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Using creative exhaustion to foster idea generation

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Abstract Numerous studies have shown the value of introducing cognitive supports to encourage the development of creative ability, and researchers have developed a variety of methods to aid in generating ideas. However, design students often struggle to explore more ideas after their initial ideas are exhausted. In this study, an empirically validated tool for idea generation, called *Design Heuristics,* was introduced as a means of productively pushing past creative exhaustion in an industrial design course at a large Midwestern university. Students worked on a simple design task on their own, generating an average of 6.1 concepts in a 30-min session; then, after 10 min of instruction on the *Design Heuristics* tool, students generated an average of 2.8 additional concepts for the same task using Design Heuristics for an additional 30 min. The concepts created in this second session using Design Heuristics were rated as higher in novelty, specificity and relevance. These results suggest that students benefit from introducing support tools following a period of working on their own ideas. Once their own ideas are exhausted, students may be more open to using and learning from support tools, and these tools may support skill development while producing higher quality outcomes.

Keywords Creativity · Design education · Design Heuristics · Idea generation · Creativity skills · Design methods

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Introduction

Studies of design practice show that professionals make extensive use of tacit knowledge—including patterns of thinking, user experience, and design precedent—in the designerly task of imagining possible futures (Cross 2011; Lawson and Dorst 2009; Polanyi 1966). For beginning students, practice in engaging with design processes takes place without this tacit knowledge in place. As a consequence, students may struggle to generate new concepts during the idea generation phase, and may be unable to consider a variety of possible concepts due to creative exhaustion. This study addresses means to support design students' development of idea generation ability, specifically focusing on instructional strategies and tools that can assist students in developing novel and creative ideas.

Prior research has established that generating more ideas, or idea *fluency*, is of critical importance in order to effectively explore the problem space and achieve successful outcomes (Crismond and Adams 2012). Fluency has long been used as a measure of creative ability (Clark and Mirels 1970), and as Simonton (1990) suggests, generating more ideas will result in a larger set from which to choose the most promising idea. In individual tasks, the generation of more alternatives has been found to produce more creative solutions (Mumford et al. 2001; Rostan 1994; Redmond et al. 1993). But at times, generating not just more, but a more *diverse* set of ideas may prove challenging. Designers have been shown to fixate on a particular design feature or concept direction, potentially resulting in fewer concepts or a set with a high degree of similarity among concepts (Purcell and Gero 1996; Jansson and Smith 1991; Linsey et al. 2010). Alternatively, designers may become overwhelmed by the constraints or challenges of a particular design space and fail to explore possible concepts (Santanen et al. 2004).

Design tools

To improve design students' production of novel concepts, previous research has resulted in the creation of tools to support designers in the iterative process of idea generation (Altshuller 1997; Daly et al. 2012; Eberle 1995; Gordon 1961; Smith 1998; Zwicky 1969). In a design education context, tools, methods, and strategies form a repertoire of potential design moves the designer can draw from in a non-deterministic, abductive way (Gray 2016; Cross 2011; Stolterman et al. 2008). The need for students to understand and value available design tools, methods, and strategies (Cross 2011; Stolterman et al. 2008) requires what Nelson and Stolterman (2012) define as *instrumental judgment*. The development of students' sensibility toward design tool use requires not only objective knowledge of commonly used tools, but also the professional judgment in knowing *when* an external tool is needed, *what* tool is most relevant for the specific situation and phase of the design process, and *when* the tool's generativity has been fully realized.

For beginning designers, the need for, and value of, ideation support tools may not be readily apparent. Students may not have the reflective or metacognitive skills to recognize their progress (or lack thereof) during ideation (c. f., Pressley et al. 1998; Adams et al. 2003), and they may lack the expertise to select support tools that are likely to be helpful (Harrison et al. 2006). As a result, designers may still prefer to generate solutions on their own (Purcell and Gero 1996) using their own ideation techniques, such as prior experiences, rather than seek assistance from such tools. This may be particularly true in the early stages of the design process because many initial ideas may emerge with little apparent cognitive effort. For idea generation, when imagining and creating new design ideas, instructional supports or cognitive scaffolding that expand students' awareness of design methods and the judgments required to employ them successfully (Harrison et al. 2006; Woolrych et al. 2011) may be particularly beneficial.

However, at present, there is a relatively little instructional guidance available on how to productively encourage the development of ideation skills, particularly in relation to support tools (Daly et al. 2012). Jonassen's (2011) suggestion of providing *scaffolding*, or a supporting structure for cognitive activity, to learners, indicates an area of potential promise for increasing cognitive ability and awareness during idea generation. Within this paradigm, a goal is to build appropriate experiences to encourage the modelling of desirable problem solving behaviours, often mediated by particular tools such as case-based reasoning or problem based learning (Hmelo-Silver et al. 2007; Jonassen et al. 2006). When introducing or manipulating scaffolds, instructors must be able to recognize when students reach instructional barriers, and provide appropriate cognitive support tools to challenge students' assumptions and make their strategies more explicit, thereby enabling further development.

Another guide for instruction, learner-centric instructional practices and Self-Determination Theory, suggests that if students have a "felt need" (or sense of the relatedness of a learning resource to a direct benefit), it may increase their effectiveness (Deci and Ryan 2011; John-Steiner and Mahn 1996; Vygotsky 2004). In the generation of concepts, *creative exhaustion*—or an inability to continue generating creative solutions on one's own—may be one natural place to offer support tools in design. Rather than providing students with a range of tools at the beginning of an idea generation task, beginning designers may benefit from tool use when provided in a "just in time" manner as a means of decreasing cognitive load (van Merriënboer and Kirschner 2012) and increasing the relatedness of the tool to the present task (Deci and Ryan 2011).

