Thinking Skills and Creativity 54 (2024) 101657

Contents lists available at ScienceDirect

Thinking Skills and Creativity

journal homepage: www.elsevier.com/locate/tsc

Modality and fidelity: Understanding how creative stimulus combinations impact design outcomes and process across different conceptual design phases

Pei Chen [a,b], Zhuoshu Li [a,*], Yexinrui Wu [a], Hongbo Zhang [a], Jiaxuan Zhou [a], Lingyun Sun [a]

[a] *College of Computer Science and Technology, Zhejiang University, Hangzhou, 310027, China*
[b] *Zhejiang-Singapore Innovation and AI Joint Research Lab, Hangzhou, 310027, China*

ARTICLE INFO

Keywords:
Creativity
Creative stimuli
Conceptual design
Multimodal stimuli

ABSTRACT

During conceptual design, creative stimuli are an external source of inspiration to support students' ideation process. Although existing research has explored the roles of creative stimuli, they rarely consider the intertwined influence brought by stimuli's multiple characteristics, and overlook variations in stimuli's effectiveness at different design phases. To fill this gap, this research conducted a 3×3 experiment, involving 72 design students in a three-phase design process and presenting combinations of textual and visual stimuli at distinct fidelities. We assessed different stimulus combinations' influence on creativity, and employed behavior coding and linkograph to reveal students' behavior and cognitive patterns throughout the process. The results revealed the mutual influence between the fidelity of texts and images, and students commonly needed more concrete stimuli in later design phases. Furthermore, students provided with different stimulus combinations exhibited variations in time allocation for behaviors including task analysis, idea generation, and evaluation, and they employed distinct approaches to generate new ideas. These findings highlight the necessity for design educators to dynamically provide creative stimuli based on the design phase, educational objective, and students' state.

1. Introduction

During the conceptual design process, design students should fully develop creativity to extensively explore potential design space (Liu et al., 2003) and conceive inventive solutions in response to specific design problems and requirements (Benami and Jin, 2008). The outcomes of conceptual design greatly determine the innovation level in the final product. However, issues like creative blocks and design fixation usually occur due to students' lack of inspiration (Sio et al., 2015), thus hindering their creativity and impeding the conceptual design process. As inspiration is evoked by external triggers instead of being initiated personally (Thrash and Elliot, 2003), students in the fields including design, literature, and science commonly arise inspiration from creative stimuli to enhance their creativity (Thrash et al., 2010b).

Creative stimuli are an external trigger of inspiration aimed at increasing the amount of available information in the conceptual design process, helping students derive novel design proposals from relevant fragments (Gomes et al., 2022). According to the method of discovery learning, stimuli also serve as constraints that provide starting points (Haught-Tromp, 2017) and instruct students to

* Corresponding author.

https://doi.org/10.1016/j.tsc.2024.101657
Received 24 May 2024; Received in revised form 7 September 2024; Accepted 1 October 2024
Available online 10 October 2024
1871-1871/

understand the design task's scope (Tromp and Baer, 2022). For example, in the task of designing the future mobile phone, the visual stimuli of a projector inspired students to design a phone with presentation feature (Paay et al., 2023).

Considering that creativity is dynamic and the effects of stimuli are influenced by the actual situation (Tromp and Sternberg, 2022), extensive research explores the working principles of creative stimuli and compares the effectiveness of different stimuli through various experiments. For instance, prior studies have investigated how creative stimuli of distinct modalities impact the quantity and novelty of ides (Goldschmidt and Sever, 2011; Gonçalves et al., 2014; Malaga, 2000) and further utilized multimodal stimuli to reduce the ambiguity of unimodal information (Chan et al., 2011). Researchers have also explored stimuli's roles, revealing that low-fidelity stimuli such as texts about product attributes foster abstract thinking (Huang et al., 2015), while stimuli about specific examples aid in generating novel ideas (Eckert et al., 2005). Furthermore, existing work has considered factors such as timing of presentation (Kulkarni et al., 2012; Viswanathan and Linsey, 2013), semantic distance (Chiu and Shu, 2012; Dahl and Moreau, 2002; Fu et al., 2013; Wilson et al., 2010), and quantity of stimuli (Kazakci et al., 2015; Sio et al., 2015), and their influence on the conceptual design process.

Despite these, current research rarely addresses the impact of multimodal creative stimuli on the conceptual design process and overlooks their varied effectiveness at different design phases. On one hand, the conceptual design process requires support from creative stimuli of various modalities, but different stimulus combinations have distinct effects. Existing studies mainly compare the effectiveness of stimuli in different modalities (Borgianni et al., 2017; Koronis et al., 2021; Shi et al., 2017) or focus on unimodal stimuli with different fidelities (Agogué et al., 2014; Paay et al., 2023; Yuan et al., 2023) and semantic distances (Dahl and Moreau, 2002; Wilson et al., 2010), without delving into the interplay between different stimulus types within combinations. On the other hand, conceptual design includes divergent and convergent phases, and each stimulus type has distinct impact on students' divergent and convergent thinking (Xu et al., 2020). However, most existing research treats conceptual design as a singular process, focusing primarily on stimuli's impact on the final outcome but hardly considering the varied effectiveness of creative stimuli at different design phases.

Motivated by the above research gap, our research questions include:

- RQ1: Across the three primary design phases (i.e., Rapid Divergence, In-depth Divergence, and Convergence), how different multimodal creative stimuli influence students' **design outcomes** in aspects of idea quantity, novelty, practicality, and diversity?
- RQ2: How do different stimulus combinations impact students' **design process**, including their time allocation for various behaviors and their approaches to generating new ideas?

