identify the factors that impacted psychological safety within each design stage of the design process. To analyze the open-ended questions required at the end of the psychological safety survey, "Please describe any positive/negative team interactions or activities that impacted the rating," qualitative analysis was conducted. Using directed content analysis based on a codebook developed by Gong [48], we coded the 1,027 qualitative responses collected in the study at the end of each survey. Our hypothesis was that different factors impact the development of psychological safety due to different tasks and skills involved in each stage of the engineering design process [30]. Specifically, psychological safety can help teams feel safe to share ideas, feel open to receiving feedback, and feel safe for risk-taking [6, 10]. In all, seven main factors were coded based on [48]; see Fig. 4 for the frequencies.

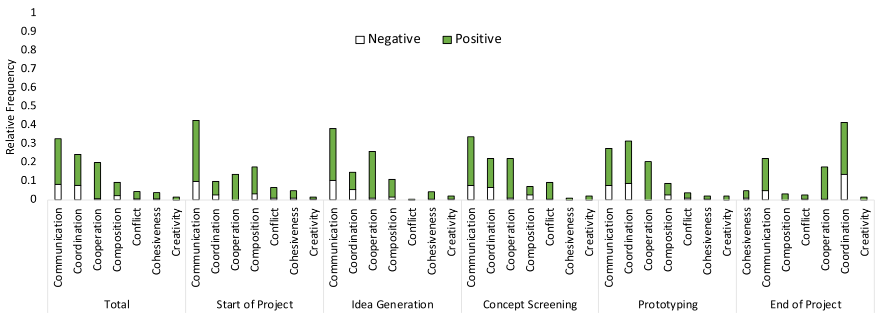

Fig. 4 Relative frequencies of discussion topics (total frequency of topic divided by total number of comments for each stage) spanning the project trajectory

Table 4 Linear regression results from the qualitative frequency and psychological safety comparisons

Concept screening	*B*	*SE B*	*β*	*t*	*p*
Negative conflict	−5.204	1.302	−0.583	−3.996	<0.001
Final deliverables	*B*	*SE B*	*β*	*t*	*P*
Total negative comments	−0.558	0.189	−0.481	−2.958	<0.001
Negative communication	−1.403	0.389	−0.557	−3.609	<0.001

Throughout the design process, the most to least frequently mentioned topics were coded in this order: communication, coordination, cooperation, composition, conflict, cohesiveness, and creativity. Based on Cronbach's alpha (RQ1), we began the analysis from concept screening. A summary of the statistical findings is shown in Table 4.

The results of the regression analyses revealed certain factors to be significantly influential on psychological safety. Specifically, these occurred at both the concept screening and final deliverables stages. There were no significant findings for the beta prototypes stage. Specifically, results of the regression analyses from *concept screening* revealed one significant prediction variable. Specifically, the frequency of negative conflict comments on a team from *concept screening* significantly predicted team psychological safety, $F(1, 31) = 15.66$, $p < 0.001$, accounting for 34% of the variation in team psychological safety with adjusted $R^2 = 31.9\%$, a large effect size. The resulting prediction equation was: team psychological safety = 6.115 − 5.204* conflict (negative). Some participants cited lack of agreeableness as a negative aspect within their teams, for example: *If someone does not agree they make sure they make it known [P378].* This aligns with the notion that teams with lower psychological safety tend to be less agreeable, particularly when someone who is less agreeable assumes a leadership role [45]. This can discourage teams from considering a broader spectrum of ideas during the screening process. Additionally, while conflict can be beneficial throughout the design process [39], lack of agreeability in this case does not stimulate productive discussion for selecting ideas.

Contrasting with significant findings for negative conflict from *concept screening*, the *final deliverables* stage revealed different findings. The results of the regression analyses at *final deliverables* revealed two significant prediction variables. Specifically, the total negative comments a team documented statistically significantly predicted team psychological safety, $F(1, 29) = 8.752$, $p = 0.006$, accounting for 23.2% of the variation in team psychological safety with adjusted $R^2 = 20.5\%$, a medium effect size. The resulting prediction equation was: team psychological safety = 6.435 − 0.558* total comments (negative). Particularly, negative coordination comments (f = 31) focused on topics such as being absent or late, lack of efficiency, working remotely, finishing on time, and work contributions. For example, participants cited examples about efficiency: *We wouldn't immediately address the confusion, instead of trying to figure out the problem for ourselves [P302].* Such comments imply that the virtual teams did not always understand the instructions, nor did they have the self-control to stay on task. Particularly, lack of social and visual cues [12] from classroom instructors, and social loafing [26] can detrimental to virtual teams.

Additionally, several other participants complained about team members being either late or absent, for example: *[Student A] left class without telling us multiple times, then claimed he/she had doctor's appointments multiple times. When we ask for help [he/she] doesn't respond or does underwhelming work [P379].* These kinds of comments imply a lack of trust in others, which can be detrimental to psychological safety [34], particularly online [11, 25]. Additionally, it implies that the team member may be free-riding, another issue in virtual teams [27, 36]. Issues related to communication were prevalent even more so. Specifically, the total communication negative comments statistically significantly predicted team psychological safety, $F(1, 29) = 13.027$, $p < 0.001$, accounting for 31.0% of the variation in team psychological safety with adjusted $R^2 = 28.6\%$, a large effect size [49]. The resulting prediction equation for final deliverables was team psychological safety = 6.336 − 1.403* communication (negative). Many participants lamented about the lack of communication from team members along having discussions. For example, a participant said: *Not everyone talks very often there could be more feedback on the topics that are brought up throughout the discussions [P376].* This comment hints at the need for addressing the common issue of lack of social cues in the online environment [12, 24], which is blamed for limiting teams' abilities to communicate naturally [13, 37]. Additionally, other team members voiced issues about contributing honest feedback: *Members did not criticize one another ideas too harshly, in fear of hurting others feelings [P351].* This is part of low psychological safety where teams may be afraid to challenge the status quo [10]; in this case, not feeling safe to challenge others' ideas during the design process.

While statistical analyses cannot be completed for team formation and idea generation, there are some qualitative insights that may aid in understanding why this is, as well as potential plans for technological intervention development. Specifically, at *team formation*, the category with the highest negative frequency was communication (f = 22). Many complaints centered around team members not talking much, for example: *One person on my team didn't talk the entire time. They were talking in the background, texting, and overall seemed very uninterested in what we were doing [P379].* Other comments were very similar, and some participants thought that the lack of conversation was due to being in a new team: *I do not think that there were any negative interactions besides the fact that it can be a little quiet the first time you with work new people [P354].* This could be why psychological safety was unreliable, as lack of communication could make it difficult to gauge various facets of psychological safety, as well as make it difficult to build a TMM through getting to know one another.

Similar to team formation, the frequency of similar issues about communication (f = 21) were presented by the participants during idea generation. Specifically, some participants were still thought that awkward silences were due to still being a new team, for example: *Occasional stops where there was silence, possible cause we were* *out of ideas and still new to the group [P271].* Such comments hint at the need for an intervention method that could encourage more participation in group conversations.

Conclusion and Discussion

In this paper, we investigated how the construct of psychological safety stabilizes in a virtual environment, the role of technology in the development of psychological safety, and potential interventions for supporting psychological safety development through a mixed-methods study of a first-year engineering design students over the trajectory of a course project. The key findings from our study are as follows:

- Individual perceptions of psychological safety take longer to establish and may be less reliable earlier on in virtual teams than traditional teams.
- There was no statistical difference in the psychological safety of virtual teams during concept screening, beta prototypes, and final deliverables compared with traditional teams.
- Negative comments about team conflict and communication were linked to lower psychological safety during concept screening and final deliverables, respectively.

At the first two design stage, *team formation* and *concept generation*, the data were unusable for statistical analyses at RQ2 and RQ3 because they did not meet the criteria set by Cronbach's alpha. Scale reliability can deteriorate due the presence of heterogeneous constructs in the scale [16], and because psychological safety covers various dimensions [6], that could be interpreted as heterogeneous constructs. However, psychological safety is valid across various settings [10], and has been successfully applied to traditional teams in engineering design [22]. This prompted further investigation of the comments from these design stages. The majority of comments from these design stages were categorized under *communication*, where most participants voiced concerns over the lack of discussion in their breakout rooms. This lack of communication early on signals that teams simply do not interact enough to understand how safe they feel, as lack of social cues can limit teams' abilities to communicate naturally [13, 37]. Thus, teams are prevented from building a Team Mental Model that promotes understanding the team's motives [14]. This calls for instructors to implement strategies to encourage communication earlier on in a project with virtual teams.

Because it is usually more difficult for communication to occur organically in a virtual team [12, 24, 32, 35], we recommend that instructors address this challenge before a project begins. To help students get to know one another, prior studies found that icebreakers and social games can be implemented to foster trust (which is conducive to psychological safety [34]) within teams [41] and encourage socializing to build psychological safety organically [38]. Similarly, prior work suggests utilizing informal exchanges and text chats to build a sense of community and avoid anxiety when using webcams [3], helping students to feel more comfortable.

While lack of participation can hinder the establishment of psychological safety, conflict can disrupt its building. Although conflict has its benefits for promoting higher team performance in engineering design [39], in this study, conflict was more likely to be associated with lower psychological safety during *concept screening*. This calls for encouraging students to tactfully confront issues and listen to others to increase psychological safety in the long run and prevent issues from festering [6]. Thus, teams can use conflict combined with higher psychological safety to their advantage [10].

Additionally, lack of communication hinders the development of psychological safety early in the design process. Although we suggest team-building activities to allow team members to get to know one another, such activities may not fully solve the communication problem. From research in MOOCs, structuring distributed synchronous peer-learning interactions and adding incentives for participation [42] could be applied to encourage more input from members within each team. However, this would require the development of a plugin that can be applied to various communication tools, such as video conference software. In addition to a lack of participation and interactions within teams, qualitative results point to issues with social loafing, which is a notable deficiency in virtual teams [26]. Thus, we suggest developing a tool to detect and discourage social loafing (e.g., when the room is quiet) within breakout rooms without being too intrusive.

For virtual teams, there was a lack of responses to the psychological safety survey at many design stages, so data points from teams with at least 50% participation were used in the analysis. However, r_{wg} values show that the team psychological safety values tend to become stabilized as the time progresses, aligning with the notion that psychological safety takes time to manifest and stabilizes over time [10]. Thus, we can assume most teams would be in agreement regarding their psychological safety in the later points of the project.

Additionally, findings from RQ2 show that because psychological safety does not vary between the team types (virtual versus traditional), psychological safety is dependent on more than whether a team is virtual or not. Thus, further investigation as to what causes differences within each team is necessary, as we currently lack an understanding of what specifically causes psychological safety to increase or decrease within a virtual team. For example, undetected interactions, such as students communicating via text-based messaging during activities in the main Zoom "classroom" could have impacted psychological safety in various ways in the virtual teams. However, we do not believe these interactions occurred frequently, if at all, as students were not motivated in any way to covertly communicate. Other confounding factors could come from stress induced by the pandemic; however, this was not studied here, nor were individual personality factors and gender. Furthermore, while design task, task duration, and task complexity may be impactful on design outputs, its impact on psychological safety was not investigated due to the scope of the paper. Similarly, prototyping may have been affected as well, but this was also outside the scope. Finally, while the guidance in this first project of the course may have impacted whether psychological safety changed, such changes are expected to be minimal, as team interactions were not manipulated directly.

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The Effect of Design Styles and Logos on Product Preference

Wei Xiang, Pan Wang, and Hao Jiang

Product design in a company requires consideration of both design styles and brands. However, it is unclear how factors such as similarity with existing products and logos together affect preferences for products. The current study analyzed the effects of design style and logos using an event-related potential experiment. The results revealed that design style and logos together affected the preference of products. However, logos only enhanced the preference for similar design styles and impeded acceptance of dissimilar design styles. Moreover, the differences in event-related potential components between similar and dissimilar design styles were amplified by logos, but not brand names. The current results provide insight into people's cognitive processing of product appearance, with implications for product design.

Design Styles of a Product

Multiple factors, including design styles and brands, affect the perception of a product. Logos represent the brand, acting as the foundation of brand visual strategies [1]. Previous studies have examined the effects of design styles on product perception [2], and also demonstrate the effectiveness of logos for enhancing people's acceptance and preferences [3, 4]. However, the ways in which the logo and design style together affect the impression of a product remain unclear. A logo has dual properties, functioning as both a visual element and a symbolic icon. These dual properties might

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help add brand properties to similar and dissimilar products to unify people's impressions. In addition, a logo may also limit people's expectations and preferences for products to those of similar design styles and make the dissimilar ones unappealing. Clarifying this issue could be useful for revealing the features of design style-related cognitive processes. Moreover, the decisions on design styles are ubiquitous in the design process. Companies need to develop new products, and some of them imitate the dissimilar design style of successful products while proposing new product lines. Should designers imitate the dissimilar design style? Or, should they keep the design similar to prior products? The results of our study might inform product design.

Neuroscientific methods such as event-related potentials (ERPs) can be used to reveal unconscious reactions in humans, providing data regarding responses and preferences other than self-reported measures. Changes in brain signals have been used to support the evaluation of advertisements and products [5, 6], as well as problem-solving in design [7]. The current study analyzed the effects of design style and logo using an electroencephalography (EEG) experiment in which ERPs were monitored while participants viewed product images.

