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ORIGINAL PAPER

Towards effective communication with users in the design process: an experimental study on the validity differences of different representation forms in delivering conceptual design information

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Abstract
Users' participation in early stages of the product innovation process is conducive to accelerating the convergence of the design process. To provide insights into the design or selection of a design representation that is suitable for efficiently and accurately transmitting design information to users in the conceptual design phase, this paper compared the validity differences of three common representation forms, a sketch, a function-behavior-structure (FBS) tree and a semantic network, in conveying design information to ordinary users in the conceptual design stage. The experimental results show that when multi-dimensional design information needs to be conveyed to users in the early stage of design, the storyboard with sketches and text descriptions would be a better design expression method than FBS tree and semantic network. When only the design information of the Kansei image dimension needs to be conveyed, the representation form of a sketch or semantic network is better. When only the design information of the function & structure dimension needs to be conveyed, it is better to use the form of a sketch or FBS tree. When only the design information of the human-machine interaction dimension needs to be conveyed, the representation form of a sketch is better. Also, it was observed that improving the sense of presence and interactivity of design representation will help users better participate in the collaborative innovation in the early stage of design.

Keywords Customer integration · Design representations · Information representation · User evaluation · Design cognitive ergonomics · Early design stage

1 Introduction

With the increasing homogeneity of consumer products, consumers no longer only consider the function and quality of a product; they also pay more attention to the use process and experience [1]. A key issue in user experience design is to consider the multimodal interaction process between users and products in the product development stage to provide products with a good appearance, personal functions, and excellent interaction characteristics. The user's response to the shortcomings of an existing product concept can provide clues to optimize the product concept, enrich the design solution space, and thereby improve the user experience of the final product [2, 3]. To help designers revise the direction of a design in a timely manner [4], more and more companies have begun to remotely invite users to participate in concept evaluation with the help of open innovation platforms to obtain more design feedback. In this scenario, users only view the concept design scheme through the evaluation system, and there is no face-to-face communication process with the designer. Therefore, how to deliver the design intention and design information quickly and accurately to the user in the short time when the user views the conceptual design scheme is the key to success. Accordingly, how to choose an appropriate design representation form becomes very important.

As the stage that has the greatest impact on the direction of product innovation [5, 6], conceptual design itself is

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an imprecise and uncertain design process, and the design information it involves is vague and incomplete. Due to different design habits and differences in the understanding of system models [7, 8], different designers often vary considerably in the final expression of the same conceptual design scheme. In addition to the designer, other stakeholders involved in the conceptual design (such as managers and manufacturing engineers) are affected by their individual expertise and may fail to accurately understand the designer's intent [9, 10], leading to a failure of concept selection [11]. Furthermore, it is difficult for ordinary users without professional knowledge to deeply and effectively participate in the product innovation process and understand the designer's intent [2], especially through online user communities [12, 13]. Facilitating more effective communication between ordinary users and designers in the early product innovation process has therefore become an urgent issue.

According to reference [14], experience refers to an overall designation of how the user experiences a system. The design information related to user experience is diverse and has its own characteristics. For example, the appearance model is mainly visual and static, the product function must reflect situational and dynamic interaction, and the Kansei image [15, 16] involves the comprehensive psychological feeling evoked by the above two categories. Although the above representation forms provide a bridge for communication with ordinary users to some extent, there is little discussion about the adaptability of different representation forms to convey different dimensional design information to ordinary users. The choice of representation forms is closely related to the specific content of the designer's design intent and the completeness of the design information at that time. Design expression must fully consider the characteristics of the product concept and the perceptual patterns of ordinary users [17, 18] in the conceptual design stage and flexibly use various representation forms to systematically express the design information related to user experience so that users can fully understand the product concept and provide accurate design feedback [19]. Otherwise, the significance of users' participation in the early stage of collaborative innovation will be lost. Therefore, it is necessary to help designers choose or design the appropriate product concept representation form to organize user experience-related design information in early product design to better serve users in the early innovation process and improve the accuracy of product design.

To provide insights for the design or rational selection of design representation forms during the user-involved collaborative innovation process, especially through remote online evaluation [20], this paper first analyses the growth and evolution process of product concept forms and clarifies the types and characteristics of design information contained in the product concept. Then, an intelligent sweeper is selected as the experimental object. Its design concept is expressed in three representation forms, a sketch, an FBS tree and a semantic network, and three representation schemes containing the same design information are obtained. Finally, the validity of different representation schemes to convey design information to ordinary users is compared through experiments.

2 Literature review

From the various and widely used sketch to high fidelity, preproduction prototypes design representation is employed as an essential tool to support the practice of industrial design [21]. Designers use design representation for a variety of purposes, from the quickly drawn thinking sketch to persuasive renderings and digital CAD models [22–25]. In this way, design representation is employed both as a means to support the designer's thinking and reflection in action [26] and to communication design intent to other stakeholders [21, 27]. Considering their various and critical role in support of design practice, studying design representation provides opportunities to develop understanding of the nature of design activity and the kinds of knowing and thinking it entails [25].