Creative exhaustion in an open-ended idea generation task may provide a unique opportunity for students. When the students' own techniques have played out, they may be more prepared to learn new techniques without interference from their self-generated ideas. When a support tool is introduced following exhaustion, students may experience increased motivation for learning because there is a direct, immediate, and meaningful need for applying the cognitive support tool, as indicated by Self-Determination Theory. And, just when students are demonstrably unable to proceed on their own, they experience further successful generation with the support tool. The ability to progress in the task, rather than wait in frustration, has immediate benefit to the learner. They may also experience the cessation of generation as a cue for recognizing the need for support tools, and identify a role for tools within their own creative process.

In addition, this instructional strategy may lead to the development of students' sensibilities regarding instrumental judgment (Nelson and Stolterman 2012; Self et al. 2014). While past research has focused on various support tools (Smith 1998), less is understood about how students are able to develop their abilities with these tools, or how to capitalize on student frustration or perceived lack of creative skills. Instrumental judgment, in particular, represents a space where self-learning must continue to occur in professional practice (Adams et al. 2011; Gray 2014). Preparing for this "far transfer" of skills—from learning a specific method in a managed classroom setting to locating and teaching oneself a needed technique in future professional practice—is an important part of becoming a professional and acting in expert ways (Lawson and Dorst 2009).

In this study, we focus on the “just-in-time” introduction of a cognitive tool to support students in generating creative ideas and learning about *when* a support tool may be beneficial to them. A large number of cognitive strategies to assist in idea generation exist in the psychological, cognitive science and engineering literatures (e.g., Santanen et al. 2004; Smith 1998). In particular, a variety of idea generation methods have been suggested for beginning design students, including brainstorming (Osborn 1957), SCAMPER (Eberle 1995), morphological analysis (Allen 1962), TRIZ (Altshuller 2005; Hernandez et al. 2013; Orloff 2003), C-Sketch (White et al. 2012), and analogy (Goel and Bhatta 2004).

For beginning designers, a simple method requiring minimal training appears to be an advantage (Gray et al. 2015). In addition, research on generating solutions for unstructured, simple tasks suggests that using directed brainstorming (where “primes” introduce relevant material) produces more creative solutions compared to free brainstorming (Santanen et al. 2004). Based on these and other considerations, such as availability of materials, we selected *Design Heuristics* as the ideation support tool for this study. *Design Heuristics* have been shown to be effective in prior studies with beginning (Daly et al. 2012; Yilmaz et al. 2010), engineering and industrial design students advanced (Kramer et al. 2015; Daly et al. 2012), and with professional engineers (Yilmaz et al. 2012, 2015a, b).

Design Heuristics

Design Heuristics are an idea generation tool that has been empirically validated through multiple studies of industrial and engineering designers (Yilmaz et al. 2015a, b) product analyses (Yilmaz et al. 2016a, b), and case studies (Yilmaz and Seifert 2011). *Design Heuristics* provide prompts to help designers generate alternative concepts by varying elements in design concepts (Yilmaz et al. 2016a, b). In particular, *Design Heuristics* have been shown to improve beginning students’ ability to generate creative concepts (Yilmaz et al. 2010; Daly et al. 2012). Based on this empirical support, we selected *Design Heuristics* as the cognitive support tool for the present study.

The *Design Heuristics* tool is designed to assist in idea generation by prompting a designer to consider alternative concepts for a given problem, resulting in a richer set of concepts to consider (Yilmaz et al. 2016a, b). The prompts are “cognitive shortcuts” that introduce intentional variation in the concept set. For example, one might use a heuristic like *Roll* to create a novel cake concept, *Layer* to blend flavors within a gum, and *Nest* to design shopping cart storage. The *Design Heuristics* tool is presented as a set of 77 cards describing each prompt (see Fig. 1 for a complete list of titles). A designer can select a prompt at random, or choose one most suited to a given product. Each *Design Heuristic* can be applied to any product design problem to suggest how to generate possible concepts.

Each card includes a specific design prompt, descriptive text and graphical representation that provides information on how to use the prompt. In the example shown in Fig. 2, the heuristic *Adjust function through movement* prompts the designer to consider a concept where the product can be adjusted by moving a piece of it to alter its performance. On the back of each card, two different consumer products are shown as examples for card users. The “Shower Massage” is an example of an existing product where users adjust water spray by moving the showerhead up or down. On every card, one of the two product examples is a “seating device,” demonstrating that each heuristic can be applied to the same design problem. These card components guide designers in applying each heuristic to

1	Add levels	20	Change geometry	39	Incorporate environment	58	Scale up or down
2	Add motion	21	Change product lifetime	40	Incorporate user input	59	Separate functions
3	Add natural features	22	Change surface properties	41	Layer	60	Simplify
4	Add to existing product	23	Compartmentalize	42	Make components attachable/detachable	61	Slide
5	Adjust function through movement	24	Contextualize	43	Make multifunctional	62	Stack
6	Adjust functions for specific users	25	Convert 2-D material to 3-D object	44	Make product recyclable	63	Substitute way achieving function
7	Align components around center	26	Convert for second function	45	Merge surfaces	64	Synthesize functions
8	Allow user to assemble	27	Cover or wrap	46	Mimic natural mechanisms	65	Telescope
9	Allow user to customize	28	Create service	47	Mirror or array	66	Twist
10	Allow user to rearrange	29	Create system	48	Nest	67	Unify
11	Allow user to reorient	30	Divide continuous surface	49	Offer optional components	68	Use common base to hold components
12	Animate	31	Elevate or lower	50	Provide sensory feedback	69	Use continuous material
13	Apply existing mechanism in new way	32	Expand or collapse	51	Reconfigure	70	Use different energy source
14	Attach independent functional components	33	Expose interior	52	Redefine joints	71	Use human-generated power
15	Attach product to user	34	Extend surface	53	Reduce material	72	Use multiple components for one function
16	Bend	35	Flatten	54	Repeat	73	Use packaging as functional component
17	Build user community	36	Fold	55	Repurpose packaging	74	Use repurposed or recycled materials
18	Change direction of access	37	Hollow out	56	Roll	75	Utilize inner space
19	Change flexibility	38	Impose hierarchy on functions	57	Rotate	76	Utilize opposite surface
						77	Visually distinguish functions