This study provided three main contributions. First, the study examined how people react to products that differ from their expectations. Second, the different effects of logo and design styles on people's preferences provided neural activity-based design guidance for products. Third, our results suggested possibilities for the neural decoding of design styles.

Background

The Effect of Design Styles and Logos on Products

Design styles are an important factor in participants' perception. Visual elements involving shape, color, and textures have been found to affect preferences for products, as shown by both subjective feedback and neural signals [2, 8]. Brands induce an expectation of design style and affect product preferences. Lin observed participants' reactions to furniture, reporting that the style descriptions affected subsequent experiences of furniture styles [9].

Logos represent brands, and can be used to enhance branding, convey trustworthiness and benefit the branding of a product [1, 10, 11]. Logos provide a symbol of a brand, as well as a visual element. The brand impression conveyed by logos can guide participants' feelings. For example, extension products with brand logos have been found to perform better than those with brand names but no logos [3]. Meanwhile, as a visual element, the visual properties of logos also affect the perception of products. Asymmetrical logos have been found to be associated with excitement, leading to higher inferred aesthetic value [12]. The angularity of logos was reported to activate concepts of softness or hardness, affecting product-related imagery and evaluations [13]. Other dimensions of logos, such as simplicity [14], descriptiveness [15], and color are also reported to be influential [4].

Although the representative role of logos for brands, and the beneficial effect of logos on product preference are widely recognized, these studies have not thoroughly explored the effect of design styles together with logos. The brand, the logo that visually represents the brand, and the design styles of product appearance should all be taken into consideration when analyzing preferences for a product.

ERPs in Product Evaluation

Multiple non-invasive methods measure brain response involving EEG, ERP, fMRI, etc. EEG and ERP are superior in temporal resolution. The amplitudes and microstates of EEG show the degree of activation during perception and cognition. For example, it supports the analysis of brain activation for groups of varied design performance[16]. fMRI has a high spatial resolution in brain regions, enabling the localization of design-related brain regions [17]. The results of fMRI connect design evaluation tasks with similar tasks such as visual processing and decision making [18].

ERP is the measured brain response to specific stimuli or events in the waveform. Compared with EEG and fMRI, ERP focuses on hundreds of milliseconds after stimulus onset and eliminates self-initiated neural activities. This restricts the task ERP can be applied to, while making ERP an experimentally robust method and being sensitive to subtle changes in stimuli. Also, ERP unfolds the cognitive process, with the prior components reflecting sensory related processing and the latter reflecting cognitive related processing. Therefore, ERP complements the fMRI method and supports the analysis of design-related factors of products [19]. Because the waveform is complex, researchers focused on specific components of the wave. Three ERP components, the N1, P2, and N2, are frequently utilized in visual tasks to analyze the attention and effort involved in processing. The amplitudes and latency are two widely used data of ERP components, indicating the size and the timing of components.

N1 is a negative evoked potential that peaks around 100 ms after the onset of a stimulus. N1 activity is correlated with the early selection of sensory stimuli and changes with the involvement of attention and effort [20]. Previous studies had found that the amplitude of N1 was increased when artists attended to modern art [21] and when musicians listened to a specific structure of pieces of music [22]. Positive descriptions induced greater N1 activity than neural descriptions [23], and positive emotions induced greater N1 activity and made brands more appealing [24].

P2 is a positively evoked potential that peaks around 200 ms after the onset of a stimulus. P2 activity is linked to higher-order visual processing involving memory and visual search, being modulated by various aspects of visual stimuli as well as the viewers' expertise and experience [21, 25]. The majority of previous studies have reported an increase in P2 amplitude for positive emotions and beautiful pictures.

For example, Ma et al. applied negative and positive framing into a decision-making process and observed a smaller P2 for negative framing options [26]. Similar results are reported in the study of emotional stimuli; pleasant stimuli induced enhanced P2 amplitude compared with unpleasant and neutral stimuli [27]. However, in cases in which negative stimuli induce substantial cognitive conflict, greater P2 amplitude might reflect additional attentional resources and difficulty in processing [28].

N2 is a negative evoked potential that peaks 200 to 350 ms after the onset of a stimulus. N2 activity is also correlated with attention [29], while also being reported in broader topics involving emotion and familiarity [30]. In general, unfamiliar information sources [31], negative emotions [26], and low aesthetic scores induced higher amplitude of the N2 component [32]. Recommendations from familiar individuals were reported to induce a smaller amplitude of N2 [31], while recommendations from people of the same race were reported to result in smaller N2 amplitude compared with those from people of different races [33]. Affective pictures, deceptive conditions, and framing methods can all induce negative emotions, resulting in N2 changes [30]. Fu et al. allocated people to a deceptive price condition and observed greater N2 amplitude compared with those in a truthful price condition [34]. Ma et al. also reported that inducing negative emotion amplified the amplitude of N2 when viewing new products of a brand [35]. These studies validated the applicability of N2 for measuring cognitive reactions in branding [36], and in the prediction of people's future choices [37].

Preferences for products are strongly correlated with observers' emotions, attention, and aesthetic experience. Thus, the N1, P2, and N2 have been examined in multiple studies of product preferences involving pendants, beverages, clothing, and household appliances [35, 38, 39]. Ding and colleagues conducted a series of studies to measure aesthetic preferences for smartphones, reporting greater amplitudes of N1 and N2 for phone interfaces with low aesthetic scores [38] and enhanced P2 amplitude for preferred smartphone form designs [40]. Shang et al. evaluated two kinds of extension products, including brand logo extension-products and brand name extension-products [3]. Extension products with logos were found to be more acceptable than those with brand names, and induced lower N2 amplitudes [3]. These studies provide a feasible approach for studying product preferences using ERPs.

Methods

In the current study, we measured the effects of logos and similar-dissimilar design styles using a product image viewing experiment. We focused on the holistic appearance of products, rather than color or shape alone, because brands also build general expectations. Additionally, as an initial exploration, we focused on the design in existing product categories of a brand rather than extension products in new domains. The brand impression is uncertain in a new product category and thus be difficult to explain without first measuring the effect in existing domains.

It is worth noting that the design community has developed sophisticated and robust methods on similarity ratings and preference ratings. For example, factors affecting design similarities involve physical principles, working principles, and embodiment [41]. The design similarity could be calculated using edit distance, template matching, and Euclidean distance of vectors [42, 43]. Each method calculates a specific perspective of similarity.

The product preference could be collected using Likert ratings, pairwise comparisons, and behavior features [18, 44]. The product images act as a convenient and reliable medium to rate preference [45]. Product preference is a holistic feeling and is hard to judge on independent variables. Therefore, researchers employ discrete choice models and conjoint analyses to analyze the relationship between design variables and product preference [46].

According to the research on similarity and preference ratings, one possible experimental approach would be to design similar and dissimilar styles of product appearance for brands, and recruit participants to rate their preference. ERP experiment requires a thorough consideration of varied factors including the effect of image features, novelty effect of new designs, and the changed variables between similar and dissimilar design styles. In this way, each brand requires preference ratings of multiple product images to isolate the effect of these factors. Each preference rating then needs to be repeated multiple times to increase the signal ratio while recording ERP data. Because this study focused on the holistic effect of design styles, we took another experimental approach to involve multiple brands. This approach displayed the same product image for two brands. The product appearance was similar to the style of one brand's existing products and differed from the other. In this way, when observing the same product appearance of the two brands, the ERP components revealed participants' reactions to similar and dissimilar design styles. For example, assume there are brand A and brand B, the product has the design style of brand A. The two factors (logo and design style) correspond to four conditions: product image of brand A without logo (no logo, similar design style), product image of brand B without logo (no logo, dissimilar design style), product image of brand A with logo (logo, similar design style), and product image of brand B with logo (logo, dissimilar design style).

Materials

Ten products were used in the experiment, covering a broad range of product types including phones, shoes, and bottled water. Each of the ten products has two brands and four product images. All of the details of the images were kept the same, except for the logos. The details of the product designs are shown in Fig. 1.

Fig. 1 Ten products, each with two brand names and four images used in the experiment. The product designs were based on existing products of a brand, so were similar to the style of one brand and differed from the other

Participants and Procedure

Four males and four females between 22 and 30 years old participated in the experiment. Participants were all right-handed and had a normal or corrected-to-normal vision. None of the participants had any neurological or psychiatric disorders, and all were fluent in English and familiar with the brands involved in this study. The university research ethics committee approved this experiment, and all participants signed an informed consent form.

The experimental design involved two factors and four conditions, as follows: similar product design without a logo, similar product design with a logo, dissimilar product design without a logo, and dissimilar product design with a logo. Each condition contained 50 trials, leading to a total of 200 trials in the experiment. The whole process had three steps and lasted for approximately 1 h.

1. Introduction. Participants were introduced to the EEG recording facilities, and fitted with an electrode cap. Participants were instructed to view a series of product designs for various brands.
2. Product image viewing. There were five sessions with 40 trials each session. In each trial, participants first saw a brand name, then a black screen followed by the image of the product (Fig. 2). Participants were instructed to press a button as

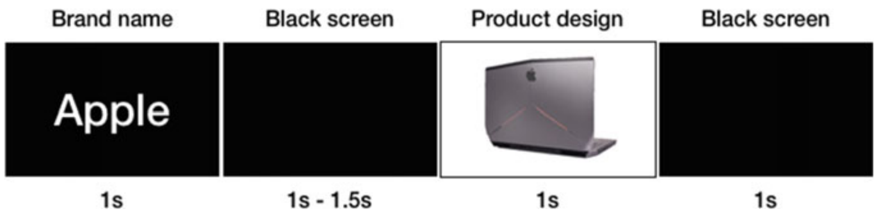

Fig. 2 Procedure for one trial, showing a dissimilar design style with a logo

soon as the black screen appeared after the product image to keep them focused. Each trial lasted approximately 4–5 s, with a 1-s presentation of a picture of brand followed by a 1–1.5 s presentation of a black screen, a 1-s presentation of a product image, and a 1-s presentation of a black screen. The black screen duration was randomized between 1 and 1.5 s to keep participants focused and avoid the inference of periodic signals. Each session lasted 3 to 4 min in total. Participants rested for 2 min between each session. The order of all trials was randomized for each participant.

3. Subjective evaluation. Participants rated their preference for the product designs using a 7-point Likert scale.

EEG Recording and Analyses

For each participant, EEG signals were recorded using a g.Nautilus 64-electrode cap with a sampling frequency of 250 Hz following the standard 10–20 system of electrode location. The signals were processed using both EEGLAB [47] and ERPLAB [48]. First, the EEG data were re-referenced to the average of the left and right mastoid electrodes, and a band-pass filter with a cut-off frequency of 0.1 Hz was applied. Eye blinks and heartbeat signals were eliminated by deleting the corresponding components from independent component analysis. The data were then epoched from—200 ms to 500 ms around the product image onset. Then, the data from nine electrodes including prefrontal (F1, Fz, F2), frontal (FC1, FCz, FC2), and central sites (C1, Cz, and C2) were chosen for statistical analysis. The epochs for each condition were then averaged to identify the N1 (60–140 ms), P2 (100–200 ms), and N2 (150–250 ms) components. The time windows were selected by referring to prior studies and the averaged waveform of our study [38, 49, 50]. The amplitudes of each component were calculated by averaging the 24 ms (six sampling points) signals around the maximum negative or positive amplitudes over the specified window, and the latencies of components were measured by the peak. Then, a 2 (similar-dissimilar design style) × 2 (logo-no logo) × 9 (the nine electrodes) repeated measures analysis of variance was conducted for the average amplitude and latency of each component. Results were considered significant if $p < 0.05$.

Table 1 Preference ratings of the product images

	Similar	Dissimilar
Logo	6.24	2.16
Without logo	4.84	4.84

Results

Subjective Ratings

The presence of a logo increased participants' ratings for similar designs and decreased ratings for dissimilar designs ($F = 2.307$, $p = 0.026$). Because participants only rate their preference of the product images, the same product images without logos receive same ratings (Table 1).

N1

The N1 amplitude was not affected by logo or similarity (similarity: $F = 0.555$, $p = 0.480$; logo: $F = 4.640$, $p = 0.761$). The latency of the N1 was also not affected by logo or design similarity (similarity: $F = 0.069$, $p = 0.800$; logo: $F = 0.014$, $p = 0.909$). The N1 component exhibited an average amplitude of 3.43 and an average latency of 87.79 ms.

P2

The P2 amplitude was significantly affected by design similarity ($F = 6.761$, $p = 0.035$). Similar design style achieved a higher amplitude of 5.36 compared with 4.50 for dissimilar designs. The presence of a logo did not affect the amplitude of the P2 component ($F = 0.109$, $p = 0.751$). There is an interaction tendency among logo and design styles ($F = 0.4.352$, $p = 0.075$). The effect of logos enhanced differences in responses to similar and dissimilar designs. Logos increased the average amplitude differences between similar and dissimilar design styles from 0.04 to 1.76 (Fig. 3). The latency of the P2 component was not affected by design similarity or logo (similarity: $F = 0.344$, $p = 0.576$; logo: $F = 0.019$, $p = 0.895$). The P2 exhibited an average latency of 143.42 ms.