The medium for designers to communicate design intent to ordinary users is mainly through the visual representation of the design scheme, for example in the form of visual scenarios, draft UI specifications, physical mock-ups, or a combination of these. There are many existing forms of product concept representation. Some designers use sketches to express product concepts [28]. Self [29] believes that the ambiguous intention expression of the sketch is easier to explain than other specific design expressions (such as engineering drawings). Bilda and Demirkan [30] suggested that paper sketches are conducive to the designer's thinking and modification. With the emergence of the FBS (function-behavior-structure) model and its derivative models, the function and structure tree has been widely used by designers to express information related to product functions and structures [31]. Some designers use knowledge of design semantics for reference when communicating the operating mode and functional goals of a product [7, 32]. The theory of constructed preferences from psychology suggests that the product form presented will influence customer judgements. Reid, MacDonald and Du [33] presented a study in which subjects were shown computer sketches, front/side view silhouettes, simplified renderings, and realistic renderings to test the extent to which a variety of judgements, including opinions, objective evaluations, and inferences, are affected by the form of presentation. The results show a

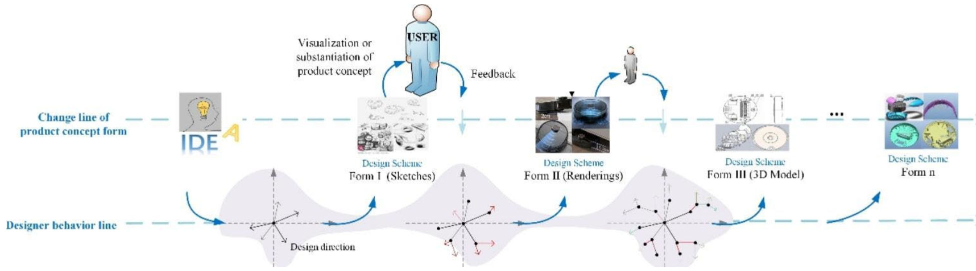

Fig. 1 Schematic diagram of the growth and evolution process of product conceptual form

variety of phenomena, including preference inconsistencies and ordering effects that differed across types of judgement. Österman, Berlin and Bligård [3] explored the ability of three types of simple three-dimensional (3D) models to act as mediating objects for representative users to elicit design feedback in a use scenario-workshop format. They found that all three types of 3D models, when coupled with a scenario description, elicited useful design feedback that served not only as direct input to change proposed design parameters but also as an unprompted long-term learning opportunity for the design team to gain insight into the lives and challenges of their users. Chamilothori et al. [34] conducted an experiment to compare users' perceptions of a real daylit environment and its equivalent representation in VR and to test the effect of the display method on the participants' perceptual evaluations. MacDonald et al. [35] draw from an analysis of 60 interviews with experienced UX professionals to argue that a nuanced understanding of communication strategies should be explicitly included in HCI education. Specifically, they identify five goals that shape communications between UX practitioners and four distinct audiences and show that they select specific methods (techniques, artifacts, and tools) to achieve these goals. They also discuss three key implications for HCI educators: embracing rhetorical complexity, simulating real-world communication challenges, and highlighting the performative elements of communication. Ungureanu et al. [36] extracts and analyses the most frequent natural language expressions used by participants in two real-world collaborative design sessions, and suggest that ambiguous and vague expressions used by participants can initiate mindful explorations of design space. Wang et al. [37] explores which elements of User journey, Storyboards and Wireframes contribute to communicating these qualities, and how they might integrate with sketching. Results show depictions of user and temporal elements alongside low fidelity sketches are deemed most important.

3 Product conceptual form growth and evolution process

Product conceptual design is an extremely important and creative stage in the product design process and has an enormous impact on the end user experience of consumer electromechanical products. The formation process of the product concept is an oscillating evolution process of the continuous combination, growth, and coupling of multimodal design elements in a certain time and space under the dual effects of users' needs and the designer's creative input. As shown in Fig. 1, with the continuous expansion of design intent and design direction, the conceptual form of the product gradually evolves from the original vague ideas to a complete and clear design scheme, and the design information, such as the shape, color, material, texture, function, behavior, structure, and interaction methods, is continuously enriched and clarified. To revise the design direction in a timely manner, the conceptual form of the product is often visualized or materialized into sketches, FBS models, renderings, clay models and other views at a specific stage to facilitate users' participation in conceptual testing and evaluation. Still, representations are used in another way - by the designer as distribution of their own thinking. In the above commonly used product concept representations, sketches, or renderings, FBS trees and semantic networks can be used in online communities.