To answer these questions, we conducted a 3 × 3 user experiment involving 72 design students. The experiment presented combinations of textual and visual stimuli at distinct fidelities, with which students completed the three design phases. For RQ1, by collecting students' and experts' quantitative feedback, we preliminarily illustrated the effective stimulus combinations in each phase and summarized the multifaceted impact of each combination across three phases. For RQ2, linkograph and behavior coding were employed to provide qualitative insights. By synthesizing both quantitative and qualitative data, we further discussed the inconsistency of stimuli's impact on design outcomes and process, as well as the necessity of dynamically providing creative stimuli during conceptual design based on the design phase, educational objective, and students' state. These findings extend previous theoretical and empirical findings, inspire upcoming research to further explore how stimuli's various characteristics affect different design phases, and provide practical evidence for design education based on creative stimuli.

2. Related work

2.1. Characteristics of creative stimuli

Current research has extensively examined how various characteristics of creative stimuli impact the design outcomes and process, considering factors such as modality, fidelity, semantic distance, and timing of presentation.

Modality Texts and images are common modalities of creative stimuli, usually derived from patent databases (Sarica et al., 2020), bionic databases (Ruiz-Pastor et al., 2023; Vattam et al., 2011; 2011), and commercial product cases (Song et al., 2017). Fernandes and Ogliari (2018)) applied textual and visual stimuli about biomimicry to help students conceive practical and diverse design solutions, while Goldschmidt and Sever (2011) found textual stimuli enhance idea novelty but not affect practicality.

Comparing textual and visual stimuli, an experiment revealed that texts aid in knowledge recall while images facilitate active thinking (Shi et al., 2017). Another study utilized patents in different modalities as stimuli, revealing that texts reduce idea quantity in early stages but not in later stages (Chan et al., 2011). Furthermore, simultaneous presentation of textual and visual stimuli texts' ambiguity (Borgianni et al., 2017; Shi et al., 2017). Physical and digital models are also utilized to provide multisensory and three-dimensional stimuli (Broek et al., 2000; Dybvik et al., 2022; Gomes et al., 2022; Koronis et al., 2021). Despite substantial research, no consistent conclusion exists regarding the effects of multimodal stimuli on creativity, with the most suitable modality possibly depending on individual's current design task and stages (Toh and Miller, 2014; Vasconcelos and Crilly, 2016).

Fidelity Creative stimuli can be roughly categorized into abstract and concrete stimuli based on their fidelity. Abstract stimuli provide descriptions of design scenarios, general concepts, or system attributes, while concrete stimuli include explicit functional examples or detailed design solutions (Ezzat et al., 2020). Studies have proved that abstract stimuli foster abstract thinking (Huang et al., 2015), thereby increasing idea quantity (Vasconcelos and Crilly, 2016) and novelty (Gonçalves et al., 2012). Another research found abstract images more effective in enhancing diversity and novelty compared to concrete ones (Paay et al., 2023). Conversely, concrete stimuli often inhibit idea generation (Jansson and Smith, 1991), potentially leading to design fixation (Ezzat et al., 2020).

However, the effects of stimuli with different fidelities vary. For example, a study demonstrated that specific examples aid in generating novel ideas in engineering design (Eckert et al., 2005), while another found both categorical and specific examples facilitated originality (Yuan et al., 2023). Additionally, Koronis et al. (2022) believe that different modalities inherently possess various fidelities, with physical models being more concrete than texts. Moreover, Paay et al. (2023) considered both fidelity and modality in their study, suggesting the interconnectedness of these factors and the need for comprehensive research to explore the multifaceted impact of creative stimuli.

Semantic Distance Semantic distance delineates the distance between creative stimuli and the design task, with some research asserting that distant stimuli facilitate more creative ideas (Dahl and Moreau, 2002) and close-range stimuli may diminish idea diversity (Wilson et al., 2010). Chiu and Shu (2012) further discovered that stimuli opposed to the design task foster novel solutions. However, other research found that distant stimuli may not consistently enhance creativity, especially when they lack relevance (Fu et al., 2013; Srinivasan et al., 2018). Moreover, Chan et al. (2015) found that while creative ideas often originate from distant stimuli, close-range stimuli enhance idea quantity. These inconsistency suggests that semantic distance's impact is relative, influenced by factors like stimuli's fidelity (Koronis et al., 2022). Furthermore, previous studies revealed an optimal semantic distance between stimuli and tasks (Vasconcelos and Crilly, 2016), suggesting that similarity between them prompted designers to utilize information from stimuli and generate more innovative solutions (Holyoak and Koh, 1987).

Other Characteristics Certain studies have explored the impact of factors such as the presentation timing, quantity, and novelty of creative stimuli. According to Kulkarni et al. (2012), creative stimuli enhanced creativity at early stages but led to repeated ideas at later stages. Similarly, at early phases, constraints as stimuli were proven effective in facilitating problem definition and avoiding information overload (Damadzic and Medeiros, 2022; Farh et al., 2010), but they might interrupt students' thinking process and cause frustration at later phases (Medeiros et al., 2017). However, some research suggested that providing stimuli after a certain period benefits designers in utilizing information more effective, especially when they face challenges (Moss et al., 2011). For the quantity of stimuli, Sio (2015) suggested that substantial stimuli can offer diverse perspectives for design students to conceptualize ideas. However, excessive stimuli may hinder deep exploration, evaluation, and expression of ideas, negatively affecting idea quality (Kazakci et al., 2015). As for novelty, Perttula and Sipila (2007)) observed that stimuli with low novelty reduce idea quantity and diversity, while Chan et al.'s study (2011) noted uncommon stimuli promote novel ideas more effectively. Nevertheless, Purcell and Gero (1996) argued that the novelty of stimuli has minimal impact on design fixation.