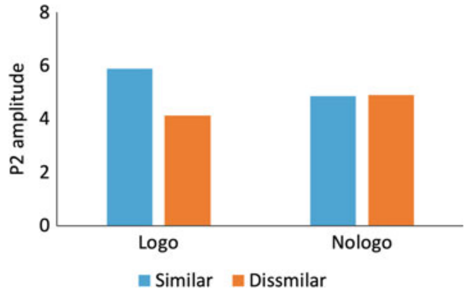

Fig. 3 Effect of design style and logo on P2 amplitude

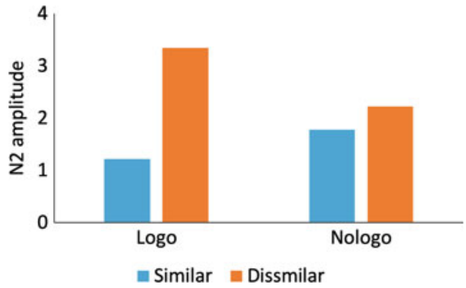

Fig. 4 Effect of design style and logo on N2 amplitude

N2

The amplitude of the N2 was affected by design similarity ($F = 7.403$, $p = 0.030$), and the interaction effect of logo and design similarity ($F = 5.413$, $p = 0.053$). Dissimilar designs evoked greater N2 amplitude. Dissimilar designs exhibited an amplitude of 2.79 while similar designs exhibited an amplitude of 1.50. The inclusion of a logo induced greater N2 amplitude for dissimilar designs, resulting in smaller amplitude for similar designs (Fig. 4). It should be noted that the differences induced by the presence of a logo were larger than those induced by brand names. When there was no logo on the product, the amplitude difference between similar design and dissimilar designs was 0.44, while the difference increased to 2.12 when logos were present. The latency of the N2 component was not affected by design similarity or logo (similarity: $F = 2.623$, $p = 0.149$; logo: $F = 3.418$, $p = 0.107$). The N2 exhibited an average latency of 205.66 ms.

Detailed effects of design styles and logos on ERP waveforms are shown in Fig. 5.

Discussion

The current study employed an image viewing experiment and monitored ERPs during observation to analyze the effects of logo and design styles on people's preferences for products. The results confirmed that both design style and logos affected

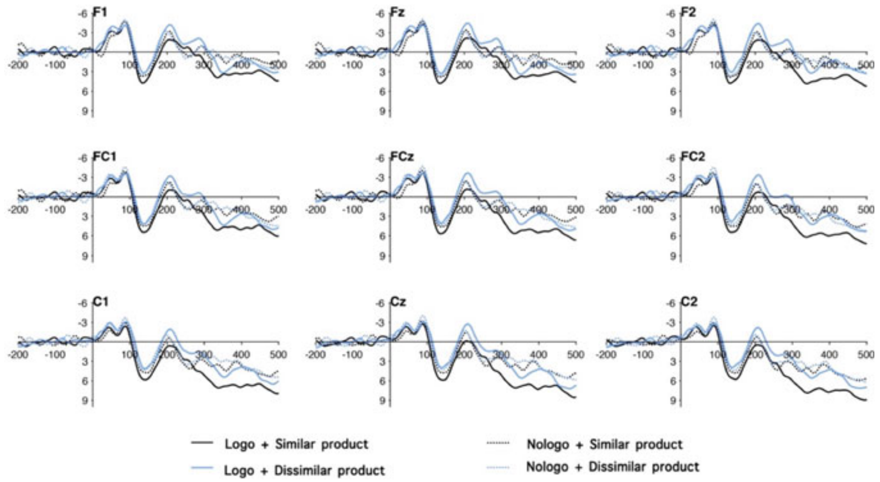

Fig. 5 ERP waveforms from electrodes F1, Fz, F2, FC1, FCz, FC2, C1, Cz, C2. The data were time-locked to the onset of product images. Amplitude in microvolts (μV) is shown on the y axis and time in milliseconds is shown on the x axis

participants' preferences for products and the amplitude of the P2 and N2 components. Moreover, logos acted as an amplifier that enhanced both preferences for similar products and negative responses to dissimilar products. This study demonstrates the interactive effects of logo and design style on product preferences, and that brand name alone exerted a weaker effect than logos on brain activity signals. These results shed light on how people perceive brands and products, potentially informing design guidance.

Previous studies have reported larger N2 amplitude and smaller P2 amplitude during the experience of unpleasant emotions and while viewing paintings and products with an unfavorable appearance [38]. In the current study, dissimilarity of design styles also caused increased amplitude of N2 and decreased amplitude of P2, while logos amplified the amplitude differences between similar and dissimilar design styles. Dissimilar design styles might induce negative feelings and affect the attention and resources devoted to product processing. In the current study, logos may have supported people's recall of brand design styles, making participants less tolerant of new designs. This preference difference indicated by changes in P2 and N2 amplitudes was also reflected in subjective ratings. Participants gave dissimilar designs with logos lower ratings than similar designs with a logo, and even lower ratings than the same design without a logo.

It should be noted that the amplitude differences induced by brand names were substantially smaller than those induced by brand logos. When participants saw different brand names followed by the same product design images, the amplitude of the P2 component and N2 component did not exhibit substantial differences. This relatively small difference seems to indicate that participants' feelings towards similar designs tended to stay the same despite differences in brands. Similar results have been observed in imitation design, where imitative products tend to be positively evaluated as long as they are in a related category and are carefully designed [51, 52]. Another possibility is that prior priming of brand names has a relatively small effect compared with priming of logos as a visual element of products. Logos strengthen participants' expectations of brand-typical design styles and induce substantial conflict for dissimilar design styles. Therefore, products with a brand logo increased differences substantially more than products without a logo. This stronger influence of logos might also be observed in brand extension. When people have no expectations for new domain products, logos make product extension more acceptable than brand names alone [3].

The neural activity-based experimental results provide guidance for product design. Logos, rather than brand names strengthen impressions of the typical design style of a brand. Similar ERP signals for the same design of different brands reflect the significance of logos on product appearance. While extending product lines, keeping similar styles or similar features on products might make use of the amplifying effects of logos, enhancing people's preference for the product. When designing dissimilar products, for example co-products that are dissimilar to design styles of both brands, adjusting the existing logo or using the brand name instead may be more appropriate. Indeed, co-products of two brands benefit from integrative logos displaying features of both brands, and breaking logo frames to extend the breadth of the brand.

The current study suggests possibilities for brain activity decoding and brand impression analyses. First, because the logo amplified the differences between participants' reactions to similar and dissimilar products, it may be possible to extend our experimental methods and match logos with various designs to detect users' impression of brand design styles. This method has the potential to show the typicality and range of brand design styles using products that participants feel are similar, offering a method for implicit brand impression detection that does not rely on subjective reports. It may also be possible to build a brand space and examine brand positioning by testing similar design styles. Moreover, brain signals while observing logos could be used in brain activity decoding to generate product designs, because they contain a stable impression of brand design styles. These potential applications support neuro-based design guidance. In contrast, since logos might have distracting effects on brain activity signals during product observation, images without logos may be more appropriate for brain activity decoding of product categories.

The current study involved several limitations related to experimental materials and contexts. This experiment represents an initial exploration of the effect of similar-dissimilar design styles, and did not consider the "similarity distance" of design styles or similarity metrics. We did not measure detailed similarity features such as color similarity, shape similarity, or texture similarity. In addition, this study did not distinguish the features of brands, and some brands may be more inclusive than others. Therefore, it is difficult to measure the "similarity distance" of our experimental materials without knowing the detailed similarity features and brand features. Also, the social value of brands, which is a key factor of competitiveness and differentiation for companies, affected participants' preference for both similar and dissimilar products [53, 54], especially in a world full of social media. The effects of these attributes need to be analyzed in a next study. However, it is reasonable to suggest that clarifying the general effect of similarity and logo can provide a basis for further and more detailed analyses of varying levels of design similarity and brand properties. A previous study reported that consistencies among product appearance affected preferences for brands [55], which should be measured in further studies.

Second, this study employed product images rather than real products. Previous studies have shown that although similarity exists in most perceptual responses of images and real products [56], significant differences are still important. Whether the current observations in response to product images would be replicated in experiments using real products requires further exploration.

Third, this study measured how participants perceived a product at first sight, which is similar to browsing and glancing at products. This setting is useful for revealing the initial cognitive effects of design styles and logos. The ways in which initial preferences and reactions are correlated with subsequent behaviors, and how the design styles of products affect brand impression and people's expectations, also warrants further study.

Conclusion

Given that brands often use unified visual strategies while continuously launching new products with new features, the ways in which people react and perceive these products is an important issue. The current study explored reactions to similar and dissimilar design styles of products. The results revealed that people reacted similarly to the same designs of different brands, while the brand logos enhanced participants' awareness of design styles and induced larger preference differences. These results emphasized the different effects of brand name and logo on preferences for product design styles, and could be useful for informing product design and brain activity decoding.

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How Does Machine Advice Influence Design Choice? The Effect of Error on Design Decision Making

Ananya Nandy and Kosa Goucher-Lambert

Engineering design relies on the human ability to make complex decisions, but design activities are increasingly supported by computation. Although computation can help humans make decisions, over- or under-reliance on imperfect models can prevent successful outcomes. To investigate the effects of assistance from a computational agent on decision making, a behavioral experiment was conducted (N = 33). Participants chose between pairs of aircraft brackets while optimizing the design across competing objectives (mass and displacement). Participants received suggestions from a simulated model which suggested correct (i.e., better) and incorrect (i.e., worse) designs based on the global design space. In an uncertain case, both options were approximately equivalent but differed along the objectives. The results indicate that designers do not follow suggestions when the relative design performances are notably different, often underutilizing them to their detriment. However, they follow the suggestions more than expected when the better design choice is less clear.

Introduction

A typical engineering design process consists of several stages, such as planning, concept development, system-level design, detail design, testing and refinement, and production ramp-up, where humans must make many decisions related to the design [1]. They often utilize several methods and sources of information, including objective measures obtained from controlled prototype testing or "rule of thumb" heuristics from experience to make these decisions. Additionally, engineering designers have

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the increasing ability to augment their design process using computational methods and models [2]. For instance, generative adversarial networks (GANs) can be used to synthesize general concepts according to text descriptions (e.g., a chair shaped like an avocado) [3], or natural language processing-based machine learning methods can automate the evaluation of early-stage design concepts for novelty [4]. GANs can also be used to synthesize designs that meet specific engineering requirements (e.g., airfoils with particular lift-to-drag ratios [5] or part interdependencies [6]) for the detail design stage. Data-driven surrogate models can then allow engineers to simulate their designs more efficiently and allow design optimization across these numerous design options for the testing and refinement phase [7]. Additionally, intelligent assistants have been developed to augment designers across the various phases of complex system design [8]. While computational models for generation or evaluation of designs can assist decision making, engineering designers typically make the final choices on how to utilize the model outputs for design activities.

The assistance of computational models and interfaces may generally help designers make difficult design decisions or navigate an expansive design space. However, this type of decision making, sometimes referred to as "AI-assisted decision making," relies on the ability to calibrate human trust in the system to ensure that joint decision making leads to an overall improvement in outcomes [9]. Therefore, it is important to investigate what happens when these models are wrong or when they clash with a designer's intuition or intent. For example, how might a human's design decisions be impacted by a concept evaluator that does not find novel concepts or a GAN that generates a design that is not functionally viable? There can be significant financial or safety-related costs to the outcomes (i.e., final designs) if suboptimal decisions are made during the engineering design process. These poor decisions might stem from erroneous judgement on the human side, erroneous information provided by any computational tool that is used, or a combination of both. Engineering designers may have enough domain expertise to recognize errors, at the cost of diminishing trust in the systems.

Engineering design requires making tradeoffs based on a variety of factors, adding another layer of complexity to collaborative interactions. In a case where a design decision may not be clearly "right" or "wrong," how would a model's output be interpreted and inform decisions? There is evidence that in uncertain domains (where uncertainty cannot be resolved until the event has taken place), people, and particularly experts, prefer to use human judgement even when assisted by algorithms that can outperform them [10]. Uncertainty often cannot be resolved until after costly testing or deployment procedures in engineering design, motivating the need to understand how the behavior might persist in this domain. To investigate the behavioral impact of suggestions from a computational model during design, we conducted an experiment where participants were asked to optimize a design while trading off between two objectives. During decisions, participants were provided with the assistance (in the form of a suggested solution) of an imperfect simulated computational model as well as information to make their own judgements. The results provide initial insights into the decision-making behavior and performance of engineering designers in collaboration with an agent during an uncertain, multi-objective task.