In early involvement in the product innovation process, users are mainly concerned with the design information related to the user experience, such as the functional quality, appearance, interaction mode, and cost performance of future products. However, the existing representation methods are mainly for professional designers or back-end manufacturing engineers and lack attention to the cognitive characteristics of ordinary users. Therefore, studying how to organize and express the design information contained in different product conceptual forms from the perspective of user experience and improve the reliability and validity of design intent transmission can help users better understand the design intent and help designers obtain effective design feedback as well as improving the design information related to a product's user experience in the conceptual

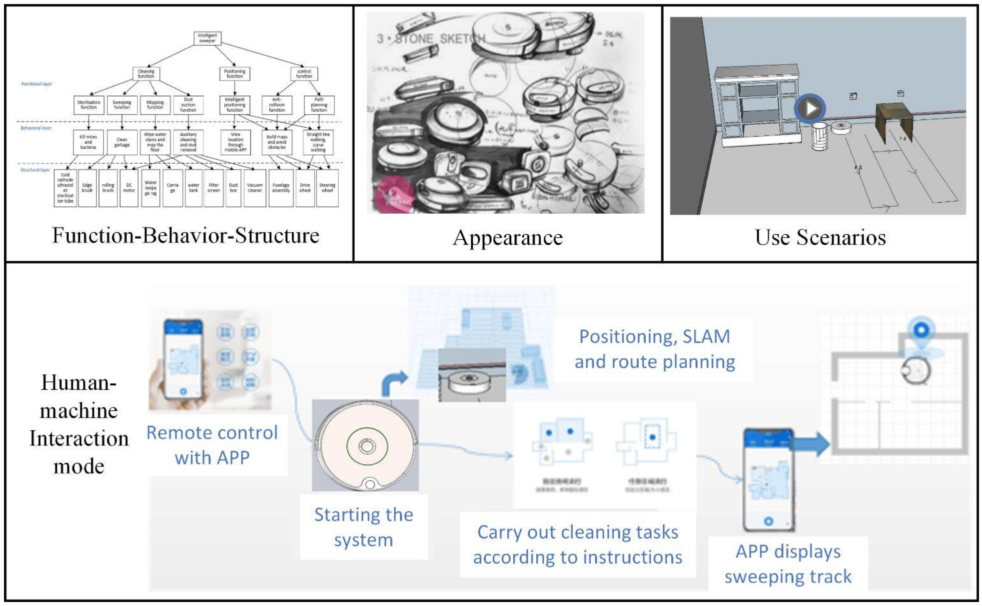

Fig. 2 Conceptual design scheme of sweeping robot

design stage and reducing the uncertainty of conceptual design.

4 Methods

The research team first carried out creative design with the theme of "intelligence and fashion", and formed a conceptual design scheme of the sweeping robot for young people, as shown in Fig. 2. The experimental process of this paper is based on the evaluation process of the conceptual design scheme.

Allowing users to accurately obtain the design intent in the design scheme is the prerequisite for obtaining design feedback. In the scenario of remote online testing, quickly attracting users' attention and accurately delivering design information is the guarantee for successful online evaluation. Therefore, the validity of the design scheme to convey design information is reflected in the efficient and accurate transfer of design intentions to users. Consider the main factors that affect the user experience [38–40], this paper divides design information into three dimensions: Kansei image (KI), function & structure (FS), and human-machine interaction (HMI). Three commonly used forms of design expression, a sketch, an FBS tree, and a semantic network, are used to organize and express the design information of these three dimensions the above conceptual design scheme.

According to the experimental data from the questionnaire related to the design intent that was completed by users after viewing the three representation schemes, the validity of different representation forms to convey design information and the suitability of design information dimensions are analyzed. Among them, the efficiency of information transmission is reflected by the answering time, the accuracy of information transmission is reflected by the answer accuracy rate, and the adaptability of the expression form and the design information dimension is reflected by the accuracy of each of the three design information dimensions.

During the experiment, the subjects were required to not bring communication equipment into the laboratory and to complete each questionnaire continuously and energetically to ensure that the subjects' answering time was only related to the time needed to find answers from the representation schemes. In addition, because the three representation schemes are designed around the same concept, to prevent the same subject from answering multiple questions and affecting the objectivity of the answering time, each participant decided which representation scheme he or she would view by drawing lots and only completed the questionnaire once. The number of subjects who viewed each representation scheme was the same.

4.1 Participants

A total of 135 participants (70 males, 65 females) were recruited for this experiment, ranging in age from 19 to 27 years (M = 22.64, SD = 2.630). The subjects were all undergraduates in non-design-related majors (52 in industrial engineering, 50 in mechanical engineering, 16 in international economy and trade, 12 in financial management, and 5 in English language and literature). All subjects voluntarily participated in this experiment after fully understanding the experimental process.