Fig. 1 List of *the 77 Design Heuristics* © Design Heuristics, LLC; used by permission

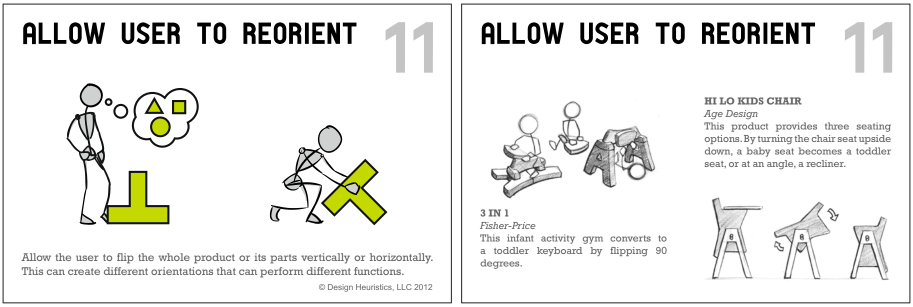


Fig. 2 Example card (front and back) from the Design Heuristics set © Design Heuristics, LLC; used by permission

their own design problem. They can be used repeatedly and in combination to generate additional concepts (Yilmaz et al. 2015a, b; Daly et al. 2012).

Research focus

What happens when students use this support tool only *after* their own ability to generate concepts is exhausted? And what implications does this instructional strategy have for the development of pedagogical experiences that encourage creative ideas? In this paper, we introduce a creativity support tool during a specific part of the idea generation process: when design students have exhausted their initial ideas. The study results should determine whether this instructional strategy is effective in boosting creative outcomes.

To examine the impact of tool use during idea generation, students were asked to first generate as many design ideas as possible on their own while using their own existing methods. Next, the *Design Heuristics* tool was introduced, and the students were asked to continue working on the same design problem while using this tool. The intention of was to "exhaust" the students' ideation processes through the initial session, and then test whether the *Design Heuristics* cognitive support tool would stimulate further idea production. We address the following research questions in this study:

RQ1 Can the *Design Heuristics* creativity support tool expand idea generation even after creative exhaustion?

RQ2 Are there differences between concepts created with and without the *Design Heuristics support tool*?

RQ3 How does use of the *Design Heuristics* cognitive support tool influence idea generation process?

Method

An undergraduate industrial design class at a large Midwestern university (n = 34) participated in a conceptual design session as part of a course. Participants included 12 females and 22 males, aged 19–22, who were sophomore level industrial design majors.

These students were presented with a simple, familiar design problem, stated as follows: "Please design a seating unit. Generate as many solutions as you can." The goal was to provide a problem that would be immediately accessible to students early in their design training by avoiding technical requirements. This simple problem would allow students to generate multiple alternative concepts while working on their own using their past experiences with a variety of such products. Deemphasizing technical criteria in the design problem, in addition to allowing students to freely explore the possible candid solutions, likely increased students' capability to generate more creative solutions across the both sessions (Barlex and Trebell 2008).

Procedure

The 70-min session was divided into three parts, including two ideation sessions of 30 min separated by a 10-min period of formal instruction on the *Design Heuristics* tool. First, participants were asked to individually generate multiple concepts for the design problem while working on their own, using a brainstorming approach that valued quantity of ideas over evaluation of ideas for specific markers of quality. No additional instructions were provided at this phase. Participants were instructed to draw each concept on a new sheet of paper, and to provide a short, written description of each concept's function.

Next, the participants were provided a brief instructional lesson on *Design Heuristics* (Yilmaz et al. 2010; Daly et al. 2012). This lesson gave an overview of the approach, presented two examples of heuristic cards (see Fig. 1), and provided instruction on how to use this tool to produce new concepts. The lesson provided students with knowledge about the heuristic cards and how to apply these cognitive strategies to create new concepts or variants of concepts. Students also practiced applying one of the heuristics to a practice design problem (a salt and pepper shaker set).

For the second 30-min session, participants were asked to continue working on the same design problem as before, but this time using *Design Heuristics* cards to assist in their concept creation. Each participant was given a different set of 10 Design Heuristic cards selected at random from the 77 Design Heuristics cards. In addition to drawing each concept on a new sheet of paper and providing a description of the concept's function, participants were asked to identify any Design Heuristic cards they used to generate each concept, if any.

Analysis

The concept sheets from both ideation sessions were randomized without providing any indications about which concepts were generated in which session. Two junior industrial design students who had expertise in developing concepts in industrial design evaluated each concept sheet using the Consensual Assessment Technique (CAT; Amabile 1982). Each evaluator worked independently, and rated each concept on a seven-point scale for novelty, feasibility, relevance, and specificity. The evaluators were not given any particular definitions of the rating criteria, as suggested by the CAT (Amabile 1982), and were rather asked to use their own definitions. Each rater completed a rating for every concept on one dimension before moving on to rate the set again on a different dimension. These scales represent four distinct characteristics of a creative concept (Dean et al. 2006):

Novelty The degree to which an idea is original and modifies a paradigm

Relevance The degree to which a solution applies to the stated problem and will be effective at solving it

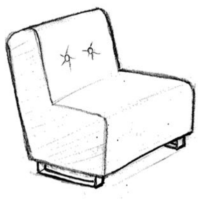
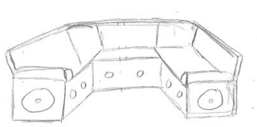
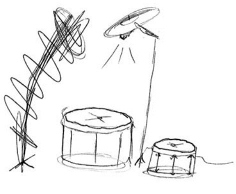
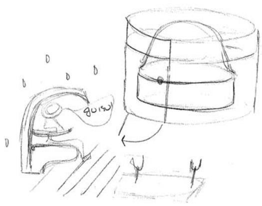
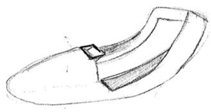
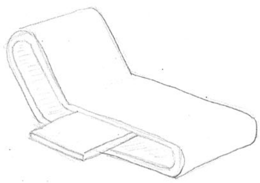
Feasibility The degree to which an idea can be easily implemented and does not violate constraints

Specificity The degree to which an idea is specified (i.e., worked out in detail)

Dean et al. (2006) identified these four dimensions from a review of constructs, including eight associated sub-dimensions, in 90 empirical studies of creativity. While Shah et al. (2003) proposed a different metric that is frequently used (novelty and quality), the four dimensions in Dean et al. (2006) may capture more qualities of successful solutions. These four dimensions appear especially relevant to the concepts that are developed in early phases of ideation. Table 1 presents an example of high and low scoring concepts in each rating category.