Related Work

Human–Computer Collaboration in Engineering Design

Human–computer collaboration has been envisioned to take advantage of designers' ability to formalize design problems while overcoming the cognitive limit of the many variables in a design problem in engineering design [2, 11]. Multi-objective optimization algorithms are specifically useful for engineering design problems [12] and prior work finds that bringing humans in the loop for this process, for example, by using a decision-making paradigm called trade space exploration, helps in the search for optimal designs [13]. Similarly, a study of side-by-side human–robot trade space exploration for complex system design finds that collaboration leads to better designs than solo efforts. However, downsides arise when humans become aware of (and sometimes frustrated with) the limitations of the agent and its suggestions [14]. The effect of algorithmic or AI advice has also been examined through tasks such as drone or truss structure design. In the case of drone design, the effect of AI assistance, which provides Pareto optimal design suggestions from a generative algorithm, is measured by its impact on the overall quality (defined as a utility function of several objectives: range, velocity, cost, and payload) of a designer's final design submissions. A between-subjects study reveals that the quality of drone designs is generally higher when participants (self-reported experts and nonexperts) are provided with the AI assistance compared to when they design alone [15]. The truss structure design study investigates the effect of AI assistance on design teams instead of on individuals. Experimental results find that, unlike for the drone design task, the AI assistance appears to hurt the performance (as measured by the strength to weight ratio of the truss) of high-performing teams [16]. These studies demonstrate the budding potential for human-AI collaboration in engineering design by separating participants into conditions where they either have or lack access to the AI assistance and measuring resulting differences in performance [14–16]. However, these performance improvements might only be realized if people are willing to accept AI assistance in the first place. The study conducted here shares similarities with the previous engineering design studies in its task (having multi-objective criteria) but focuses, in addition to resulting performance measures, on the tendency to follow or ignore assistance during the task.

Human Trust in Automation and Acceptance of Algorithmic Advice

A survey on studies of human interactions with technology reveals that a variety of human factors, such as trust, mental workload, and automation accuracy, affect whether automation (defined in this case as a machine agent carrying out a previously human function) is used by a human or not. Humans can exhibit both overreliance and underutilization of automation, influenced by different combinations of these factors. Overreliance can be caused by using the automation as a decision heuristic, a possibility for experts and nonexperts alike. Underutilization, on the other hand, is often a result of a lack of trust from the human side [17]. Prior work typically frames the lack of proper reliance on “machine advice” as two conflicting human biases: algorithmic appreciation and algorithmic aversion. Algorithmic appreciation refers to humans preferring assistance from an algorithm over another human [18], while algorithmic aversion refers to resistance to accepting recommendations from algorithms (even if they may outperform humans) [19]. Experimental results relating to algorithmic appreciation vs. algorithmic aversion are inconsistent. Several forecasting experiments indicate that people were generally more likely to accept advice from an algorithm than from other humans, lending support for algorithmic appreciation. However, prior work has found that appreciation of algorithmic advice reduces when people choose between the algorithm and their own judgement and when they have domain expertise. Notably, in the forecasting experiments, experts exhibited reduced accuracy compared to nonexperts due to their discounting of the algorithmic advice [18]. Supporting algorithmic aversion, some experiments find that people were likely to disregard suggestions after observing a mistake, even if the algorithmic results outperformed human decisions on average [19]. Experimental data from a perceptual decision-making task also indicates algorithmic aversion behavior, explaining this behavior through a meta-cognitive bandit model [20]. Unlike the tasks in many of these studies, which have a ground truth for comparison, the tasks in the engineering design studies tend to be more open-ended. The study conducted here introduces some of the open-endedness typical of design but maintains similar structure to previous studies on algorithmic appreciation and aversion by utilizing repeated decision-making trials.

Methods

A human subject experiment was conducted to explore the impact of computational model output on design decision making. The study consisted of a task, where participants made repeated decisions, and a post-task survey, where participants answered questions related to the task and themselves.

Participants: Data was collected from 33 participants, recruited from a university’s design, mechanical engineering, and materials science engineering departments. Data collection was IRB-approved and participants were compensated $10 for their time. To be eligible for the study, participants indicated that they were over the age of 18 and had taken a course in structural/solid mechanics. Participants ranged from 19 to 31 years old (M = 22.5, SD = 3.0). 21 participants were men, 10 were women, and 2 were non-binary. There were 17 undergraduate students, 13 graduate students (Ph.D., and masters), 2 working professionals, and 1 recent graduate. Finally, 25 participants indicated that they had 0–4 years of engineering/design experience, while 8 indicated that they had 5–9 years of engineering/design experience.

Context: This study utilized the redesign of a jet engine bracket for additive manufacturing. The task was based on the real design challenge hosted by General Electric on GrabCAD, where engineers had to assess a weight vs. strength tradeoff and submit optimized bracket designs, which were then evaluated using simulation [21]. A dataset of these designs, their properties, and simulations of their performance was made publicly available and a subset of this dataset was used as the stimulus set for this study [22]. Participants in our study were provided with pairs of the designs with accompanying information and asked to select the "better" design, utilizing the same tradeoff. The provided information included 3D models of the designs, performance graphs, visualizations of the simulation results, and a suggestion (Fig. 2). Participants were informed that the suggestion was from a computational model trained on many designs (the actual mechanism for determining the suggestion is explained in the next section). This "model" could be erroneous, indicated by whether it correctly suggested a better design according to the multi-objective criteria.

Experimental design: There were 381 bracket designs in the dataset, representing the global design space explored during the GrabCAD challenge. Each design had an associated mass, maximum displacement (determined across the four loading conditions in the original challenge), and category (determined qualitatively [22]). Bracket designs were compared based on Pareto optimality with two equally weighted objectives. The Pareto frontier refers to where no individual criterion can be made better without making another criterion worse. Therefore, to classify the multi-objective performance of each design, the Pareto optimal set was calculated iteratively across the designs as follows: (1) the Pareto optimal set (designs on the Pareto frontier using mass and maximum displacement as criteria) was found across the full set of designs, (2) that optimal set was removed, (3) the Pareto optimal set was calculated again for the rest of the designs, and (4) this process was repeated until each design was in one of the sets. The results of this process are visualized in Fig. 1, where the lower (i.e., earlier) iterations indicate the more globally optimal designs as opposed to the higher (i.e., later) iterations. This method provided a quantification of designs that were "better" or "worse" than each other and those that were similar in performance.

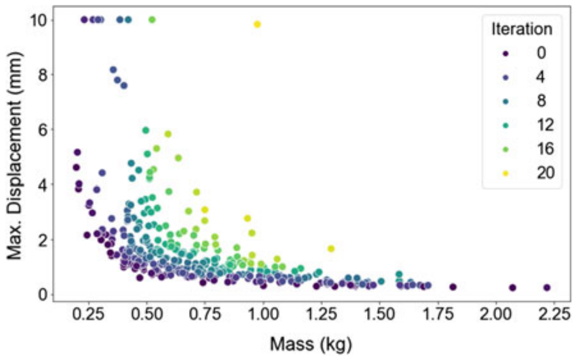


Fig. 1 The Pareto optimal set was iteratively calculated to quantify comparisons between pairs of designs based on multi-objective criteria. Iteration 0 refers to the globally optimal set of designs

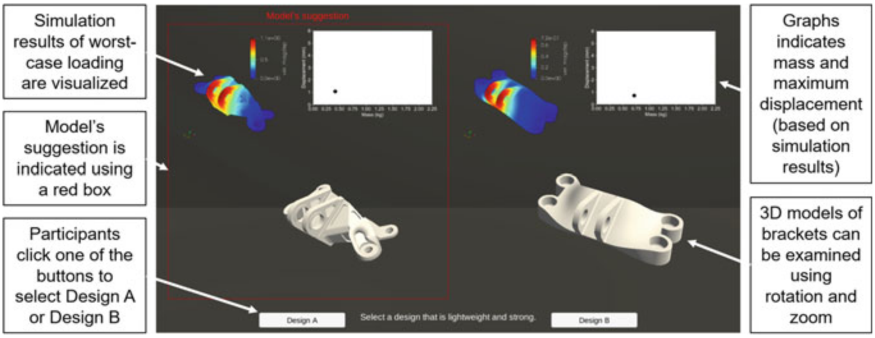


Fig. 2 Participants were instructed to select designs based on the information provided, using the interface shown

The iteration classifications were used to quantify which design was suggested to the participants as the "model's suggestion." This simulated model emulates a data-driven model in several key aspects. For instance, data-driven models make use of large amounts of data that humans cannot synthesize on their own. In this experiment, while the participants could only access a local set of designs (the two designs they decide between), the "model" assessed which design was better based on the global set (all the designs that were submitted as potential solutions in the challenge). The Pareto optimal sets were calculated based only on designs that were explored during the original challenge, excluding any possibly better designs that were left unexplored and are therefore unknown. Real data-driven models share this limitation, as they may struggle reach new areas of a design space.

The experiment had one manipulation (the model's suggestion—Table 1) and participants were exposed to all conditions (within-subjects) with the trials shuffled pseudo-randomly. The accuracy of the model was set to 71% (only counting trials where there is a "ground truth" for the better design) to try to ensure that the participants did not immediately lose trust in the suggestions. This meant that fewer trials were presented for the incorrect suggestion condition compared to the other conditions.

Constraints on the task length and the number of suitable stimuli limited the number of trials conducted for each participant. Additionally, because participants were required to have some amount of domain expertise within design, the availability of participants was limited.

Table 1 Conditions and trials in the experiment

Condition	Number of trials	%
Correct suggestion (suggested design was optimal in an earlier iteration)	15	50
Equivalent suggestion (both designs were considered optimal in the same iteration)	9	30
Incorrect suggestion (suggested design was optimal in a later iteration)	6	20

Stimuli: The stimulus set was selected so that their multi-objective properties would represent the global space (shown in Fig. 1) of designs. A total of 60 bracket designs (two designs per trial for 30 trials) were shown to participants for the main block, with an additional eight for four practice trials and one for the instructions. None were repeated. Several factors were counterbalanced within conditions. First, the distance between the maximum displacement values were balanced since they are found via simulation and may represent a source of error. Next, categories (flat, block, butterfly, beam, and arch), referring to the rough general shapes of the brackets, were balanced as they have notable visual differences. Finally, the locations of the designs in the multi-objective design space were balanced. Some factors were not fully accounted for due to the visual diversity of the designs in the dataset, the qualitative nature of the categorization, and the imbalance of the number of designs in each of these categories. We did not counterbalance if the same underlying stimuli were associated with "correct" and "incorrect" model responses (this would allow for counterbalancing only a subset of the items due to the unequal number of trials in each condition).

Interface: The task was deployed online and participants were directed to a Google Forms survey after completion. The data from the task was collected through a custom online interface developed in Unity (using the UXF [23]) and sent to a database in Amazon Web Services. Figure 2 shows the interface and the types of information available, including an interactable 3D object. Since the two design alternatives were presented side-by-side, a counterbalancing factor was included to account for if the suggested design was on the right or left. Every participant had the same four practice trials, which contained the correct and incorrect suggestion conditions with similar accuracy to the remaining trials (75%). Participants were given feedback on how many times they selected the optimal design during practice (e.g., ¾ times), but no information about which trials they answered correctly.

Data was collected about the designs selected by the participants as well as the time spent on each trial. Prior to analyzing the data, four trials (of 990 trials total, not including practice trials) were removed because the response time was not greater than 500 ms (approximately the time needed to consciously recognize and respond to a visual stimulus).

Survey: Participants were directed to a survey after the task and asked questions about the perceived accuracy of the model, the information they used to make their decisions, the strategy they used during the task, their knowledge about the task domain, and their experience in engineering and design more generally.

Results

The Effect of Model Error on Suggestion Acceptance and Performance

The trials were analyzed to investigate how the simulated model's suggestion of a better or worse-performing design solution impacted participants' decision making. Only conditions with a ground truth ("correct suggestion" and "incorrect suggestion," not "equivalent suggestion") were included in these analyses. Figure 3 shows the proportion of participants' decisions that aligned with the provided suggestions (median = 0.57).

The proportion of decisions that was expected to align with the suggestions—if the participant and the simulated model agreed—was 71%, the actual proportion of correct suggestions. A non-parametric Wilcoxon signed-rank test was conducted as the data violated the assumption of normality, showing that there was a significant difference between the hypothesized value and the observations ($W = 24.0$, $p < 0.001$). *When the performance of the two alternatives differed, participants' selection of the suggested design was lower than expected.* The participants' performance was also quantified by their accuracy, referring to the proportion of the time the correct, better-performing design was selected (the same design as the model's suggestion in the correct condition and the non-suggested design in the incorrect condition). Figure 4a shows the accuracy distribution across participants (median = 0.76). Figure 4b displays the accuracy of participants across each of the two conditions. Notably, *participant accuracy was higher when given the incorrect suggestion (median = 0.83) than when given the correct suggestion (median = 0.73).* A non-parametric Wilcoxon signed-rank test was conducted to test this effect, showing that there was a significant difference in the participant accuracy across the conditions ($W = 152.0$, $p = 0.02$).