Table 1 User Perceivable Design Information Questionnaire

Design information dimensions	Question number	Content
KI	1	This sweeper has a circular design with no edges and corners, which can effectively prevent damage to the machine itself and the furniture in the home. Is this description correct?
	2	When the sweeper is cleaning in the bedroom, the sound is round and not harsh and will not affect people's sleep (except for those with sensitive nerves). Is this description correct?
	*3	The height of this sweeper is 81 mm, which is equivalent to half the length of an adult's palm. The bottom area of the bed and sofa cannot be cleaned. Is this description correct?
FS	1	When the cleaning area is large, the smart sweeper will automatically return to the base station to charge after the battery is used up. After fully charging, it will return to the original place to continue cleaning; that is, there is a breakpoint continuous sweep function. Is this description correct?
	2	After the smart sweeper has finished cleaning, a child spills snacks on the floor. At this time, the spot cleaning mode can be used to sweep only one area. Is this description correct?
	*3	When this smart sweeper encounters obstacles such as wire entanglement, the motor will run idly until the power is exhausted. Is this description correct?
HMI	1	The smart sweeper has a voice recognition function. If an elderly person at home cannot read, the smart sweeper can be activated to clean the house by voice. Is this description correct?
	*2	The front-end camera of this smart sweeper cannot recognize human gesture information and cannot change the cleaning direction with gestures. Is this description correct?
	3	After making an appointment for the cleaning time, the user can check the cleaning area and cleaning trajectory at any time through the mobile phone app. Is this description correct?

* - Indicates that this question is a reverse question type

4.2 Apparatus

The experiment was conducted in a quiet and natural light laboratory. The laboratory was equipped with a Lenovo computer and a mobile phone. The computer was used to display the stimulus in the centre of a 21-inch LCD monitor (1080P resolution), and a mobile phone was available for participants to answer questions.

The design team selected 9 representative questions according to the design intention they hoped to express in the conceptual design scheme, and formed a user perceivable design information questionnaire. As shown in Table 1, this questionnaire included three questions in each of the three design information dimensions: KI, FS, and HMI. A 7-point Likert scale (1 = absolutely disagree, 7 = absolutely agree) was employed to collect feedback from the subjects. On this scale, 7 indicated that the subject strongly agreed that the statement in the question was consistent with the design information they obtained from the experimental materials, 1 indicated that the subject strongly disagreed, and 4 indicated that the subject was unsure whether the statement in the question was related to the design information obtained from the experimental materials. In order to avoid the inertial thinking of the subjects in answering the questions, questions marked with * in the questionnaire are reverse questions.

4.3 Stimuli

The stimulus material for this experiment was the conceptual design of an intelligent sweeper, which was characterized in three ways: a sketch, an FBS tree and a semantic network. Scheme I is a sketch, Scheme II is an FBS tree, and Scheme III is a semantic network (hereinafter referred to as Scheme I, Scheme II and Scheme III). Part of the content is shown in Fig. 3.

4.4 Procedure

Before the experiment, the subjects were randomly divided into three groups through a lottery and numbered 1 to 45 (group 1, using Scheme I), 46 to 90 (group 2, using Scheme II) and 90 to 135 (group 3, using Scheme III). After the experimental background was introduced, the participants signed informed consent forms and received pre-experiment training. The training content included three representation forms: the experiment purpose, answering rules, and the pre-experiment and formal experiment process.

The experimental process is shown in Fig. 4. After the pre-experiment confirmed that the subjects were in a good state of mind, they were told to complete the questionnaire by viewing the representation scheme corresponding to their group. After completing the questionnaire, the examiner conducted unstructured interviews with the subjects (see Table 2), asked the subjects to express their opinions and provided suggestions on whether the characterization schemes viewed would help them obtain the corresponding design information to mutually confirm the questionnaire data. Each participant completed the questionnaire independently in a closed laboratory, and the entire process of