2.2. Mechanism of creative stimuli to enhance creativity

Creativity is defined as the ability to generate original ideas, insights, inventions, or products (Eysenck, 1994), intimately intertwined with creative ideas and creative thinking. Creative ideas are the outward manifestation of creativity, while creative thinking forms the foundation of creativity (Goldschmidt and Tatsa, 2005). Creative thinking involves both divergent and convergent processes, paralleling the conceptual design process. In the divergent phase, design students employ divergent thinking to generate ideas from various perspectives based on design tasks or problems. During the convergent phase, they utilize convergent thinking to assess, filter, and refine existing ideas, ultimately producing an optimal solution (Guilford, 1956).

To clarify how creative stimuli facilitate creative thinking, Search for Ideas in Associative Memory Model reveals the relationship between creativity and memory (Nijstad and Stroebe, 2006), positing that idea generation relies on the retrieval process of long-term memory, influenced by both internal memory and external cues (Nijstad and Stroebe, 2006). Multimodal stimuli serve as external cues, assisting students in memory retrieval and thereby foster idea generation. The Memory in Creative Ideation (Memi C) framework further categorizes memory into episodic and semantic memory (Benedek et al., 2023). In the divergent phase, a plethora of concepts aids in retrieving semantic memory and activating knowledge structures, while context-related stimuli help construct relevant scenes and details in mind. For the convergent phase, comparing design solutions with relevant knowledge in semantic memory and life experiences in episodic memory allows for a better assessment of idea novelty and practicality. Another branch of research suggests that stimuli enhance creativity by facilitating analogical thinking. As a core design thinking process (Thagard, 2005), analogical thinking fundamentally connects existing knowledge or solutions with problems or tasks (Perkins, 1997), thus stimulating the generation of novel ideas. During this process, creative stimuli enrich the sources of analogical knowledge and assist students in establishing more connections.

As creativity is also associated with subjective experience such as self-esteem, optimism, and well-being (Thrash and Elliot, 2003; Thrash et al., 2010a), the effect of stimuli could also be explained by students' mental state. For instance, a study indicated that creative stimuli facilitate students to transition into a non-focused state, in which they tend to be more creative (Liu et al., 2022). Moreover, the prepared mind theory posits that creative stimuli have a more pronounced effect when students encounter difficulties or lack inspiration (Seifert et al., 1995), as individuals maintain openness towards problem-solving methods and become more active in information acquisition when facing difficulties (Moss et al., 2007). Meanwhile, creative stimuli could ignite individuals' curiosity and intrinsic motivation during conceptual design process, thus facilitating students to enter a flow state characterized by highly motivated and absorbed experiences as suggested by the Creativity Flow Theory (Csikszentmihalyi, 1996; 1997). Such flow experience invoked by stimuli is important as it not only improves students' confidence in the current design task (Moral-Bofill et al., 2020) but also maximizes their creative potential (Czikszentmihalyi, 1990).

2.3. Roles of creative stimuli in conceptual design

During the divergent phase, design fixation can limit design students' focus and lead to analogous ideas (Jansson and Smith, 1991;

Purcell and Gero, 1996). Formulating concrete solutions is another challenge, as design problems in early stages are often nebulous and indistinct (Crilly, 2015). Additionally, sustaining continuous idea generation is imperative but challenging, because students commonly lack sufficient inspiration as the design process progresses (Howard et al., 2010). Creative stimuli, serving as inspiration triggers and external constraints, hold promise in helping students confront these challenges. For example, according to Thrash and Elliot (2004), stimuli about the context of the design task work as an illumination that trigger students' inspirational experience, which helps to enhance ideation fluency (Thrash et al., 2014). For the challenge of ambiguous design problems, the potential constraints posed by stimuli help students narrow down the problem space (Tromp and Baer, 2024) and focus on specific aspects (Tromp, 2023). To acquire substantial textual and visual stimuli, design students often utilize search engines (Herring et al., 2009) and platforms such as Pinterest. Furthermore, prior research extracted concepts or principles from patents, academic papers, and other sources as creative stimulus cards (Yilmaz et al., 2016). However, these cards may not be a panacea as exposing students prematurely to specific product concepts may simultaneously lead to decreased idea diversity (Jansson and Smith, 1991; Vasconcelos and Crilly, 2016).

Regarding the convergent phase, the lack of explicit evaluation standards impedes students' intuitive judgment of idea novelty and practicality (Liu et al., 2021). Moreover, as design fixation deepens, students tend to selectively ignore issues in their ideas, hindering idea iteration and optimization (Alipour et al., 2018). For these issues, creative stimuli of existing design examples serve as a reference for students to identify shortcomings and defects in their current ideas (Xu et al., 2021). For instance, Paragon facilitated the selection and optimization of graphic designs through providing relevant graphic designs with different layouts and color schemes (Kang et al., 2018). However, creative stimuli are still underutilized in the convergent phase although proven effective (Liu et al., 2022; Xu et al., 2020), warranting further research on their influence on convergence.