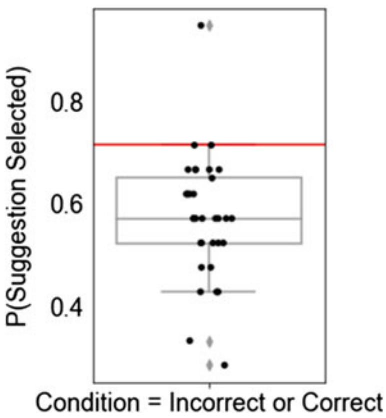


Fig. 3 Distribution of the probability of selecting the suggested design across all participants (median = 0.57) versus the expected proportion (0.71)

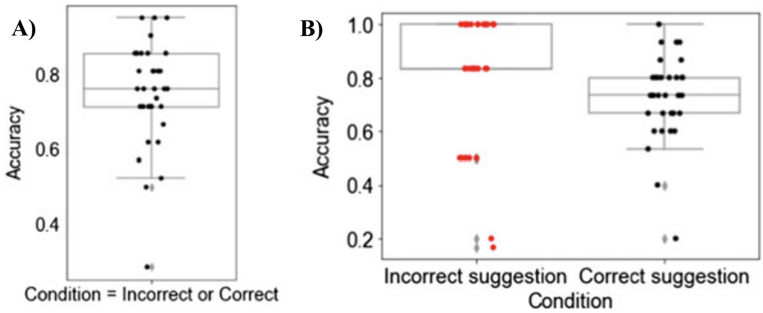


Fig. 4 **a** Accuracy across all participants (median = 0.76) **b** Accuracy for incorrect (median = 0.83) vs. correct (median = 0.73) trials ($p = 0.02$)

The Effect of Suggestions in Uncertain Scenarios

The equivalent condition was analyzed to investigate how the suggestions impacted participants' decision making when both design alternatives were close in multi-objective performance. These design pairs were considered optimal on the same iteration, but differed in which property was prioritized (e.g., a bracket with high mass but low displacement vs. a bracket with low mass but high displacement). Figure 5a shows a distribution of the proportion of selections that aligned with the model's suggestions across participants (median = 0.78). Considering that the suggestion for this condition was arbitrary, it was expected that the participants' design selections would align with the model's suggestions ~50% of the time. However, a Wilcoxon signed-rank test shows a significant difference in participants' proportional selection of the suggested design compared to this expected chance ($W = 5.0, p < 0.001$). *When both design options were close in multi-objective performance, participants chose the model's suggestion more frequently than chance alone.* A Pearson correlation indicates that the proportion of a participant's selections that are aligned with the model's suggestion (in the equivalent condition) is moderately positively correlated with the participant's accuracy ($r_p = 0.36, p = 0.04$), shown in Fig. 5b. The accuracy tended to be higher for those who decided to follow the model's suggestion even when both choices were valid as the “better” design.

Participant Perception of Model Accuracy and Self-Reported Decision-Making Strategies

The effect of several self-reported factors related to knowledge and perceptions were analyzed to determine if these factors were related to participants' performance and decision making. There was no significant Spearman correlation between accuracy and participants' self-reported knowledge (1–7 Likert scale value) in the topics of

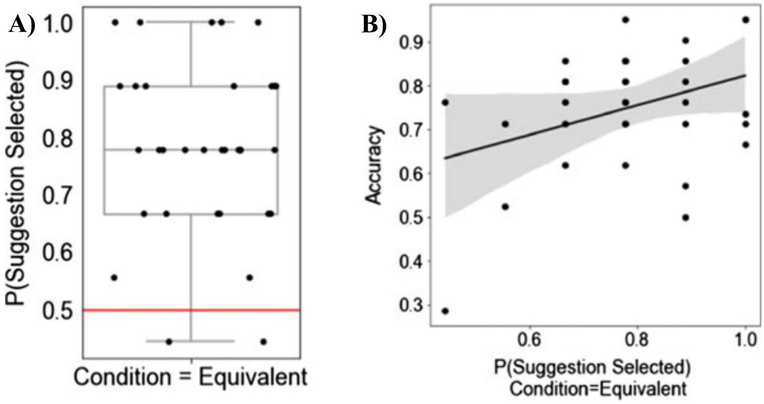


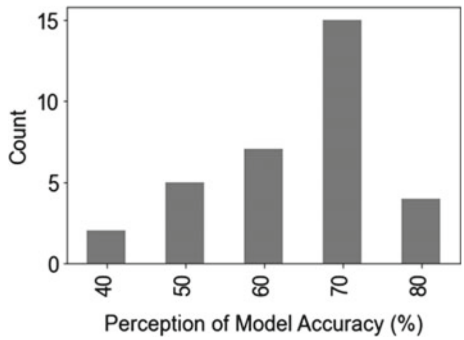
Fig. 5 **a** Proportion of trials in the equivalent condition where participants chose what the model suggested (median = 0.78) **b** Relationship between participants' suggestion selection in the equivalent condition and their accuracy. The two have a moderate positive correlation ($r_p = 0.36$, $p = 0.04$)

structural mechanics ($r_s = 0.18$, $p = 0.32$) and multi-objective optimization ($r_s = 0.26$, $p = 0.88$). Looking more closely at the self-reported perceived model accuracy, Fig. 6 shows the distribution of the perceived accuracy has a median of 70%.

As the accuracy of the suggestions was set to be 71%, not including the trials in the equivalent condition, it appears that participants were relatively good at assessing how often they were receiving correct/incorrect suggestions.

While participants' design selections revealed the outcomes of their decision making, the answer to survey questions provided more insight into participants' decision-making process. These insights are valuable because they can point towards why participants may have performed poorly or well, in addition to why they may or may not have adhered to suggestions. Answers from the open-ended question ("Please describe your decision-making process and strategy in detail.") explained participants' selections. The highest accuracy, achieved by three participants, was 95%. One of these participants had the following strategy:

Fig. 6 Distribution of participants' answer to the question "What percentage of the time do you think the model suggested the better design?" (median = 70%). The answer choices ranged from 0–100% in increments of 10



> …An example thoughts process is: 'If part A has less than half the weight of part B and also less than twice the deflection, then part A has a better strength to weight ratio and is the better part'. If I was given a more explicit cost/benefit function then I could have optimized better, eg 'I need the deflection to be below this value, and from there the lowest weight it best'. If the points were too close or I wasn't sure from the graph, then I may go with the Model's suggestion, since the Model has access to the numerical data and can make a more precise calculation than I can in my head …

Notably, the participant made decisions using their own judgement and synthesis of information but recognized when they would benefit from assistance from the suggestion.

Those who had the lowest accuracy commonly exhibited a preferential weighting of one criterion over the other. For example, one participant (accuracy = 29%) mentioned that "*if the graph was more shallow for one design but the stress was significantly larger, then I would choose the design with the smaller stress*," indicating that they focused more on the strength criterion versus the weight criterion. Similarly, some participants focused on the geometry of the bracket, but only considered the geometry with respect to the displacement and not the mass. One participant (accuracy = 50%) noted that "*[they] focus on the 3D model essentially and check if there is some panel with small thickness, where the stiffness would be weak,*" while another (accuracy = 57%) also focused on "*how detailed the model is designed and the edges; whether it is too thick or too thin.*" Finally, the decision-making strategy from one participant (accuracy = 52%) provided a detailed view into a preference towards a specific type of bracket, as they wrote "*… I look at the stress distribution over the model, personally, I like to pick the brackets that have a more even stress distribution instead of it just concentrated at the connection collar.*" This response specifically illustrates how decisions in design can be influenced by the designer's intuition, which may be at odds with computational outputs (the simulated model here only considered the maximum deformation not the distribution).

Examining qualitatively how participants ranked the information that they used to make their selections in the survey shows that the graph with the objective values is most selected as the most important source of information (21 of 33 participants). No one who reached the highest accuracy among participants ranked the 3D model as the most important information for their decisions. In comparison, a few participants who achieved a low accuracy rank the 3D model as the most important information for their decisions and describe using judgements based on its properties. Across participants, regardless of accuracy, 15 of the 33 participants rank the model's suggestions as the least important source of information, while only one ranks them as the most important source.

Discussion

As computation is used to assist increasingly complex decision making, it is important to understand the effects of erroneous or questionable model output on these decisions. In this study, we examined these effects in a multi-objective engineering design decision context.

Designers Utilize Agent Suggestions Less Than Expected When There is a "Ground Truth"

We found that participants appeared to rely on their own judgement and not on the suggestions in the incorrect and correct conditions, often selecting the alternative design even when the correct one (with respect to what was determined as correct in this study) was suggested. A statistically significant difference in participants' selection of suggested designs and the expected proportion (57% instead of 71%) in these conditions indicates suggestion underutilization. This is supported by the self-reported rankings of importance of information sources, where participants tended to rank the model's suggestions lower and other sources higher. However, when the participants were not able to synthesize the provided information to determine the right ratio of mass and deformation, not utilizing the suggestions harmed their performance. The statistically significant higher participant accuracy for the condition where they were given the incorrect suggestion compared to when they were given the correct suggestion (83% vs. 73%) also indicates that participants tended to catch when they were given the incorrect suggestion, but erroneously ignore correct suggestions.

These results align with prior work that observes algorithmic aversion [19, 20] and particularly with the finding that experts hurt their accuracy by disregarding the algorithm's suggestions [18]. The group of participants in our study were not necessarily experts in the topic. Though they were required to meet a minimum amount of knowledge in the general area, we did not assess how participants perform without suggestions. However, relatively high participant accuracy (especially in avoiding incorrect suggestions) and qualitative survey responses indicate at least a baseline level of knowledge, which may explain the similarity in findings. Prior studies of AI-assistance in engineering design have found that AI-assistance improves design quality for solo designers [14, 15], yet in this study, these opportunities for improvement are underutilized. In the context of human–computer collaboration in engineering design, the incorrect and correct conditions represent scenarios where the computer can easily find a "better" design (by ensuring the design is closer to Pareto optimality) compared to a human. Therefore, our finding of algorithmic aversion may be an issue, as it conflicts with humans' desired ability to leverage the strengths of computation.

Delving into the qualitative insights from participants' open-ended answers regarding their strategies demonstrated that low accuracy was sometimes explained by a difference in how the participants were making decisions (weighing one objective over the other) and how the model was providing suggestions (weighing both objectives equally). Thus, low accuracy does not necessarily reflect poor performance or lack of knowledge but can alternatively be a result of the mismatch between what is deemed important for the task. Additionally, these responses reflect realistic situations where a designer/engineer may have to prioritize a specific criterion, although the participants in this task were not instructed to prioritize one over the other. In a more realistic setting, there would likely be more factors involved in the process of selecting a design. For example, the background information for the task indicated that the brackets would be made using additive manufacturing. However, if this information was excluded, the choice of design might be influenced by a participant prioritizing manufacturability, which was not included into consideration for the suggestions. For instance, people with more experience might be more likely to consider the manufacturing of the bracket despite not being explicitly instructed to do so. Though expertise was not explicitly examined in this study, it is possible that differences in expertise across participants would be important with the additional consideration of different manufacturing methods.

Designers Are More Willing to Accept Agent Suggestions When the "Better" Design Alternative is Uncertain

The results indicate that participants made their own informed decisions rather than relying on suggestions in the "ground truth" conditions, even though the "better" design can be determined computationally in these conditions. On the other hand, the equivalent condition represents a collaborative scenario where the strengths of human decision making might be particularly important. A computer can output several viable solutions based on the multi-objective criteria but may not be able to distinguish between them. Counterintuitive to this, participants appeared to readily follow suggestions in the equivalent condition. This was demonstrated by a statistically significantly higher proportion of suggestion selection than expected in the equivalent condition (78% instead of 50%) and qualitative data on decision-making strategy.

Outside of the engineering design domain, a study of AI advice acceptance reveals that when people lose self-confidence, they may begin to rely on poor AI suggestions [24]. While participants did not generally follow model suggestions that were clearly wrong, they may have been more likely to follow arbitrary ones when the decision was less clear. Prior studies also indicate that once a design team starts following the advice, they often stop exploring the design space themselves [16] and that a collaborative agent can decrease the coverage of the design space explored [14]. Therefore, based on the results of this study, it is possible that the concerns above could be raised around the influence of computational outputs on design decisions, even if they are not clearly "poor suggestions."

On the other hand, the correlation between a participant's suggestion selection (equivalent condition) and their accuracy (all other conditions) indicates that participants who were more willing to accept the model's suggestion did better. It is possible that participants were able to figure out when the suggestion was bad and make their own decision. However, those who were less likely to choose the suggestion in the equivalent condition (possibly an indication of less trust in the model) more likely failed to follow the model even when it was correct. This, in turn, affected their accuracy. Thus, the results show the delicate balance necessary to appropriately take advantage of human–computer collaboration in design.

Trial-By-Trial Design Properties and Their Implications on Decision Making

To examine if specific properties (i.e., the mass or displacement) of the designs affected suggestion selection in a way that may explain the findings, a follow-up analysis was conducted by considering each trial separately and aggregating across participants. Each trial was therefore examined by condition and the difference in properties between its suggested and non-suggested design. The differences across the correct trials (shown in Fig. 7a) implied that the group (and not just individuals) made decisions with some implicit weighting of criteria. If the suggested design had a higher deformation but the tradeoff for lower mass was not subjectively enough, the suggestion was followed less often (though the mass tradeoff for those trials was considered "enough" by the optimization procedure).