Using the raters' scores, we ran a linear mixed model for each dimension. This model included *Working on Own/with Design Heuristics* and *Rater 1/Rater 2* as effects, with *subjects* as the random effect. This approach removes the variability of raters from the error term in the model. The model tests for differences in means, and assesses rater consistency and agreement through intraclass correlations (ICC) (McGraw and Wong 1996). Consistency and agreement are measured separately in ICC, with *consistency* measuring correlation between raters and *agreement* measuring absolute agreement on values between raters. ICC has been used in previous studies of creativity, drawing on Amabile's CAT (1982) and extending the analysis of results beyond simple correlation (e.g., Kaufman et al. 2007). Baer and McKool (2009) note that interrater reliability among expert judges should be above 0.70. Using this benchmark, consistency was above

Table 1 Examples of Concepts with High and Low Ratings on each Creativity Dimension

	Low-Scoring	**High-Scoring**
Novelty	1.5/7 (P12) 	6.5/7 (P25) 
Specificity	1/7 (P6) 	6.5/7 (P19) 
Relevance	1.5/7 (P28) 	6.5/7 (P24) 
Feasibility	1.5/7 (P31) 	6.5/7 (P12) 

acceptable levels for all four rating dimensions. Agreement requires exactly the same score from each rater, and the ICC for this measure is close to or above acceptable levels for all dimensions except Feasibility. For the Feasibility ratings, the low agreement reliability but high consistency reliability suggests a given concept was viewed in roughly the same by the two raters, but they didn't use the scale values in exactly the same way.

Results

RQ1 Can the Design Heuristics creativity support tool expand idea generation even after creative exhaustion?

While working on their own in the first 30-min session, participants generated an average of 6.1 concepts each (SD = 1.43), with a total of 205 concepts across all participants (N = 34). This high rate of concept generation suggests the problem was readily accessible to these beginning students, likely due to its simplicity and the absence of technical criteria. The participants' extensive personal experiences with different types of seating devices may have also helped them create their own concepts. Also, although we have not specifically studied *when* 'exhaustion' took place in this session, we observed that majority of the students stopped adding new concepts before we moved onto the next session, which suggests that they may have experienced exhaustion of their immediate ideas and needed external prompts to assist them in order to move forward with new solutions.

In the second 30-min session, participants used *Design Heuristics* to generate concepts for the same design problem. They generated an average of 2.8 additional concepts (SD = 0.96), with 93 new concepts across all participants. Even though the participants generated fewer concepts compared to the first session, the fact that they continued generating concepts for another 30 min suggests they were able to use the *Design Heuristics* tool effectively.

The smaller number of concepts generated in the second session was likely due to the additional time needed to read and think about each *Design Heuristic*, and then apply it to the problem. Though two students generated the same number of concepts in the two sessions, all other participants generated more concepts in the first session when working on their own. With the 70-min session length, decreased motivation and increased fatigue in the second session compared to the first are additional potential explanations.

RQ2 Are there differences between concepts created with and without the Design Heuristics support tool*?*

Each concept generated by the participants was scored on four dimensions: novelty, feasibility, relevance, and specificity. These dimensions allow for a direct comparison between concepts generated working on their own to those generated using *Design Heuristics*. Table 2 shows the average rating (and standard deviation) of each of these measures where there is an increase from the first to the second session in the quality of concepts across multiple dimensions.

The analysis compared the ratings for concepts generated while working on their own to those generated while working with Design Heuristics. The results showed a consistent pattern where concepts created with Design Heuristics were rated higher than those generated when working on their own (see Table 2). *Novelty, Specificity* and *Relevance* ratings were higher on average with *Design Heuristics* concepts. Only the *Feasibility* ratings

Table 2 Comparison of ratings for concepts generated with and without *design heuristics*

	Session 1: Working on Own	Session 2: Design Heuristics	Z	*p*	ICC agreement		ICC consistency	
					Session		Session	
					1	2	1	2
Novelty	3.84 (1.155)	4.28 (1.069)	− 2.513	0.014	0.79	0.71	0.82	0.71
Specificity	3.22 (1.301)	3.86 (1.374)	− 5.276	0.000	0.86	0.87	0.86	0.87
Relevance	3.90 (1.330)	4.19 (1.147)	− 2.588	0.011	0.77	0.69	0.87	0.72
Feasibility	4.56 (1.159)	4.36 (1.162)	1.312	0.192	0.34	0.46	0.81	0.77

showed no significant difference between the two sessions, though concepts with *Design Heuristics* were rated lower on average. This may suggest more divergent, “blue sky” thinking with *Design Heuristics*, resulting in concepts less grounded in manufacturability, but offering more novelty.

Higher concept quality was observed when Design Heuristics were used compared to when students worked on their own. Three of the four rating categories—novelty, specificity, and relevance—showed significant improvement when Design Heuristics were used. This finding indicates that even as the quantity of concepts generated decreased, the overall quality of concepts increased when using Design Heuristics. Despite potential creative exhaustion, using Design Heuristics produced an increase in concept novelty and quality.

RQ3 How does use of the Design Heuristics cognitive support tool influence idea generation process?

To demonstrate the impact of Design Heuristics on idea quality, we present an example from one participant who represents the observed pattern across students. This example is typical in that the quality of ideas increased during the Design Heuristics session. When working on his own, P1 generated 5 concepts in the first 30-min session; in the second session, he generated 2 concepts using the *Design Heuristics* tool. Two concepts from each session are shown in Fig. 3.