Overall, despite the significant roles creative stimuli play in conceptual design, their effectiveness across phases remains unclear. Although prior research has assessed the influence of multimodal stimuli in other creative tasks (Shi et al., 2017), we need exploration tailored to conceptual design tasks due to the discrepancy among different creative activities (Vasconcelos and Crilly, 2016). Furthermore, most existing studies treat conceptual design as a holistic process, overlooking the potential distinct design requirements and effects of creative stimuli on divergent and convergent thinking.

3. Research method

To fill the research gap mentioned before, our research aims to investigate the differential effects of various stimulus combinations in the conceptual design process. Specifically, we are interested in their impact on the creativity of design outcomes and on design students' behavior.

3.1. Stimuli selection

As enumerating and comparing all combinations of creative stimulus types is beyond the scope of a single paper, it is necessary to narrow down the research focus to the most important types of stimuli. When determining the stimuli, we considered the following aspects: (1) Typicality (A1): The selected stimulus types should frequently appear in related research. (2) Accessibility (A2): Design students should be able to acquire the selected stimuli in their routine design processes. (3) Research Gap (A3): Existing research conclusions regarding the effects of the selected stimulus types remain unclear or contradictory.

Based on these aspects, we went through two main steps: (1) Deciding the target characteristics of creative stimuli: As introduced in Section 2.1, typical characteristics include modality, fidelity, and semantic distance. While prior work has revealed an optimal semantic distance (i.e., when existing commonality between stimuli and the design task (Holyoak and Koh, 1987; Vasconcelos and Crilly, 2016), the effectiveness of stimuli with different modality and fidelity remains contradicted in existing research. According to A3, we narrowed down the characteristics of stimuli to modality and fidelity. (2) Determining levels of modality and fidelity: For modality, texts and images are the most typical stimuli in existing research (echoing A1) and they are more accessible in design activities than other modalities such as 3D models (echoing A2). For fidelity, relevant literature commonly divides stimuli into abstract ones (i.e., low fidelity) and concrete ones (i.e., high fidelity) (Paay et al., 2023; Yuan et al., 2023).

Considering the above facts, four typical types of creative stimuli are derived as follows, which will be combined and utilized as conditions for different experimental groups:

- Concept text (low fidelity): Brief descriptions of working mechanism or the utilized technology, without involving specific introduction to any products.
- Product text (high fidelity): Detailed descriptions of product functions, structures, appearance, etc.
- Scene image (low fidelity): Solely depictions of products' potential usage scenarios.
- Product image (high fidelity): Visual representations of product structures and external appearance.

3.2. Experiment design

During the experiment, participants were required to design a sports-assistance product for exercise enthusiasts to enhance exercise effectiveness or overall exercise experience. The product should: (1) Ensure exercise safety and avoid potential risks; (2) Be easy to use and operate, with a low learning curve. The task is closely related to daily life, mitigating the impact of variations in participants' product usage experience or knowledge (Kim and Kim, 2015). Meanwhile, the task avoided specific constraints on product functionality or form to allow participants ample divergent space.

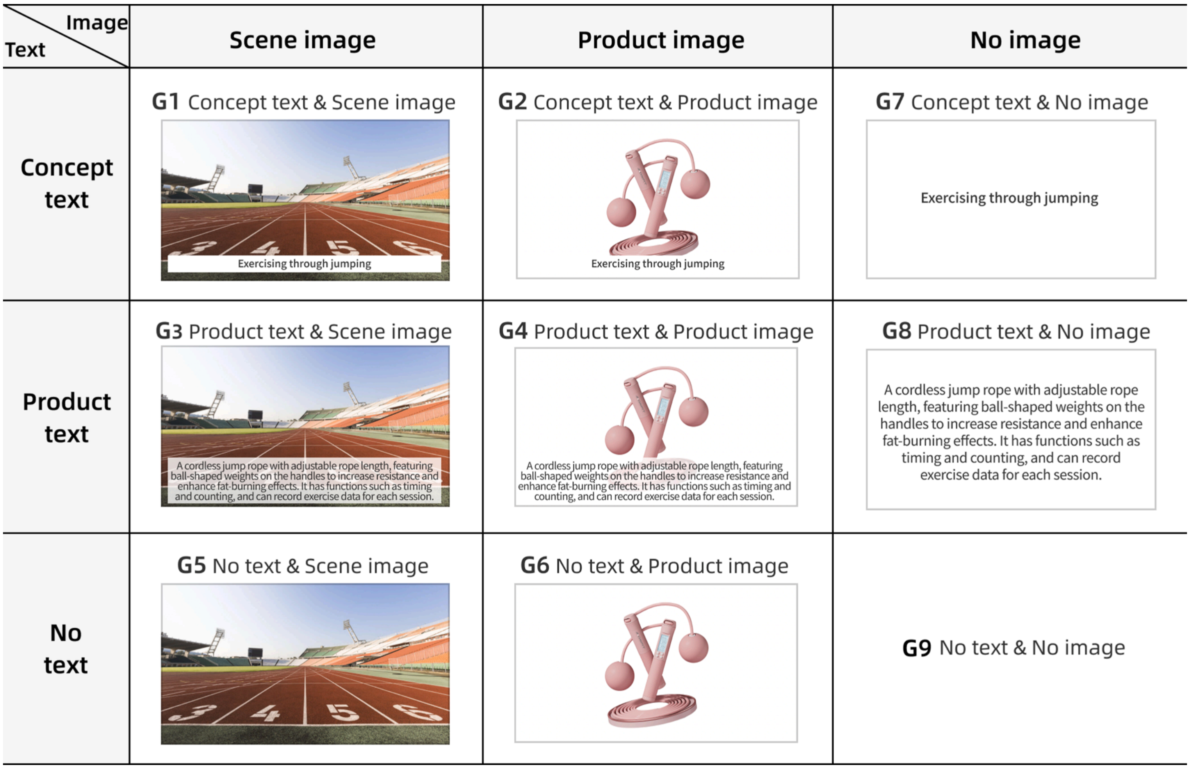

Fig. 1. An example of creative stimuli provided in the 3×3 experiment.