Yet preferential weighting of criteria was not necessarily applied in the equivalent condition. Preferential weighting of the deformation objective might lead participants to select the suggested design only if its deformation was lower in this condition (a negative difference). However, this is not the case. Even in trials where the deformation is higher for the suggested design, most of the participants selected the suggestion, as shown in Fig. 7a. Looking only at the equivalent condition, Fig. 7b

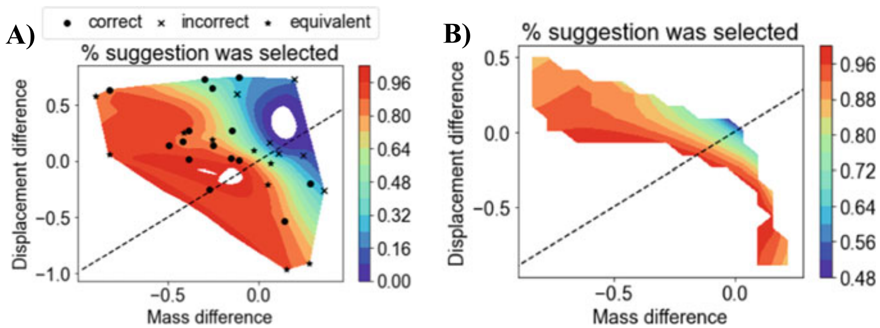


Fig. 7 The difference in stimuli properties along each objective (a positive value indicates a higher value for the suggested design) **a** for all conditions **b** as a visualized interpolation for the "equivalent" condition only

shows that lower suggestion selection in this condition does not appear to be dependent on one objective over another. Instead, when the differences between both of the properties were close to zero, the decision was arbitrary and the suggested design was selected by closer to 50% of the participants. The percentage of participants selecting the suggested design was much higher when the designs were similar, but the tradeoff was not as easy to assess (larger differences in mass and displacement). The findings from this analysis provide further evidence that the results likely reflect the impact of the suggestions as opposed to other decision-making behavior.

Limitations

There are several limitations of this study that should be considered. Design decisions take place over a longer timescale and have more context involved, making it unlikely that the two criteria would have equal weighting, as implied in this study. Additionally, errors in data-driven models related to engineering may be more subtle than the error introduced here, which involved suggesting the wrong design in its entirety. Some limitations relate to the study setup, such as a small sample size and counterbalancing. Though the bracket design pairs presented as stimuli were counterbalanced across several properties (e.g., category, criterion values), there may have been differences in trial difficulty across conditions caused by latent differences in the stimuli sets. This was due to the unequal number of trials across condition (fewer trials for the incorrect condition) and the stimuli subsets never being switched to other conditions. For example, the correct suggestion condition contained a few designs that had low mass but high deformation.

Future Directions

The results from this study point towards many possible avenues for future research. For instance, it is unclear whether the observed higher reliance on arbitrary suggestions would scale with additional complexity in the decision. To address this, it would be necessary to determine how suggestions related to certain characteristics of the design problem might invoke higher or lower levels of trust or acceptance. Studies have revealed that providing people with just the right amount of information can improve trust [25] and perceptions of a model [26]. Including more information about why a design was suggested by the model could impact participants' willingness to accept the suggestions. However, explainability alone cannot address scenarios where a model's "correct" outputs conflict with human decision-making. Instead, adaptivity may be necessary. Recent work has illuminated the importance of mental models [27] and compatibility [28] in human-AI collaboration, offering ways to address these challenges. While the current study does not incorporate these considerations, the results indicate the tendency towards algorithmic aversion, supporting the necessity to account for these factors when developing methods of human–computer collaboration for engineering design. Further examination of decision-making scenarios where a model output could be right or wrong along various dimensions, depending on the human's intent, could be useful for design. For instance, to allow the designer to properly assess how much they should rely on computational systems, it may be necessary for systems to "understand" how the human designer is approaching a problem and communicate if there are differences. Alternatively, a mismatch in decision making might be used to drive automatic adaptation of a computational system to a designer. Uncovering engineering designers' decision-making behaviors in settings where they utilize computational systems can help reveal where general findings around human-AI collaboration apply, and when special considerations must be made for a complex design context. Consequently, this knowledge can be used to develop intelligent tools that effectively fit into human design processes.

Conclusion

The effect of suggestions from a simulated computational model during a design decision-making task is investigated in this study. A jet engine bracket design problem, with a tradeoff between strength and weight, is used to find participants' accuracy in determining the "better" design provided these suggestions. The results indicate that designers' tendency to follow the model's suggestions varies according to the scenario. Designers underutilize suggestions in scenarios where there is a "ground truth," correctly ignoring bad suggestions but also ignoring good ones in the process. This finding might be explained by participants' likeliness to trust their own decision making, even at the risk of performing worse, matching experimental results in other domains that indicate underutilization of algorithmic assistance by those who demonstrate some expertise in the domain. However, when presented with a more uncertain choice between designs, participants tend to follow the model's suggestions more than expected. The results collectively demonstrate the types of behavior that must be accounted for to pursue seamless human–computer collaboration in engineering design.

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The Creation of Emotionally Attuned Patterns Through an Analysis of Line

Lewis Urquhart and Andrew Wodehouse

The creation of distinct pattern designs (decorative geometric tessellations) has been studied at the level of geometric transformations and culture, but its link with emotional experience is less well established. This paper seeks to reverse engineer the creation of pattern by examining the emotive status of abstract forms, in this case lines. By firstly establishing how line, shape and symmetry are the key building blocks of pattern and exploring the links between emotion and visual perception, a study is presented intended to explore form expression within design and emotive meaning through the free-hand drawing of lines. The results of this study are then utilized to create a set of emotionally attuned pattern designs that are then subsequently analyzed in a separate study, establishing a link between form expression, emotional experience and pattern. These links are subsequently explored further and the implications for wider design practice and scholarship are discussed.

Introduction

Pattern is a powerful tool in design, manifesting prominently in decorative aesthetic features, functional configurations such as brick work and making methods such as textiles. This paper draws on several previous studies and a diverse range of scholarship to explore the creation of emotionally attuned pattern designs. Principally, this paper will utilize *line* as a key tool in which to explore pattern creation, drawing on the principles of visual-perception to develop a set of unique pattern designs.

While pattern is an extremely common feature of the built environment and of the aesthetic make-up of artefacts or images, there has been a notable lack of focus on how these complex features are conceived and how they have been utilized within

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Fig. 1 Pattern tessellation example (left) and Celtic decorative shield (right). Both images sourced from Wikimedia Commons

a vast array of diverse human societies. The examples shown below in Fig. 1 show typical pattern work; the similarities between a modern design of a tessellating pattern (left) and an ancient Celtic decorative shield (right) are evident.

Key studies from Washburn and Crowne [1] Wade [2] and more recently by Hann [3] have presented compelling analytics of the cultural differentials of pattern work between societies and how patterns derive complexity from symmetry operations. Continuing this line of study, this work seeks to expand the analysis of pattern by exploring pattern creation and how it can link to emotive experiences and forms of semantic representation. Principally, this paper explores two key research questions: **(1) how do people express emotion through form and what visual symbols are utilized in order to do this? (2) if there are clear trends within these expressions or symbols of emotion, can these then be translated into a discrete design that will represent that emotion but through a different format, namely pattern?** The aim here is to explore this process and how, if successful, it could be used as a tool or method within wider design practice.

Firstly, the basic principles of pattern are discussed, detailing how a pattern is constructed from simple elements and rules. Furthermore, the relevance of pattern to art and expression at large is discussed, summarizing its relevance to design culture. Secondly, drawing from the literature in experimental aesthetics, we present a discussion on form-perception and how this links to pattern work with discussion deriving from previously published studies by the authors in which pattern, shape and line analysis play a key role [4–6]. This focus on line is then used as a framework for an experimental design in which participants use a free line drawing task to create subjective representations of emotion concepts e.g. "trust". Combining this with the previous studies on pattern and shape interpretation, four bespoke "emotive patterns" are designed and subsequently studied to determine how effectively they can embody the distinct meaning of particular emotions. Lastly, the results are discussed and critiqued, referring to how they could inform future study and design practice with a particular exploration of human-centered design and design-emotion.

What Is a Pattern?

While there are different definitions and uses of the word "pattern", we will limit the discussion in this case to tessellating geometry in an aesthetic context. Pattern is essentially built from symmetry operations that transform geometric elements [3]. These operations provide an emergent complexity when applied to specific geometric shapes as illustrated below (Fig. 2); (A) *Translation* (B) *Rotation* (C) *Reflection* (D) *Glide reflection.*

Depending on the arrangements and combinations of the shapes and operations, great degrees of complexity can be achieved. 17 tessellation configurations can exist to create a two-dimensional pattern in which a plane can be perfectly covered without varying any of the geometric elements. This relates to the maximal six-order rotational symmetry based on the five Bravais lattice frameworks within crystallography [3].

Culturally, the emergence of pattern has a complex history—knowledge of pattern creation operations is evidenced in many ancient societies. Washburn and Crowe's expansive study *Symmetries of Culture* [1] explored the basis of pattern design as a kind of rudimentary set-theory and how this can be linked to aspects of culture, essentially tied to the epistemological frameworks in which the societies functioned. Washburn and Crowe, through extensive scholarship, show how cultural knowledge is embedded in the forms of symmetry that make up ornamental design work. Similar work has more recently been completed by Hann [7] who analyzed the dynamic differences of aesthetic cultures and the trends that link them.

Scholars of material culture have argued that pattern work links intimately with kinds of making [8]. Stone work and brick laying, sewing and even agriculture rely on the spatial embodiment of abstract pattern structures. For this reason, pattern may be the central meta-concept for design and examination of how they are created may offer new avenues to design practitioners and researchers. To get a grasp on how pattern interacts with human perception, we must consider the semantic status of pattern i.e. what do patterns mean within human culture? Ingold [9] in his study of lines has explored how arrangements of shapes may have forms of cultural significance raging from decorative or aesthetic functions to patterning motions that create artefacts such as textiles—patterning being indispensable to making operations. Other notable work looking at pattern has examined its function as a kind of social or religious tool. As argued by Gell [10], pattern in many ancient cultures may have been used as a means of dispelling demonic forces believed to inhabit the environment. An evil spirit

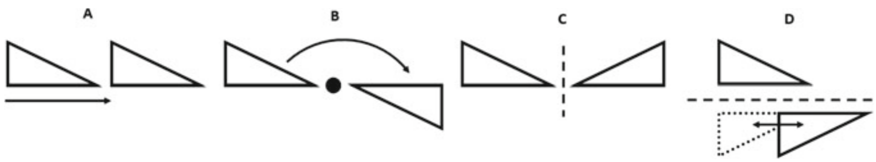


Fig. 2 Four symmetry operations

may be confused by the presence of a pattern and not enter a home—Celtic knot patterns and native American "dreamcatchers" may be an example to this practice. This form of pattern making, Ingold argues, is analogous to a maze or a labyrinth and believes that instead of confusing demonic forces, pattern making is a practice of trapping them in an environment of repeating loops. Ingold and Gell's respective analyses are interesting as they suggest that pattern has both a semantic and functional dimension. Within design scholarship, this relates to Krippendorff's studies [11] who has explored how artefacts have "layers" of semantic meaning in which different parties can understand distinct elements of an artefact or piece of technology and Norman [12] who has closely considered affordances and signifiers with respect to artefact use and engagement. Ingold [13] has also argued that forms are not just observed in a prescriptive and rational way, they are modes of expressing change; the flow of energy and material or what he has described as a "textility" present within made artefacts. In this sense, pattern making cannot be seen as simply an ornamental practice, the traditional view advanced by figures such as Owen Jones [14], but an expression of complex cultural beliefs that reflect a diverse range of meanings.

Form and Emotion

To grasp the cultural status of pattern further, we must consider the links between form-perception, meaning and emotion. Recent work in experimental aesthetics is instructive and has suggested that humans have a possibly innate preference for particular kinds of forms and associate particular emotive experiences with abstract geometric arrangements—notably a curvature-angularity dichotomy whereby curvature is mainly associated with positive emotions and angularity is mainly associated with negative emotions within a given context see [15–17].

Line is an important component within many of these studies as it allows forms and representations to be distilled down into very simple structures facilitating analysis. Combining these insights with an analysis of historical stylings, the authors developed the "Line Model of Form and Emotion" see [5] presented in a previous publication in which line is presented as a critical tool in the creation of structural elements and a window into understanding the emotive and semantic connection particular aesthetic styles have. Notably, this was observed in an early study by Poffenberger and Barrows [18] who examines pre-drawn lines finding that small changes to line design and orientation could change the perceptual interpretation. Critically, the line analysis revealed the patterning that underlay the structural formations of artefacts leading to an interest in pattern.

The exploration of visual-perception of form and emotion was thus extended to explore pattern and pattern interpretation in two studies conducted by the authors see [4, 6]. Both studies examined a set of culturally important patterns as complied by Wade [2] in which participants were asked to interpret a set of 16 patterns. The first study had a limited number of participants but demonstrated clear divergences between patterns with curved forms and those with angular forms. The second study was more thorough, involving 30 participants and a comparative analysis of emotive responses. These results indicated a similar split in the interpretations which was then subsequently analyzed by linking it to culturally important aesthetic motifs such as interlocking rings, waves and mazes.