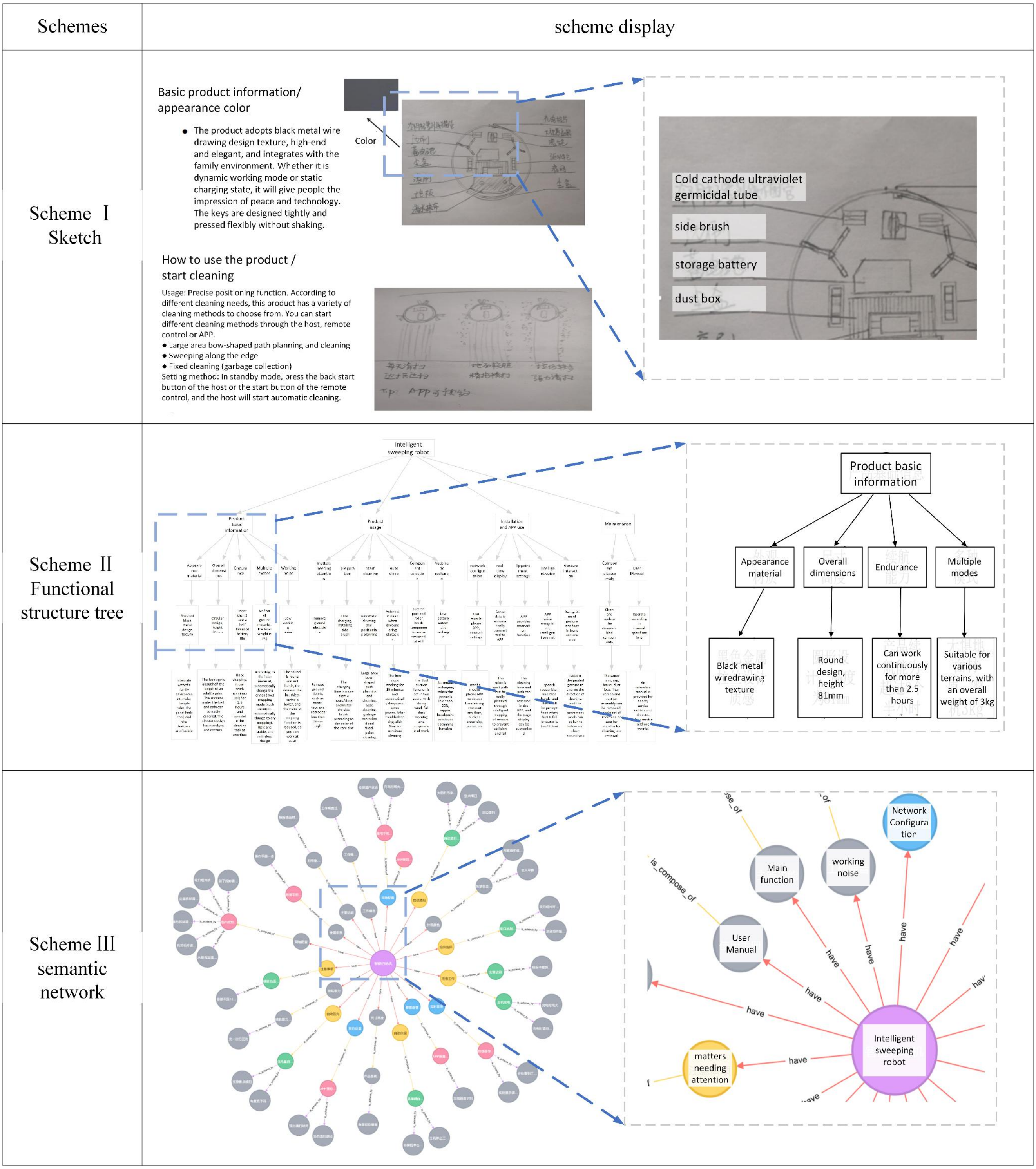

Fig. 3 Schematic diagram of three representation schemes

the experiment was conducted under the control of the chief examiner to eliminate interfering factors to ensure the validity of the experimental data.

4.5 Measures

The questionnaire was completed by the subjects on the spot. The recovery rate was 100% (n = 135), and there were 135 valid questionnaires. The experimental data set includes

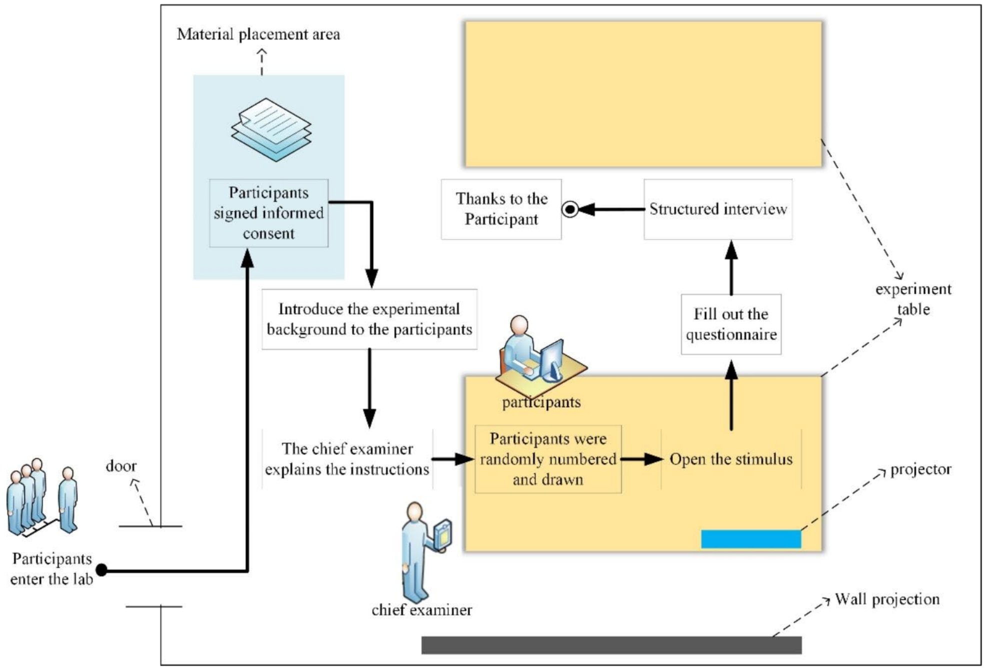

Fig. 4 Experimental flow chart

Table 2 List of Unstructured Interview Questions

No.	Content
Q1	If this is a product tailored for you, what information about the product would you like to know?
Q2	Of the several presentation methods seen in the experiment just now, which view is most in line with your cognitive habits? Why?
Q3	Of the several ways of presenting the solutions you saw in the experiment just now, which view is most helpful for you to answer the question? Why?
Q4	How do you think presenting the design scheme can allow you to obtain the information you need quickly and accurately?