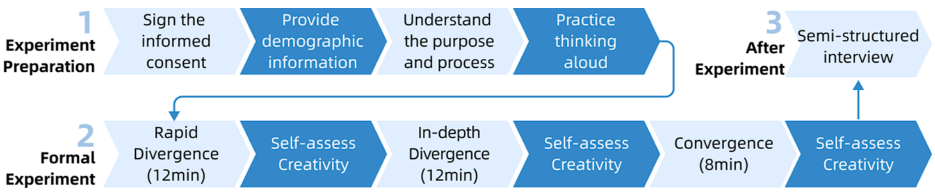

Fig. 2. Procedure of the experiment.

The experiment followed a 3 × 3 between-subject design, with the independent variables being the fidelity of textual stimuli (including concept texts, product texts, and no texts) and visual stimuli (including scenario images, product images, and no images). Each group was provided with corresponding creative stimuli (see Fig. 1), while G9 was a blank control group without any stimuli. Considering the amount of stimuli provided in previous studies (Chan et al., 2011; Paay et al., 2023), G1-G8 respectively received eight sets of stimuli (see Appendix A) displayed on a 27-inch screen through PowerPoint. Creative stimuli in each set were carefully matched to maintain consistency between the texts and images, reducing the influence of stimuli's semantic distance and novelty on results. For instance, in the first set of stimuli, while the product texts and image described the function and appearance of cordless jump ropes, the concept texts and scene image depicted the mechanism and usage scenarios of the product separately.

3.3. Procedure

As depicted in Fig. 2, the formal experiment followed the Double Diamond Model (Design Council, 2005) and comprised three sub-phases: the Rapid Divergence Phase, where participants rapidly generated ideas based on the design task; the In-Depth Divergence Phase, where participants selectively refined solutions from the previous phase and continued generating ideas; the Convergence Phase, where participants evaluated existing ideas and formed a final solution. The duration for sub-phases was referenced from prior research (Gonçalves and Cash, 2021).

Before the formal experiment, participants signed an informed consent form and provided demographic information and prior experience in designing sports-assistance through an online questionnaire. Then, the experimenter introduced the experiment's purpose and process, showcasing the design outcome requirements and examples for each sub-phase. Participants were required to think aloud during design, expressing their genuine thoughts without concerns about correctness or meaningfulness. A five-minute

Table 1
Evaluation metrics for participant ratings.

Dimension	Statement (1=strongly disagree, 7=strongly agree)
Novelty	I believe that the ideas generated in this phase exhibit a high level of novelty, possessing innovative and unconventional characteristics compared to existing products.
Practicality	I consider the practicality of the ideas produced in this phase to be high, as they can be manufactured and widely utilized in real-life scenarios.
Diversity	I believe that the diversity of the ideas generated in this phase is substantial, with low similarity among different solutions.

Table 2
Evaluation metrics for expert ratings.

Dimension	Sub-dimension	Statement
Novelty	-	Whether the idea involves innovative and unconventional features in comparison to existing products, assessed on a seven-point scale (1=not novel at all, 7=extremely novel).
Practicality	Level of importance	Whether the idea involves indispensable nature in enhancing the expe-rience or safety of sports, assessed on a five-point scale (1=not important at all, 5=extremely important).
	Rate of popularity	The proportion of sports enthusiasts likely to use the product, assessed on a scale from 0 to 1, rounded to one decimal place (0=no one would use it, 1=everyone would use it).
	Rate of use	The frequency of product usage, assessed on a scale from 0 to 1, rounded to one decimal place (0=never used, 1=used every time).
Diversity	-	The similarity among proposed ideas, assessed on a seven-point scale (1=extremely low diversity, 7=extremely high diversity).

think-aloud practice was conducted to help participants adapt to this method.

In each sub-phase of the formal experiment, participants received a design solution sheet (see Appendix B) to document ideas through sketches or texts. For G1-G8, participants could freely consult the provided stimuli from the screen if they encountered difficulties during design. At the end of each sub-phase, participants self-assessed their creativity (see Section 3.4). The entire design process was recorded for further analysis. After the formal experiment, participants underwent a brief semi-structured interview. This interview addressed reasons for their phase-specific scores, changes in scores across phases, comparisons of design processes with and without creative stimuli (only for G1-G8), encountered difficulties during the conceptual design process, and desired external assistance (only for G9). Questions were flexibly adjusted according to participants' answers. Participants received rewards upon completion of the experiment.

3.4. Evaluation metrics

The experiment evaluated creativity based on the quantity, novelty, practicality, and diversity of design outcomes (Sarkar and Chakrabarti, 2011), utilizing both participant and expert ratings. Participants rated on a seven-point scale shown in Table 1. Participants only provided a composite score for each dimension, with diversity not assessed in the Convergence phase.