Experimental Protocol

We can now introduce the follow up studies of this work. As stated in the Introduction, the research goals are to explore how people express emotion through form and then embody these emotions in distinct patterns by identifying motifs. The first part of the study consisted of 30 participants aged between 20 and 35, all from design and engineering backgrounds from a range of nationalities. Using Plutchik's [19] emotive categories (a widely used reference for emotion categorization), a worksheet was provided to each participant with one of eight emotive terms and two points separated by blank space. The emotive terms refer to what Plutchik called "basic" emotions—the emotions most central to human experience and the key components of more complex emotional experience. Each participant was instructed to, in their own time, represent the emotive terms in the form of a continuous line, inspired in part by the early studies of Poffenberger and Barrows mentioned earlier that also examined continuous line structures. Ingold [9] has made plain that forms of representation through line can be laden with significant cultural and symbolic values. This is the key property that was to be explored—using an interpretivist approach, the lines would be analyzed for aesthetic trends or coherent geometric patterns. Furthermore, it provided a bounded and simple task for the participants to complete. The emotive terms selected included fear, trust, anger, joy, anticipation, surprise, disgust and sadness. The terms were presented in that same order to each participant and were selected to explore a diverse range of emotive categories. Four of the terms were selected for their positive valence (following Ekman [20])—trust, joy, surprise and anticipation. The other four were selected as examples of negative valence and are more unambiguously associated with unpleasantness. It should be noted that surprise has more ambiguity in meaning as noted by Neta et al. [21] but within the context of design perception and interaction, surprise has been shown to elicit positive emotions (see Desmet [22]). Furthermore, the categorization of emotion and emotive valence is a challenging problem and beyond the scope of this work, we have however taken a loose and pragmatic approach to these categories and highlight some of the issues with emotional similarities, crossover and experiential context.

The second part of the study involved a kind of validation of the assumptions of the first part whereby the emotive patterns were analyzed using normative scales. Each of the 62 participants again aged between 20 and 35 were presented with a worksheet containing a set of emotive terms (derived from Plutchik) and a scale of 0 to 10 and were directed to indicate the level of intensity each pattern conveyed to them for each emotion. The emotive terms explored in this second part differed slightly as the authors felt this alternative list presented a clearer and better range of emotions for participants to select. The subsequent analysis is subjective and interpretivist, bringing in ideas from aesthetic and semantic theory and should not be seen as a definitive analysis.

Representations of Negative Emotions

Half of the words presented to the participants were ones conventionally associated with negativity or a negative valance in psychological terminology. Ultimately the goal was to examine how a set of participants would represent an emotion through line. Each negative emotion will be considered in turn starting with fear.

Fear: The key features seen below in Fig. 3 is one of disunity and chaos as a patterning emerges across the lines. This kind of unstructured line was seen frequently and the representations and may point to a feeling of powerlessness or submission. Fear will often elicit feelings of panic and is as such represented in a line that has no clear path or direction but is highly energetic. Geometrically, the lines are mostly of a curved quality, but this curvature is one that is more probably representing chaotic transitions as a sense of panic rapidly changes—a feature seen in other art forms such as music or film.

By contrast, another motif was common amongst the participants—one of a continuous spikey line with a high frequency of structured directional change (not shown for brevity). While this may also convey some of the chaotic sensations associated with fear, it is also possible this is something more primal with some theorists proposing that emotional responses to form may have evolutionary roots and are driven by survival, the fear of sharp teeth or dangerous rocks [15]. In this sense, these representations may point to these instinctive fears. While this is not definitively clear, the line drawings do bear some resemblance to these natural threats.

Anger: Many of the motifs seen in the line representations were similar to that of fear validating the positive–negative dichotomy however there were a number of distinctions. Firstly, the representations made much more consistent use of angular geometry with less use of curving motifs (Fig. 4). The lines are also highly energetic

Fig. 3 Representations of “fear”

Fig. 4 Representations of "anger"

whereby the changes in movement are frequent. Secondly, the lines on the whole were more structured—the motifs presented were quite consistent and were often drawn within a bounded area between the two points. The representations shown are similar to a number of the lines drawn for the fear exercise—suggesting the same link between anger and a symbolic representation of teeth mentioned before.

As noted many researchers [ibid] have noted that subtle changes in abstract geometry can change the overall perception of a line. Here these subtleties may also be at work with the fear lines being notably more chaotic. Although some examples from the anger exercise point away from this and can be viewed as equally chaotic as fear. The critical take away is the consistent use of angularity and the energetic nature of the line.

Disgust: Overall, the motifs presented for this emotion were very varied and made use of a range of geometry. The diversity presented makes an absolute assessment of the lines difficult, however there are a few elements that can be discussed. One such element may be a consistent sense of discontinuity; the representations were often sharply non-linear with motifs present similar to those see in the fear and anger exercises. Considering the examples shown in Fig. 5 below—while the chaotic nature of the other lines may not be present, there is certainly a similar dynamic visual energy. The emotion of disgust is related to feelings of hatred and disagreeableness—these forms may be representing these feelings through symbolic disorderliness, antithetical to the aesthetic of Western Classicism or High-Modernism.

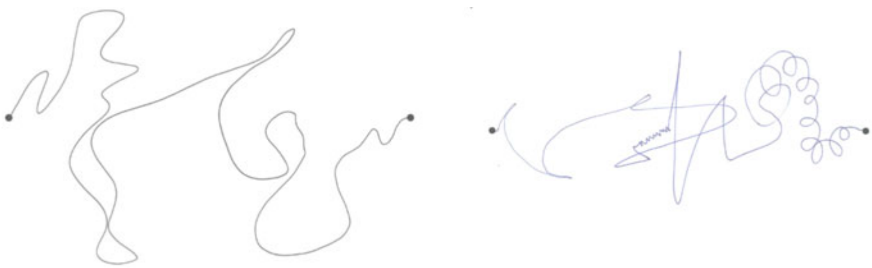


Fig. 5 Representations of "disgust"

Fig. 6 Representations of “sadness”

Sadness: The representations for this emotion were notable for their lack of visual energy and lower frequency of change across the line (Fig. 6). In addition, it appears many participants treated the worksheet space as a kind of grid system where “above” the two points is seen as positive and “below” the two point is as negative. Pallasma [23] has pointed out that this tendency to associate “up” with “betterness” is deeply ingrained within Western thought with connections to religious ideas of the transcendent as embodied in High-Gothic architecture for example [24]. With respect to this many of the lines in this part of the exercise were portrayed with this explicit depression in their journey across the page.

The lines also bear a similarity to the representation of rivers on a map but have a clear directionality, flowing downwards relative to quadrant the composition of the page. In addition to this it should be noted that there was consistent use of curvature in the representations. This is counter to some of the evidence presented earlier from other scholars who have found angularity hugely dominant for interpretations using negative valence. Curvature does seem to have its own melancholic associations—perhaps related to the character of the experience itself as something more drawn out and less energetic and dynamic as anger or fear.

Representations of Positive Emotions

Trust: The key features of the trust lines were that of simplicity and symmetry. The geometric elements tended towards abstraction with minimal dynamic changes in direction and a lack of strong visual energy or movement.

The examples shown above-left in Fig. 7 may relate to the idea of (and actual appearance of) a bridge. A bridge, in static engineering terms, is a solid structure that connects two otherwise disconnected points. It is a solid and ridged structure that is structurally designed to be extremely safe. Relating trust to this kind of motif suggests that the emotion is related to concepts of solidness and unambiguousness that are paramount in the structural design of bridges. The other interpretation is that of the path or the journey. This is also discussed by Ingold [9] were a kind of “straightness” has come to be representative of rationality in Western culture. This kind of thinking may be influencing the representations where a simple and direct line is viewed as more decisively rational and trustworthy than one that travels around the page unpredictably.

Another important motif that was explored by many participants was that of symmetry and balance and particularly the use of curving wavy motifs (above-right).

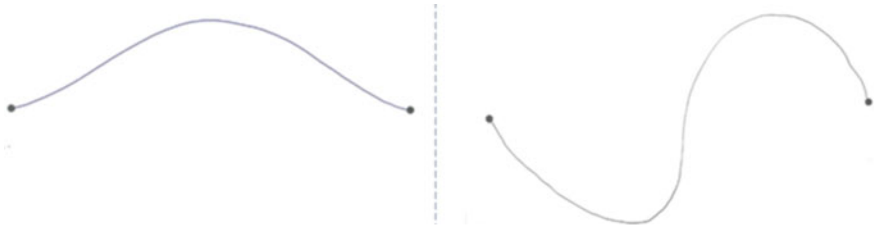


Fig. 7 Representations of "trust"

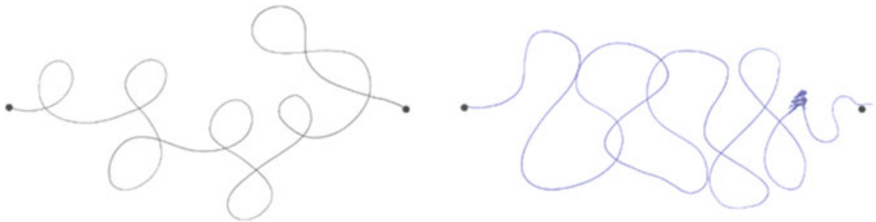


Fig. 8 Representations of "joy"

It is not clear exactly why many of the participants were drawn to this motif, but it is certainly congruent with aesthetic simplicity and, in many places, symmetry.

Joy: Representations of this emotion were coherent, with many participants aligning around several simple motifs. Similar to the motifs expressed for trust, wave-like forms were very often produced by the participants. One noticeable difference was the use of overlapping lines, a line that looped across its own path. Examples of this are shown below in Fig. 8.

The visual energy present in these lines is clear and both lines travel across a large amount of the page. Arnheim [25] has pointed point that visual energy can be conveyed by the Gestalt principles of balance and proximity. In this case, the drawing on the top left is less balanced compositionally but makes more use of the page, the line on the top right makes more direct use of proximity and is more balanced—both however achieve a similar visual character. The movement of the lines could perhaps relate to a bouncing motion; indeed, aspects of the drawing could map the path of a bouncing ball as it travels through space. Additionally, the bouncing motion may have a physically connection with positive feelings of excitement. Notably, the lines are all of a curved aesthetic, substantiating the link between curvature and positive valance.

Anticipation: Although it may be viewed as generally more positive, there is a noted ambiguity—one may anticipate an event in a negative way, evoking feelings of discomfort. The results for anticipation were also quite diverse and there was no clear preference for either curvature or angularity within the depictions. One interpretation that can be explored is viewing the lines as not just a journey across the page but in some regard a temporal journey—a journey in time and an emotional transition

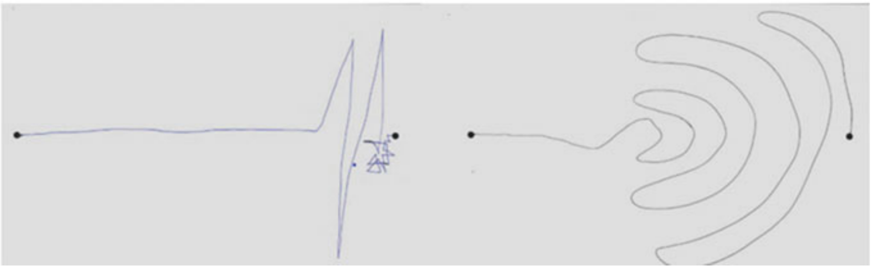


Fig. 9 Representations of "anticipation"

through time. Anticipation has an implicit sense of time within its definition—its meaning is derived from the feeling of expectation for some future event, contrasting with other emotions which may not have the same temporal dimension but are experienced more as a visceral present. It is possible that this aspect of the emotion was the key inspiration for the representations that the participants produced. To look at some examples (Fig. 9), both these lines can be interpreted as a kind of temporal journey with the left point representing a metaphorical present and the right point a metaphorical future. The line on the left explores angularity and the line on the right explores curvature but both have a similar temporal structure that may represent as a map of the emotion leading to a "climax".

Another motif that proved popular amongst the participants was one of a bounded wave-like patterns. Anticipation, for many people, may have associations with feelings of sustained excitement or ever nervousness. The feelings associated with anticipation may relate to this aesthetic representation. Overall, this emotion was notable for its variety of representations.

Surprise: Many of these lines were also interpreted as having a temporal dimension, showing explicit changes in form as they travel across the page. The main difference however is that these lines are kind of mirror images of some of the anticipation lines. As anticipation suggests a waiting or a sustained feeling leading to some kind of climax, the feeling of surprise come from something unexpected that may be highly engaging. Interestingly, in Plutchik's model, surprise is placed at a diametric opposite to anticipation and sits subjectively between amazement and distraction and is related to the complex emotions of awe and disapproval. In this sense, we can see this represented in the lines. Considering the lines below in Fig. 10, if they are read left to right in an orthodox (Western) fashion, all the lines begin with energetic movement. This dynamic visual energy that is present at the beginning of the line dissipates by the time it travels to the far side—a shock followed by a resolution.

The generated motifs were quite diverse overall but were mostly visually energetic with lots of changes in the directions of the line. While their geometric qualities are distinct and there is no clear alignment to either angular or curving motifs. Broadly they are characterized by a journey that is undulating. The visual energy implicit within these lines indicates that surprise is viewed by many as a visceral emotional experience. As there is no clear alignment with either curvature or angularity, it is

Fig. 10 Representations of "surprise"

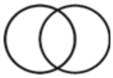
possible that the emotion is viewed with some ambiguity, characterized by feelings of the unexpected or a shock and not necessarily positive or negative in nature.

Taken together, these results and interpretations reveal a complex and layered picture of visual perception and emotional interpretation that articulates with form expression or what aesthetic theorists have defined as principles of formalist representation of metaphysical concepts such as beauty or truth (see Gotshalk's discussion on Kant's aesthetics for example [26]). Many of the participants within the study utilized principles of repetition, patterning and symmetry to build their motifs. Symmetry was often used in association with emotions of a positive valence and repetition of forms used to highlight a sense of balance. Additionally, these rules led to interesting displays of "narrative" within the forms—as if the lines contained stories.