Table 3 Reliability analysis results of the User Perceivable Design Information Questionnaire

Dimension	N	Cronbach's Alpha
Overall	9	0.762
KI	3	0.684
FS	3	0.828
HMI	3	0.807

the questionnaire scores, the time spent answering questions in three dimensions and interview recordings of all subjects. The questionnaire scores and answering time were analyzed using SPSS 22.0 for questionnaire reliability testing and one-way ANOVA test, and the interview recordings were manually sorted and verified with the results of the questionnaire analysis.

5 Results

The overall reliability test results of the User Perceivable Design Information Questionnaire and the reliability test results in three sub dimensions are shown in Table 3. The overall reliability was 0.762, and the reliability of the three sub dimensions was 0.684, 0.828 and 0.807, which were all higher than 0.6, indicating that the questionnaire score data were reliable.

The score box plots of the three representation schemes to convey design information in the three dimensions are shown in Fig. 5. The results of the one-way ANOVA and LSD (Least Significant Difference) test for the accuracy of the three representation schemes to convey design information in the three dimensions are shown in Table 4. It can be seen in Table 4 that the P values are all less than 0.05, indicating that the three representation schemes have significant differences in the accuracy of conveying design information, including overall and the three sub dimensions of the KI, FS, and HMI.

When comparing different representation schemes, the accuracy of conveying design information in a certain dimension can help designers understand how to choose the most accurate representation methods when they need to convey design information in a particular dimension. As shown in Table 4, the average overall score of Scheme I was 54.89, the average overall score of Scheme II was 50.28, and the average overall score of Scheme III was 47.52. According to the overall score, when conveying the overall design information on the product concept to ordinary users, the accuracy of Scheme I is better than Scheme II and Scheme

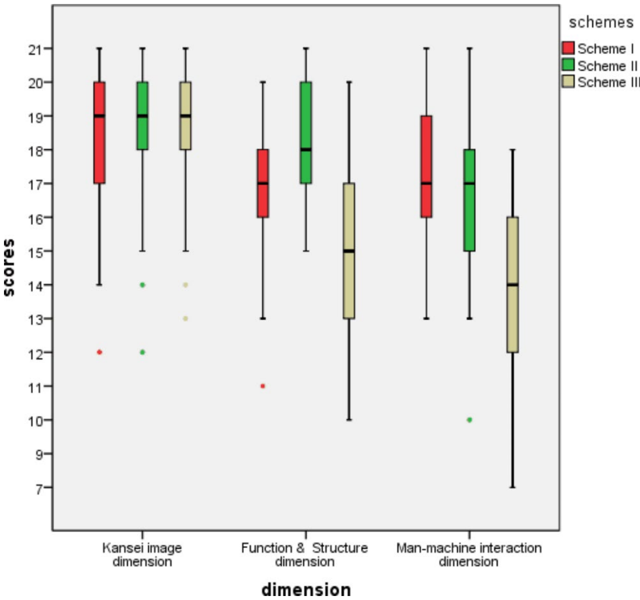

Fig. 5 The score box plots of the three representation schemes to convey design information in the three dimensions

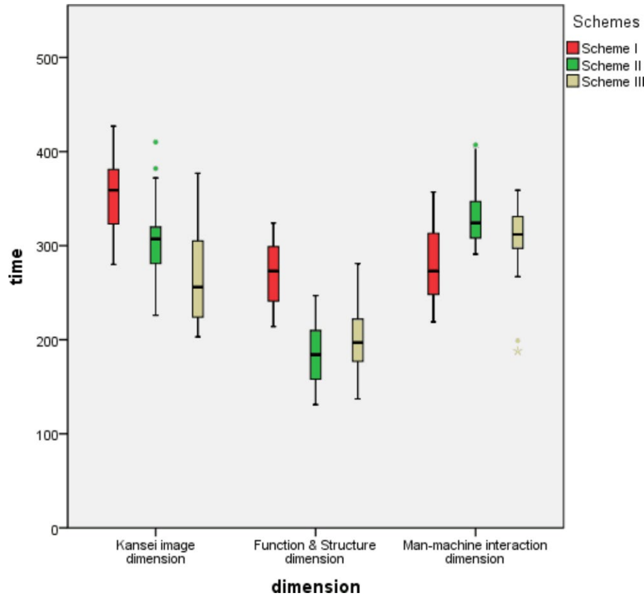

Fig. 6 Box plot of the time taken by the subjects to answer the User Perceivable Design Information Questionnaire after viewing the three representation schemes

III. According to the scores of the three sub dimensions, when conveying design information on the KI dimension to ordinary users, the accuracy of Scheme I and Scheme III is better than Scheme II, and there is no significant difference in accuracy between Scheme I and Scheme III. When conveying design information on the FS dimension to ordinary users, the accuracy of Scheme I and Scheme II is better than that of Scheme III, and there is no significant difference between Scheme I and Scheme II. When conveying design information on the HMI dimension to ordinary users, the accuracy of Scheme I is better than Scheme II and Scheme III.