In addition, three design experts were invited to evaluate the design outcomes, each with a minimum of six-year conceptual design experience and possessing independent and professional judgment. In divergent phases, experts evaluated based on the statements in Table 2, maintaining anonymity regarding participants' personal information. Practicality was calculated as the product of three sub-dimensions. Experts assessed novelty and practicality of each idea separately and provided an overall diversity score. For the Convergence Phase, the criteria for practicality remained unchanged, and novelty was calculated based on Eq. 1, where participants' final solutions were split into several functions by co-authors, and experts evaluated each function's novelty (0=not novel, 1=novel). N_{ov} is the novelty score, fe and N_{fe} denote the number of novel functions and all functions respectively.

$$N_{ov} = \frac{\sum fe}{N_{fe}} \tag{1}$$

3.5. Participants

The experiment involved 72 design students as participants. They were recruited from social media, aged from 19 to 30 years ($M = 22.53, SD = 2.05$), including 27 males and 45 females. All participants were enrolled in design-related majors like industrial design and product design, or had taken design-related courses as part of their minor. All participants possessed a basic understanding of conceptual design and relevant design experience. They were proficient in comprehending experimental tasks and expressing design concepts through texts and sketches. Participants were evenly distributed among nine groups, each comprising eight individuals. Each group consisted of 5 females and 3 males, with 6 majoring in design and 2 minoring. Moreover, each group included 1 participant with prior experience in designing sports-assistive products and 7 without relevant experience.

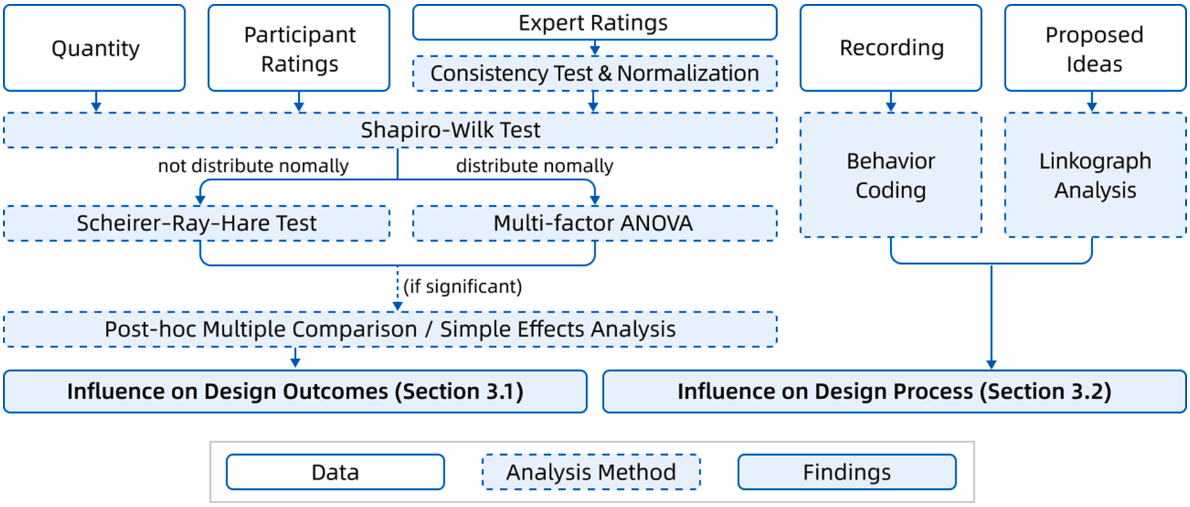

Fig. 3. Process and method of data analysis.

Table 3
Codes of behavior analysis.

Behavior Type	Code	Explanation	Example
Task Analysis	A	Exploring and analyzing design problems, including words and behaviors related to fact analysis and problem discovery.	Words: Repeating the design task, "I'm thinking about what kind of sport it might be." Behavior: Looking at the task on the display screen, using a pen to circle the task on the solution sheet.
Idea Generation	G	Expressing ideas with texts or sketches, including words and behaviors related to ideation and sketching.	Words: "I'm going to make something like a knee pro- tector now, it can monitor the pressure on the knee." Behavior: Sketching on the solution sheet.
Idea Evaluation	E	Reviewing, evaluating, and ver- ifying existing ideas, including words and behaviors related to idea selection and refinement.	Words: "There may be a problem with the previous proposal, it needs to be improved." Behavior: Looking back and forth at the solution sheet from the previous stage.
Stimuli Observation	O	Viewing and analyzing creative stimuli, including words and behaviors related to observing and evaluating creative stimuli.	Words: Repeating the text of the creative stimulus, "This is a swimming pool."Behavior: Looking at the creative stimuli on the dis- play screen and flipping through them.
No Behavior	N	No identifiable words or behavior.	/

Table 4
Codes of linkograph analysis.