Comparing the average ratings, this participant’s scores were higher for the *Design Heuristics* concepts (*Novelty* average was 3.8, then 4.5; *Relevance* 4.11–4.3; *Specificity* 3.2–3.7), with only *Feasibility* averages higher in the Brainstorming session (4.6–4.3). The concepts created with the Design Heuristics tool suggest a more sophisticated or elaborate theme compared to the concepts when working on his own. The concepts generated in the first session (natural ideation) suggest stand-alone solutions where the participant relied on ideas that come to mind immediately, such as a chair that rotates and another that has a light. However, when the concepts in the second session (with heuristics) are examined, this immediate set of ideas seems to differ. For example, the participant considered creating a carousel kind of a setup using the heuristic mirror/array, where multiple people could sit around a central table for a gathering which wasn’t specified in the problem provided. In the other example, there is an effort in building layers of seats where each seat functions separately but also can be hidden underneath each other. This kind of thinking suggests more advanced exploration of the solution space which seems to be triggered by the introduction of the heuristic cards.

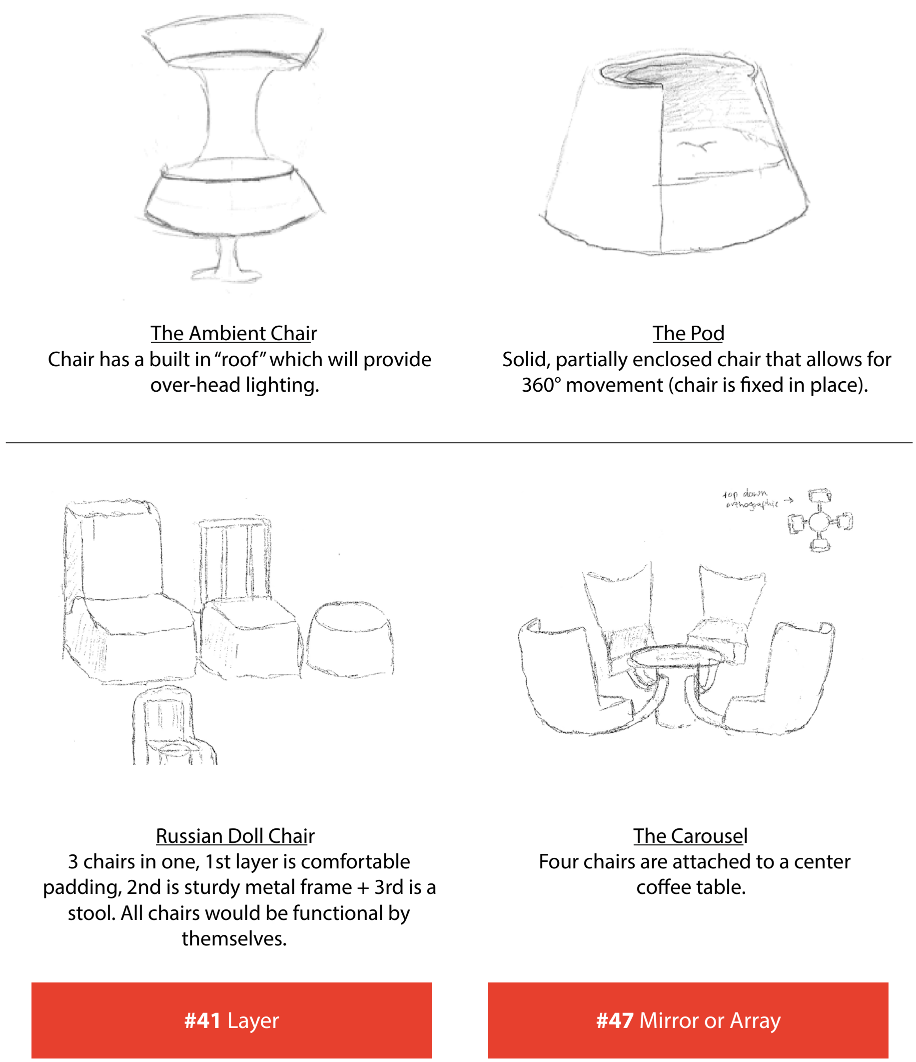


Fig. 3 Four concepts from P1, including written (transcribed) comments, while first working on his own (top concepts), and then working with *Design Heuristics* (bottom concepts)

In another example, P10 created 6 concepts in the first session (Fig. 4) without instruction on Design Heuristics. Although the quantity is higher (compared to the 2 concepts generated in the second session with the heuristics), the quality and sophistication of the concepts is rather low. The concepts generated mostly resemble existing solutions already on the market, focusing on lounge chairs either standing on the ground, or hanging on separate components.

On the other hand, in the second session where the heuristics were introduced, although the idea of the 'lounge chair' is still the focus, the form and arrangements of design elements are dramatically different from existing products (Fig. 5). In the first concept, the participant used a combination of the heuristics *Bend* and *Compartmentalize* to create a series of surfaces for multiple people to sit. The concepts create seats through bending a