When comparing the same representation scheme, the accuracy of conveying design information in different dimensions can help designers understand which dimension of design information the representation scheme is suitable for. For Scheme I, when conveying design information to ordinary users, the accuracy of the HMI dimension is superior to the FS and KI dimension. For Scheme II, when conveying design information to ordinary users, the accuracy of the FS dimension is superior to the KI and HMI dimension. For Scheme III, when conveying design information to ordinary users, the accuracy of the KI dimension is superior to the FS and HMI dimension.

The box plot of the time taken by the subjects to answer the User Perceivable Design Information Questionnaire after viewing the three representation schemes is shown in Fig. 6. The results of the one-way ANOVA and LSD & Tamhane test for the efficiency of the three representation schemes to convey design information in the three dimensions are shown in Table 5. It can be seen from Table 5 that the P values are all less than 0.01, indicating that the three representation schemes have significant differences in the efficiency of conveying design information, including overall and in the three sub dimensions of the KI, FS, and HMI.

When comparing different representation schemes, the efficiency of conveying design information in a certain dimension can help designers understand how to choose the most efficient representation methods when they need

Table 4 The results of one-way ANOVA and LSD test for the accuracy of the three representation schemes to convey design information in the three dimensions

Schemes	KI dimension		FS dimension		HMI dimension		Overall	
	Mean	Std. Deviation	Mean	Std. Deviation	Mean	Std. Deviation	Mean	Std. Deviation
Scheme I	17.96	2.276	18.38	2.208	18.56	2.029	54.89	3.984
Scheme II	16.93	1.993	18.33	1.954	15.02	2.864	50.28	4.785
Scheme III	17.13	1.926	16.46	2.262	13.93	2.700	47.52	4.858
P	0.02		0.00		0.00		0.00	
F	3.081*		10.562**		40.196**		29.248**	
LSD	I, III > II		I, II > III		I > II > III			

Note: "*" means P < 0.05, "**" means P < 0.01, ">" means better than

Table 5 The results of the one-way ANOVA and LSD test for the efficiency of the three representation schemes to convey design information in the three dimensions

Schemes	KI dimension		FS dimension		HMI dimension		Overall	
	Mean	Std. Deviation	Mean	Std. Deviation	Mean	Std. Deviation	Mean	Std. Deviation
Scheme I	353.87	42.630	304.56	38.902	264.56	45.540	922.98	100.046
Scheme II	269.73	34.696	183.44	28.999	199.20	34.781	652.38	80.640
Scheme III	278.49	36.701	327.56	27.186	309.02	34.725	915.07	67.808
P	0.00		0.00		0.00		0.00	
F	66.122**		261.593**		91.763**		151.663**	
LSD	I > II, III		III > I > II					
Tamhane					III > I > II			

Note: "**" means P < 0.01, ">" means better than

to convey design information in a particular dimension. As shown in Table 5, the average total time to answer the questionnaire after viewing Scheme I was 922.99 s, the average total time to answer the questionnaire after viewing Scheme II was 652.37 s, and the average total time to answer the questionnaire after viewing Scheme III was 915.07 s. According to the average total time, when conveying the overall design information of the product concept to ordinary users, the efficiency of Scheme II is better than Scheme III and Scheme I. According to the average time of the three sub dimensions, when conveying design information of the KI dimension to ordinary users, the efficiency of Scheme II and Scheme III is better than Scheme I, and there is no significant difference in accuracy between Scheme II and Scheme III. When conveying design information on the FS dimension to ordinary users, the efficiency of Scheme II is better than that of Schemes I and III. In terms of the HMI dimension, the Tamhane test method was used because the P value in the homogeneity test of variance was less than 0.05. The results show that when conveying design information on the HMI dimension to ordinary users, the efficiency of Scheme II is better than Scheme I and Scheme III.

When comparing the same representation scheme, the efficiency of conveying design information in different dimensions can help designers understand which dimension of design information the representation scheme is suitable for. For Scheme I, when conveying design information to ordinary users, the efficiency of the HMI dimension is superior to the FS and KI dimension. For Scheme II, when conveying design information to ordinary users, the efficiency of the FS dimension is superior to the HMI and KI dimension. For Scheme III, when conveying design information to ordinary users, the efficiency of the KI dimension is superior to the HMI and FS dimension.

From the above data, it can be concluded that: in the early stage of product conceptual design, when multiple dimensions of conceptual design information need to be delivered to ordinary users, it is better to use sketches and text descriptions. When only the design information of the KI dimension needs to be conveyed, the representation form of a sketch or semantic network is better. When only the design information of the FS dimension needs to be conveyed, it is better to use the form of a sketch or FBS tree. When only the design information of the HMI dimension needs to be conveyed, the representation form of a sketch is better. Data from unstructured interviews also confirmed the above conclusions. About 30% of the subjects mentioned that if VR/AR-like technology can be used to present the design scheme, it will effectively improve the interactivity of the scene and the user's sense of participation, and it will also help users better participate in concept evaluation and collaborative innovation.