Creating Bespoke Emotive Pattern Designs

How can this knowledge gained from the study of pattern and aesthetics more generally be applied? The model of form and emotion developed by the authors [5] illustrated how discreet geometric elements (notably lines) could be used within the framework of design to create both emotively and semantically resonant products and product stylings. As we have shown by considering scholars such as Ingold, pattern is a very important meta-concept for the functioning of design work, thus we have chosen to explore typical tessellating pattern designs i.e. patterns that cover an infinite plane. While this is not strictly necessary, it provides a useful framework in which to explore these questions and gives a coherent structure for any other researchers interested in pattern and aesthetic perception. We accept there is some jump in reasoning here, this study is however exploratory in nature and utilizing pattern as a medium to examine these complex questions around aesthetic values and perception. This section will describe the creation of the bespoke pattern designs by firstly deriving what are considered emotively resonant geometric shapes, lines and motifs and then applying these to a symmetric rule structure which allow patterns to be generated.

Table 1 Aesthetic motifs derived from line and pattern studies

Aesthetic motif	Description
	Wave motif, transitioning curved form
	Spike motif, angled transitions
	Bursting outwards motif, outward energy
	Interlocking rings motif, a "Vesica Piscis"

Final Designs

From the previous studies by the authors and the line study presented above, four bespoke pattern designs were generated additionally drawing on the motifs that are distilled in Table 1 above. The emotions of trust, joy, surprise and fear were selected as they had some of the clearest representational alignments—there were multiple points of convergence with these kinds of motifs. These motifs presented above have been simplified and amalgamated to capture the general picture of how people expressed the concepts. The completed designs are shown below in Fig. 11. Each design has been created by the authors so also represents a subjective piece of iteratively developed design styling. Abstract, as opposed to realist motifs were used to construct the designs given the focus on abstract shape and line throughout the reviewed scholarship.

Results from Visual Assessment

The presented patterns were designed in order to represent emotive concepts; visual form as embodying a subjective meaning. We have seen how this idea has notable coherence across experimental aesthetics and theories of art more generally. This work proposed to explore if this could be extended to pattern with respect to the many scholarly efforts to establish how pattern plays a role in kinds of cultural expression and knowledge. The patterns will be discussed in turn and in the same order they were presented to the participants, with principal reflection orientated around how the emotive assessments reflect those modelled by Plutchik [19].

The results are shown in full in Fig. 12. Pattern (a) was conceived to be a representation of trust, or more broadly, positive feelings of happiness or connection following an analysis conducted previously by the authors. The design made notable

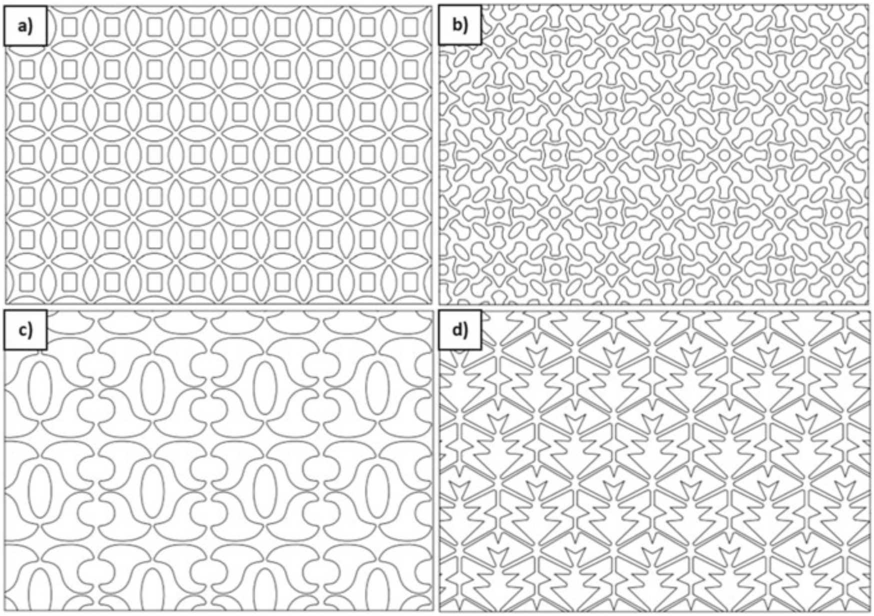


Fig. 11 Bespoke emotive pattern designs—**a** Trust **b** Surprise **c** Joy **d** Fear

use of the structural motif of overlapping rings which, it was postulated, capture some semantic representation of the feeling that is designates as a principle emotion. It is clear that this design has been successful as an abstract representation of trust with the emotion receiving the highest overall rating (2.72) in terms of a perceived visual representation. Additionally, the emotions of optimism, joy and love received high rankings. The negative emotions received contrastingly low ratings from participants, suggesting that while there was the subjective possibility that these emotions were present in some regard, the general affect was towards a positive interpretation. Trust, optimism, joy and love have very high average ratings compared with their emotional opposites such as aggressiveness and disgust.

Like pattern (a), pattern (b) has essentially achieved its envisioned design goal of embodying the emotion of surprise with this emotion receiving the highest intensity rating (2.69). Comparatively, emotions such as sadness and remorse received low scores suggesting a coherent semantic distinction. Furthermore, the ambiguity between a positive valence and a negative one that may be present in definitions of surprise, it appears is more difficult to achieve in a visual context as there is a clear skewing towards a more positive interpretation of the forms. Joy and optimism received notable high scores suggesting that these feelings are more directly related to understandings of surprise as a feeling.

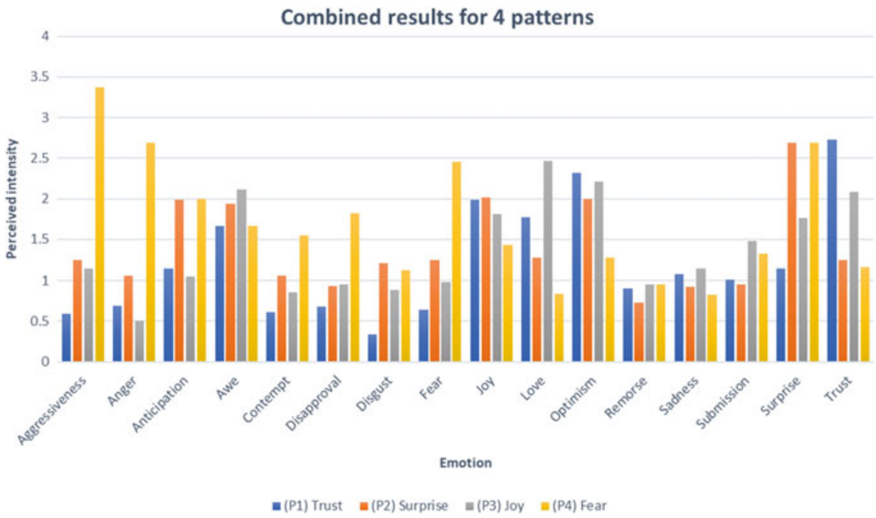


Fig. 12 Combined results from study

Results and Discussion

Like pattern (a), pattern (b) has essentially achieved its envisioned design goal of embodying the emotion of surprise with this emotion receiving the highest intensity rating (2.69). Comparatively, emotions such as sadness and remorse received low scores suggesting a coherent semantic distinction.

Pattern (c) was conceived along similar lines to pattern (a), drawing from the previous studies by the authors and other evidence drawing on curvature preferences to present a representation of joy. Unlike pattern (b), this was conceived to be a clearer representation of the emotion and positive emotions more broadly. The results demonstrate that while a positive interpretation has been achieved, the participants cohered around another emotion; love. Love is an extremely complex emotion, characterized as a feeling drawn from not only joy and trust but feelings of serenity, acceptance, and ecstasy too [19]. Love received a rating of 2.46, closely followed by optimism at 2.20 and awe measuring 2.11. In contrast, emotions such as anger and contempt received relatively low scores indicating a semantic coherence within the design tending towards a positive valence.

Pattern (d) was designed to represent a subjectively negative emotion, for the purposes of the task fear was selected as a useful starting point though the broader goal was to represent a negative valence. The principle guidance for the design was the use of angularity to counter the curvature preference. As with pattern (c), pattern (d) did achieve the negative response predicted, however, the consensus showed that the pattern was more representative of anger and aggressiveness than fear.

Interestingly, this pattern saw high scores for aggressiveness and anger—3.37 and 2.69 respectively—but notably received a high score for surprise, also measured at

2.29. It may be that the uncertainties that have already been discussed regarding surprise as an experience are manifest here in the subjective interpretation of this pattern.

Implications for Design Practice

How can the conclusions presented here feed our wider understanding of design? What is interesting is the link between meaning and abstraction, unifying in the inter-objective formulations of pattern. As stated earlier, patterning can have aesthetic uses (decoration or composition), functional uses (structural requirements in engineering or architectural contexts) and uses within making (weaving or sewing). But how can this study enhance these formulations?

In essence, this study has tried to deconstruct pattern or reverse-engineer into abstract or simple elements in order to penetrate how it could be applied in specific design contexts. What was most revealing, is how the exercise of expression-through-line, as informed by other studies in experimental aesthetics, led to forms of basic patterning, with the repetition of motifs in order to convey subjective understandings of emotions and feelings. Additionally, complex features such as narrative were also observed as a possible semantic interpretation of the line forms.

In practice, this shows that pattern can emerge in very simple forms but can also convey very complex ideas such as emotions or stories. The emotive power of designed artefacts has been well understood for two decades see [27, 28] but this decomposes these analyses further by drawing a link between abstract representations and the end artifactual result. With respect to this, this study represents a kind of methodology for the creation of attuned emotive forms. In essence, this is an exercise in human-centered design, similar to a Kansei approach (see [29]), whereby the subjective experiences and understanding of a set of individual users is utilized to elicit a specific design result like an aesthetic styling for instance. While this work has focused of decorative pattern forming, similar exercises could be applied to design other kinds of objects as seen in other interesting studies Niedderer who explored form perception with respect to movement interpretation [30] and the EmotiveModeler project which has created a topology of emotive forms [31].

Furthermore, the relationship between pattern and emotion presents possibilities in practical aesthetics and design-interaction properties such as product texturing. Could patterns for instance be used to elicit particular behaviors or enhance certain moods in specific environments? Additionally, do patterning motions elicit feelings? As scholarship from Ingold [ibid] has explored, the actual practice of creation relies of patterning motions—it may be possible to explore this further, examining further how emotional expression manifests through the processes of making and manufacturing at both the level of craft and industrial production (e.g., the patterning implicit in the movements of CNC milling tools). Such questions have already been explored by in interesting studies by Karana et al. [32] for example.

Limitations

It should be noted at this point that this work has several limitations and methodological issues. The key limitation the reader should note is that the study relies on subjective readings and interpretations of aesthetic objects that is informed purely by art historical and psychological scholarship. But has not been directly coded to ensure the interpretations are valid. Additionally, the challenges in categorizing and interpreting emotive responses are well known. This presents challenges for presenting the work in any kind of "objective" light. Culture is also a concern, as it is not clear in what ways small differences in demographic background may have influenced interpretation—for a clearer picture of the results, an analysis of cultural influence would need to be developed.

Furthermore, a number of leaps of reasoning are taken in order for the study to take place, namely generating the patterns from the line motifs is not an altogether clear logical step. With respect to this, there is opportunity for future researchers to explore this further by fleshing out a logical workflow between abstract form expressions and more discrete aesthetic objects which this study has partly begun.

Conclusion

This work has sought to build upon a set of previous studies conducted by the authors and combine it with a new study to explore the relationship between line, patterning, and emotion.

Firstly, some background on pattern and pattern creation was provided and how shape interpretation and visual perception of form can be used to inform the understanding of pattern. From there, the previous studies conducted by the authors were elucidated, providing foregrounding for the studies presented within this paper which are a conceptual extension of those.

The paper subsequently presented two linked studies. The first study considered lines and how they can embody particular emotions. The results from this study clearly showed a convergence around certain sets of aesthetic themes and motifs such as interlocking rings and dynamic forms seeming to embody a narrative. Based on the results of this study and taking results previously gathered by the authors regarding the interpretation of pattern, four bespoke pattern designs were developed to embody four specific emotions, namely joy, fear, surprise, and trust. These designs were subsequently analyzed within the second study.

The results of the second study, in which each bespoke pattern was interpreted against a list of emotive terms, showed that the designs broadly achieved the subjective emotive responses predicted by the line and pattern studies. Notably, the trust and surprise designs corresponded directly with those emotive terms, but the joy and fear design diverged, aligning towards the related emotive concepts of love and optimism, and aggressiveness and anger respectively. This highlights that the context of shape within a pattern structure is important and may lead to interpretations beyond the ones derived for the discrete elements of the patterns taken as abstract components. Overall, this study, while being experimental and interpretivist in formulation, shows how forms taken as abstract discrete elements can be utilized to attune more complex aesthetic structures around specific emotive experiences and interpretations. While there are a number of limitations with the approach that are acknowledged, it is hoped that this paper presents a fresh perspective on a hitherto understudied element of design culture.

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