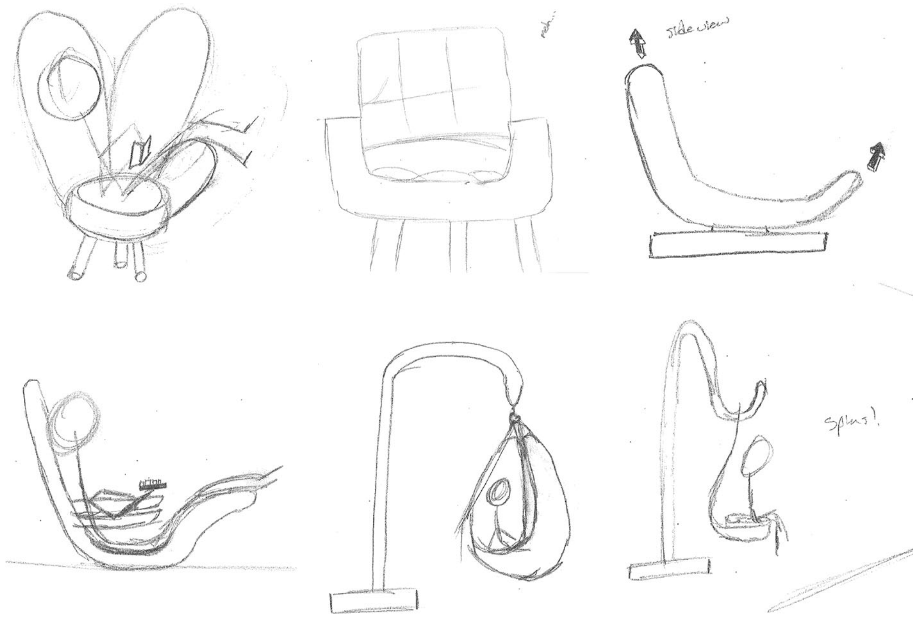


Fig. 4 Six concepts produced by P10 while working on his own. No descriptions were provided by the participant

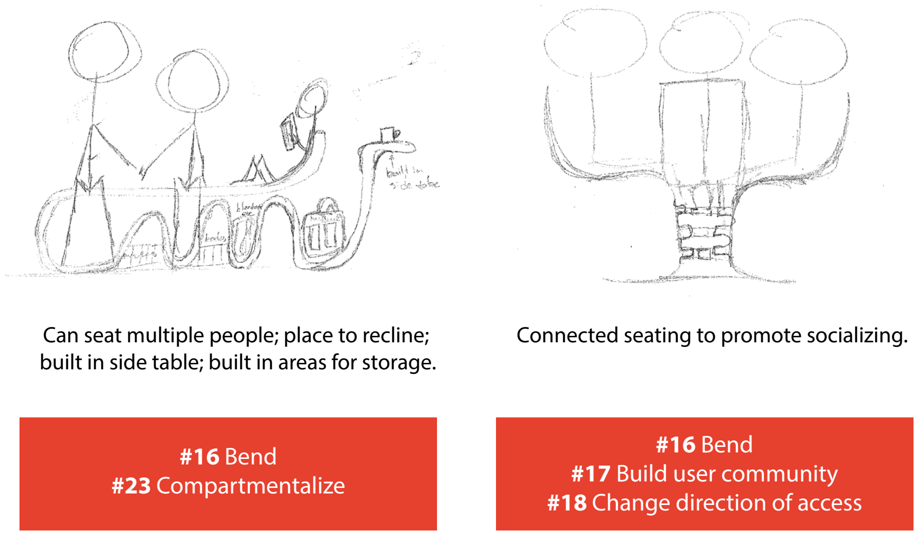


Fig. 5 Two concepts produced by P10 when working with *Design Heuristics*

flat surface into multiple segments, and by creating compartments to allow for different functions, such as storage or a side table. The second concept shows a combination of three heuristics: *Bend, Change direction of access*, and *Build user community*, to create a seating unit that would promote socializing. Here, the users would step into the center of the product in order to seat themselves in a circular arrangement.

When looking at the four measures (novelty, feasibility, relevance and specificity) and their alignment for the concepts generated in the first session versus the second session, novelty (Mean = 3.41 vs. 4.25) and feasibility (Mean = 4.58 vs. 4) scores are similar; however, there is a dramatic increase in the relevance (Mean = 1.9 vs. 4.75) and specificity (Mean = 1.83 vs. 4.5) scores, for the concepts generated in the heuristics session. This suggests that the heuristics session helped students to refine their concepts or generating alternative concepts that respond to the stated problem more directly through proposing effective outcomes, while providing more detail or elaboration for an attempt for the solutions' thoroughness. These findings support previous findings on Design Heuristics' impact on concepts' development with added detail as they prompt designers with additional features that could be embedded within their concepts (Daly et al. 2016).

A similar pattern is evident in Participant 24's ideation sessions. The participant generated seven concepts in the first session, and three for the session with heuristics. The concepts in the first session (Fig. 6) are modified minimally from the existing products in the markets. For example, the participants labels the second concept, "comfortable dentist chair", the fourth concept, "coffee cup chair", and the sixth concept, "bucket seat". These indicate that she used products she's familiar with as an inspiration source, and through minor changes or adaptations, she was able to propose 'new' ideas.

The proposed solutions in the second ideation session (Fig. 7) break this 'force-fitted adaptation' frame. In this session, this student seems to use the heuristics in a more abstract way and instead of using existing objects used for other purposes (a cup or a bucket) as a starting point, she used the heuristics to help define the function and the form. For example, in the first concept, she applied *Create a system* to suggest a solution using a series of blocks with different heights and forms. The second concept, although she still calls it a bucket chair, has now has a flat base and hallow middle space for lights, and once it's flipped, it can turn into a table. She used *Convert for second function* as the heuristic for this concept where the second function is the table. In the third concept, participant used the Cover or wrap as a heuristic to create a sheltered space to protect people from rain during football games.

The scores by the coders, blind to tool use, provide further evidence that the heuristic cards, indeed, helped the participant in pushing towards new and more diverse solutions, after the initial ideas were exhausted. All the scores demonstrated increases when the student generated solutions in the second session, with the help of heuristics: Novelty (Mean = 3.2 vs. 4.8), Feasibility (Mean = 4.21 vs. 5.3), Relevance (Mean = 3.2 vs. 5), and Specificity (Mean = 2.9 vs. 4.6).