Link Type	Code	Explanation	Example
Parallel Link	P	Repeating prior ideas, only modifying the way of expression.	Yoga breathing adjustment product Yoga bre- athing training auxiliary product
Incremental Link	I	Adding functions or refining the exi- sting solution.	Wearable device for detecting running breathing → Wearable running monitoring product, able to detect breathing, body temperature, etc.
New Idea Link	N	Obtaining a completely new solution from the problems of existing scenarios, ideas, or products.	Swimming pool → Wearable device for monito- ring swimming posture
Alternative Link	A	Modifying an element or applying it to a new scenario.	Surfing posture correction bracelet → Yoga post- ure correction bracelet
Tangential Link	T	Producing ideas with cognitive associa-tion such as the same principle, or have a part in common.	Heart rate monitoring bracelet → Health monit- oring headband

3.6. Data analysis

Data analysis followed the process in Fig. 3. For design outcomes, the Shapiro-Wilk test was first employed to assess data normality. To verify the main effects and interaction effects of different stimulus types, the multi-factor analysis of variance (ANOVA) was applied to normally distributed dimensions, while the Scheirer-Ray-Hare test was utilized for non-normally distributed ones. When main effects were significant, post-hoc multiple comparisons would be conducted to identify specific differences between each two stimulus types. In cases of significant interaction effects, we employed simple effects analysis to validate whether the fidelity of textual/visual stimuli had a significant impact when the fidelity of another modality was fixed. Expert rating analysis followed a similar process, with the Kendall's W test applied at first to verify the coherence of three experts' ratings. Expert ratings were normalized before the Shapiro-

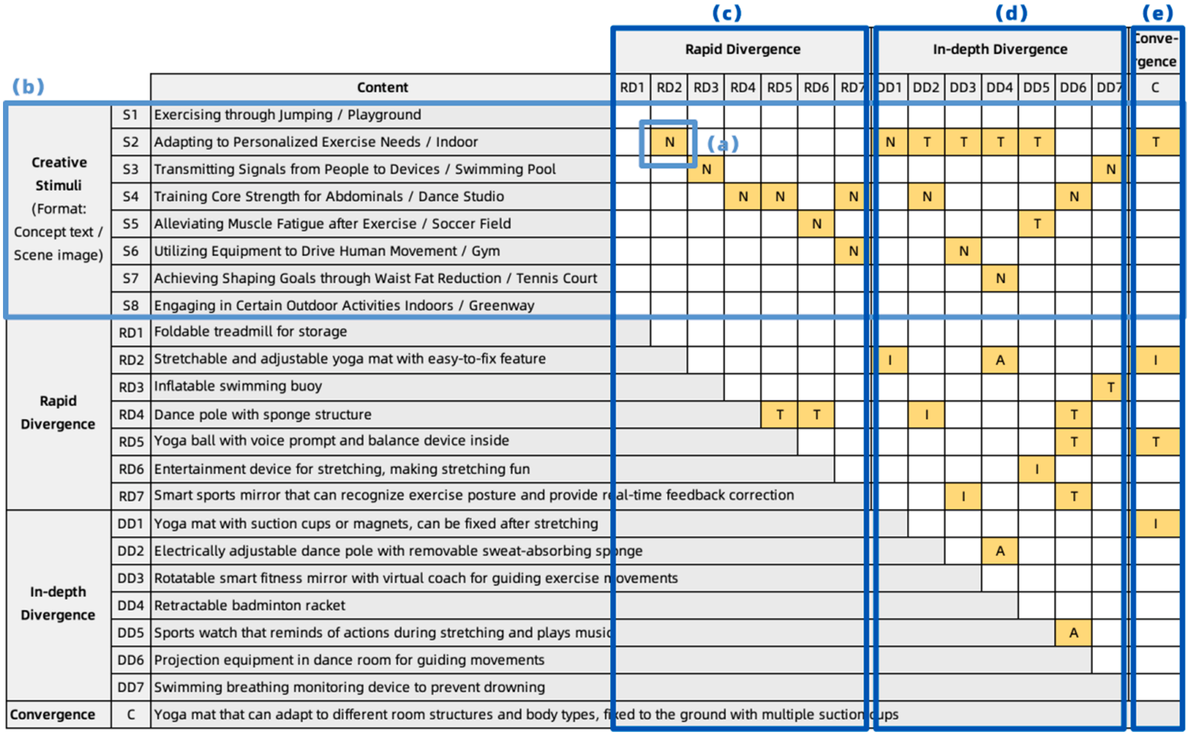

Fig. 4. An example of the coded linkograph. (a) A new idea link between the second stimulus and the second idea in Rapid Divergence. (b) Connections between ideas and creative stimuli. (c)-(e) connections between ideas during the Rapid Divergence / In-depth Divergence / Convergence Phases.

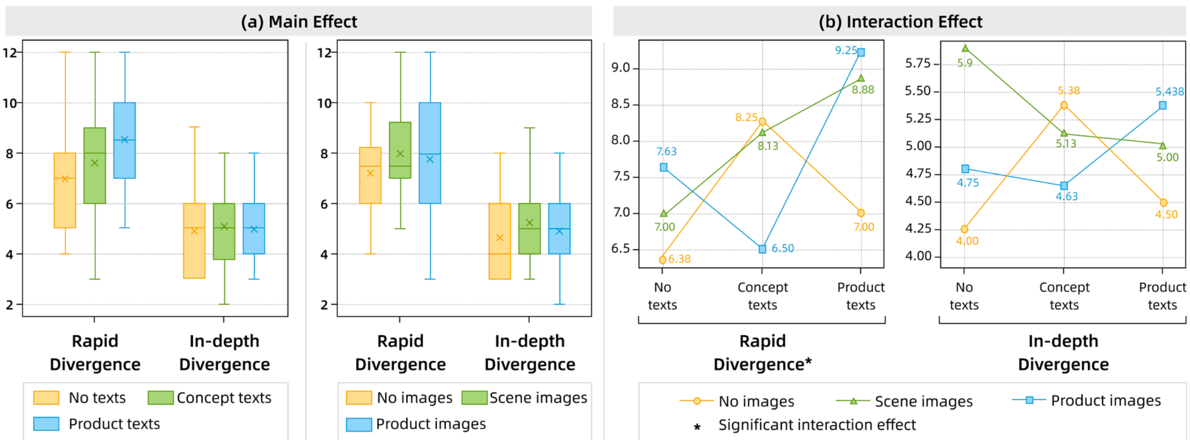

Fig. 5. Analysis results of idea quantity. In (b), the numbers beside each node represent the average number of ideas.