6 Discussion

Finding an efficient way for designers to communicate design intent to ordinary users in conceptual design is very helpful to reduce design deviation and expedite design convergence. Experimental data show that the sketch plus appropriate text descriptions are more accurate in all dimensions of information transmission when communicating with ordinary users, indicating that users are more concerned about the stimuli of storytelling and graphical elements. This is likely because of the ambiguity and speed of the designer's sketch as a rich source for concept proposition and inspiration, with the potential to open new avenues of exploration [15]. Moreover, the sketch contains a large amount of design information related to future use scenarios of the design concept, which can easily arouse the empathy of users. This was verified by the subsequent interviews. On the other hand, in terms of the time it takes to convey the same design information, the sketch representation takes longer than the other two schemes. This is likely because ordinary users need more cognitive time to understand the design intent expressed by a sketch, which reduces information transmission efficiency. Although this article is mainly aimed at online remote evaluation scenarios, considering the characteristics of sketch plus text expression in the design of information transmission validity, it can be considered to be used for the task scenarios that require high accuracy of information transmission in the early stage of design, such as focus interview materials for demand acquisition, product use situations and interaction methods in concept testing, etc.

The representational form of the FBS tree has the best transmission validity in the design information of the FS dimension, but it is not ideal in the other two dimensions of the KI and HMI. The reason for this result may be that the design information displayed by the FBS tree is more logical and faster. However, it is more difficult to attract users' attention with the description of dynamic information than with KI and HMI information, and fewer memory points lead to poor transmission effects. In the future, two or three of these representation methods can be used in combination to achieve more accurate transmission of design information in different dimensions. Considering the characteristics of FBS tree in terms of design information transmission validity, it can be considered to be used to the task scenarios that focus on functional & structure information in the early design stage, such as the review of functional configuration, product structure and cost structure.

The representation form of the semantic network has the best transmission validity in the design information of the KI dimension, while the transmission validity in the FS and HMI dimension is significantly lower than the sketch and FBS tree. This result is quite different from the author's expectation, possibly because the subjects were unfamiliar with this form of expression. In scenarios that require cluster analysis and knowledge recommendation of design information, the semantic network has advantages. Considering the characteristics of semantic network in terms of design information transmission validity, it can be considered to be used in the task scenarios that focus on perceptual and information relevance in the early design stage, such as brainstorming for product ideas.

In summary, new product development companies and design teams that conduct collaborative innovation with customers, especially through online communities, can obtain the following managerial insights. (1) When inviting users to participate in the early concept innovation process, it is necessary to consider the user's cognitive characteristics and present the design scheme in a view that is familiar so that the user can quickly and accurately obtain the design intent to provide effective feedback. (2) Ordinary users are more accustomed to the contextual interaction type of representation. A representation scheme that highlights the use scenarios and interaction process can improve users' sense of substitution. Although sketches can express the interaction between users and products to a certain extent, they are still mainly static. Some subjects mentioned that design concepts can be integrated into multimodal virtual experience scenarios with the help of VR/AR technology for multisensory collaborative expression, allowing users to deeply participate in the early concept innovation process through virtual situational interaction. However, the design schemes in the conceptual design stage are often ill-defined and highly ambiguous. The current VR/AR technology still faces many challenges when presenting such design schemes, but this does not prevent the introduction of VR/AR technology in the conceptual design stage is a worthwhile direction [41–43].

7 Conclusion

To allow ordinary users to better participate in the early collaborative innovation of product concepts, this paper explored the validity of three design concept representation forms, sketches, FBS trees and semantic networks, in conveying design intent to ordinary users. It provides insights for designers to choose a means to express design concepts reasonably. Experimental data show that under the same conditions, the accuracy of sketches in expressing design information on the HMI dimension is superior to the FS and KI dimension. The accuracy of the FBS tree in expressing design information on the FS dimension is superior to the KI and HMI dimension. The accuracy of the semantic network in expressing design information on the KI dimension is superior to the FS and HMI dimension.

The method in this paper also has some limitations. First, our research was conducted in a laboratory environment, not in a real design scenario. Laboratory scenarios allow for better control of other factors that may interfere with the experiment, but do not reflect the dynamic and complex environment when communicating with ordinary users. Considering the similarity between the large-scale online remote evaluation scenarios and the experimental scenarios in this paper, the experimental conclusions of this paper are still instructive. Future research can adopt methods such as video analysis and thinking aloud to better adapt to the situation of real design communication. Second, the subjects who participated in this experiment were undergraduate and graduate students who were not majoring in product design. More users with different backgrounds should be considered for participation in experiments to further support and verify the results of this paper. Also, to improve operability, we divided the design information into the three coarser dimensions: KI, FS, and HMI. The granularity and categories of the design information can be further refined according to actual needs. Finally, this paper mainly discusses how to effectively convey design intent and design information, but whether design expression itself can motivate users to provide better design feedback needs further research.

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