Finally, while each of the *Design Heuristic* cards provided an example of a seating product, a comparison of the card examples with the subject-generated concepts showed little overlap. It appeared that participants avoided using the *Design Heuristics* card examples in generating their own designs, with only six concepts (6.45%) based primarily on a provided, fully-worked example. In most cases, participants seemed to rely heavily on the abstract image provided in the front to generate new solutions, avoiding the fully-worked examples on the back. Although the main functionality required by the task (i.e., seating device) is the same, the concepts generated were different from the examples in every aspect, including how design elements were put together, the way the user would approach and use the product, the systems thinking underlying the concepts, and also the overall visual qualities. This approach can be considered as an intentional effort by the students to try not to replicate what is provided on the back of the support tool, rather using

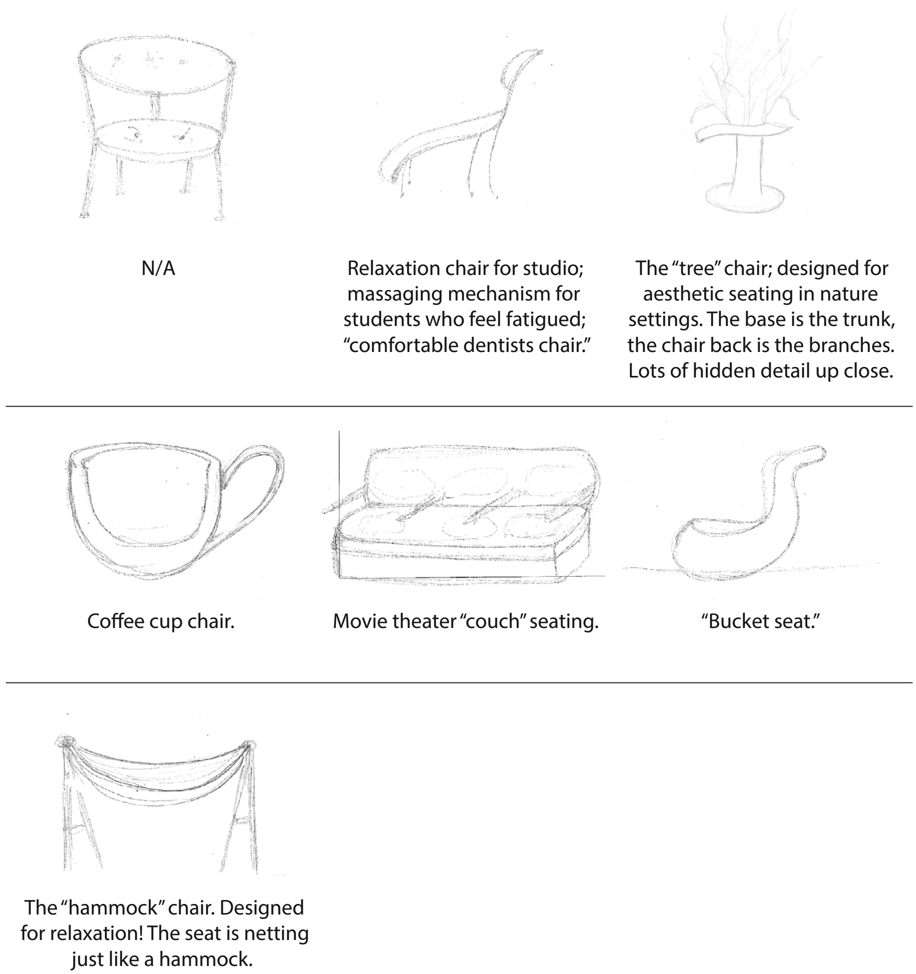


Fig. 6 Seven concepts produced by P24 while working on his own. Descriptions were provided by the participant

the abstracted notion of each heuristic in creating new solutions to a rather traditional and accessible design problem.

Discussion

Our findings suggest that an initial ideation session where students worked on their own to generate ideas resulted in more concepts (i.e., higher fluency) than a subsequent session when using a creativity support tool, *Design Heuristics.* This may reflect a tendency for multiple ideas to come to mind during the first design session. However, by the end of this session, ideas came to mind less readily, a cognitive state we define as *creative exhaustion.* For all students, the use of the *Design Heuristics* tool in a second design session resulted in the generation of additional concepts despite creative exhaustion. While the number of new concepts generated in the second session was half as many as in the first session, these later

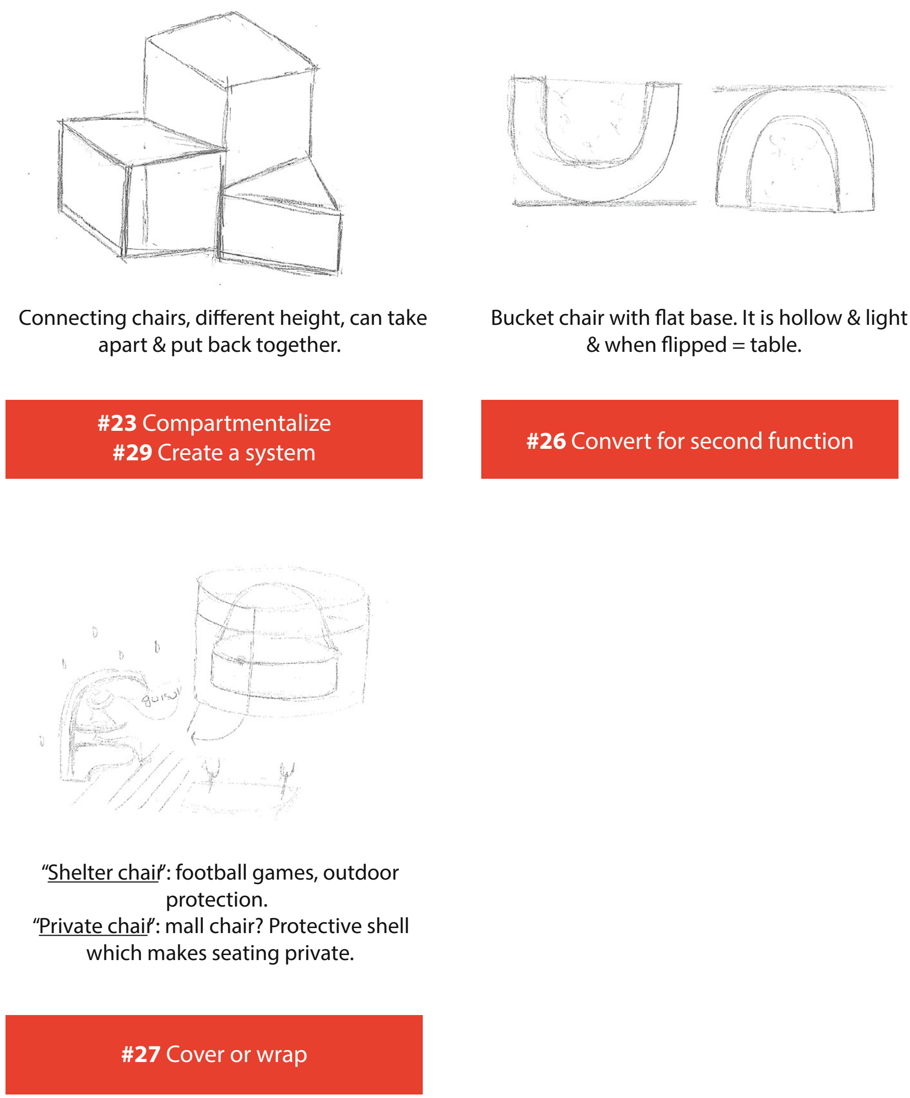


Fig. 7 Three concepts produced by P24 when working with *Design Heuristics*

concepts were rated as higher in quality on dimensions of novelty, specificity, and relevance. Only ratings of feasibility showed a (nonsignificant) decrease in the session using *Design Heuristics*. These findings indicate the potential of creativity support tools to increase performance even when students have exhausted their initial, immediate ideas.

While the quality and quantity of concepts are often bound together, these results suggest it is possible to separate quality from quantity. In this study, we first allowed students to exhaust their own ideas; then, when the creativity support tool (*Design Heuristics*) was introduced, students continued to produce more concepts, and they were of higher quality. It is possible that introducing the tool after creative exhaustion was effective because it arrived just as students felt the need for assistance with idea generation.

These results suggest the need for greater attention to *when* cognitive supports, such as *Design Heuristics*, are used in scaffolding students' creative skills. Through their experience with an ideation tool, students can enhance their abilities by learning to execute new skills at key instructional moments. In addition, this initial exploration of tool use during creative exhaustion suggests a way to encourage a design student's developing judgment and sensibility about when and how support tools are helpful.

This study was conducted with a single class using a simple design problem; consequently, the results may not generalize to other courses or to design education more broadly. Ideally, triangulation through other forms of data collection, such as interview or survey, would allow further exploration of students' perceptions of creative exhaustion, and the introduction of tools such as *Design Heuristics*. In addition, richer data sources would allow for triangulation of student perceptions of creative exhaustion, and the potential interplay between ideation sessions separated by a short incubation period. This may provide greater insight into the nature of metacognition during creativity, and how it might be developed. For instance, capturing the time for participants to generate each concept may identify more directly the point when their creativity is exhausted. Similarly, using stimulated recall of concepts with participants may increase our understanding of what these slowdowns in fluency indicate about the cognitive processes of the developing designer. Finally, an experimental research design could be used to identify the extent of creative exhaustion by comparing groups without a support tool, a group with Design Heuristics, and a group with a delayed introduction of Design Heuristics as in the present study.

Exhaustion in creative activity, specifically focusing on variation of concepts, adaptation of existing concepts, and response to failure, may be important for the learning process. It may produce a context where design tools are particularly effective in helping to move forward and generate more concepts, scaffolding students at a critical point in their ideation process. This study highlights the use of the *Design Heuristics* tool in appropriate ways to meet the situated cognitive demands of a specific design activity. Other support tools for idea generation in design and creative tasks, such as SCAMPER (Eberle 1995), TRIZ (Altshuller 2005; Hernandez et al. 2013; Orloff 2003), and morphological analysis (Allen 1962) would also likely benefit from the opportunity to exhaust initial ideas before attempting to use the tool.

Developing students' instrumental judgment

Contextual issues and learner attitudes are important to consider when identifying appropriate curricular practices. Systematically identifying and addressing issues, such as barriers to idea generation *vis-à-vis* method use, shows the value of cognitive supports like *Design Heuristics*. In particular, the cognitive and emotive experiences emerging from the state of creative exhaustion may encourage students to make better use of design tools. Such notions and resulting judgments of how to best use or conceptualize tools—called *instrumental judgment* (Nelson and Stolterman 2012)—are developed by design students as they build expertise; however, they have not historically been a focus of pedagogical practices in design education.

Instead, design education in the classroom generally relies on activities and assessment practices common in a studio approach to education (Cennamo 2016; Shulman 2005). While formal design methods, tools, and strategies are frequently taught as part of studio learning, these cognitive supports are generally not communicated in a way that heightens their situated use and adaptation—a cornerstone of method use in practice (Gray 2016, 2014; Stolterman et al. 2008). Even existing guidance from Self-Determination Theory (Deci and Ryan 2011) aimed at improving the students' sense of the relatedness of a tool to the present task may not result in building this situated knowledge. Given the increasing availability of design tools to support learning and practice, it appears important for design educators to prepare students by explicitly developing their instrumental judgment through robust and varied means. While the results of this study indicate that the exhausted creative state allowed students to make effective use of Design Heuristics to further their ideation process, future research is needed to target students' awareness of their own exhaustion, and their perception of creative support tools (i.e., instrumental judgment) in combatting this state.

Conclusion

In this study, we have demonstrated that the introduction of a cognitive support method—*Design Heuristics*—had a beneficial effect in creative idea generation, allowing students to generate additional concepts even after their creativity was exhausted. The pairing of a design tool intervention with the learner's experienced need for it (in this case, an exhausted cognitive state) suggests a pedagogical practice for making idea generation tools feel related and of potential benefit to students. Further research is needed to address how students learn to manage their cognitive abilities during design; particularly, recognizing when exhaustion has occurred in their ideation, and when to turn to additional cognitive supports. An enhanced understanding of how students develop their instrumental judgment surrounding the use of design tools will lead to a better understanding of design skill development and practice, and how to maximize pedagogical experiences to increase design expertise.

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