Wilk test to ensure consistent rating spans.

For the design process, three other coders were invited for behavior coding. The coding rules followed the Creative Design Process Model (Howard et al., 2008), encompassing behaviors of task analysis (A), idea generation (G), and idea evaluation (E). As shown in Table 3, an additional code named stimuli observation (O) was supplemented based on our experiment's objectives, and periods without identifiable words or behavior were coded as no behavior (N). All coders have at least three years of conceptual design experience, familiarity with behavior coding methods, and prior acquaintance with the rules. Due to the substantial workload, the initial behavior coding for 72 participants was jointly completed by two coders, each coding 36 participants' experiment recordings independently. Then a third coder reviewed all coding results referring to the experiment recordings, annotating disputed codes and discussing with the other two coders until reaching a consensus.

Furthermore, linkograph was employed to analyze the influence of creative stimuli on participants' cognitive patterns. Specially,

Table 5
Main effect analysis results of participant ratings.

Stage	Modality	Novelty		Practicality		Diversity	
		H	p	H	p	H	p
Rapid Divergence	Text	0.828	0.441	1.281	0.285	0.802	0.453
	Image	6.463	**0.003***	0.742	0.480	4.399	**0.016***
In-depth Divergence	Text	1.006	0.372	0.437	0.648	1.457	0.241
	Image	5.853	**0.005***	1.166	0.318	2.163	0.123
Convergence	Text	0.183	0.833	2.853	0.065	/	
	Image	8.693	**<.001****	3.690	**0.031***		

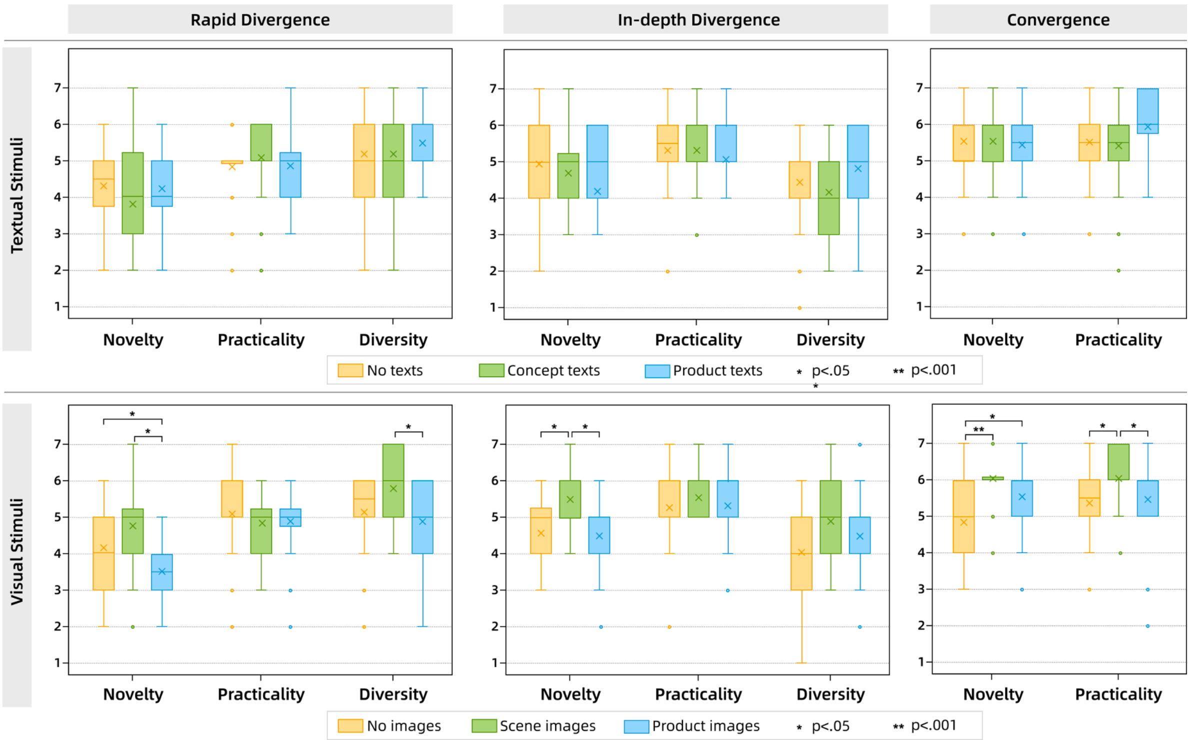

Fig. 6. Visualization of main effect analysis results (participant ratings).

the linkograph included links between ideas and ideas/stimuli, helping to clarify the source stimulus that participants derived ideas from. Building upon Hatcher et al.'s work (2018), we focused on five types of links as shown in Table 4. The three expert coders also participated in the linkograph analysis, following the same coding process. Fig. 4 illustrates an example linkograph, with yellow boxes depicting links and letters indicating the link type.

Based on the coding results, the number of links in each linkograph region was tallied. The link density was calculated according to Eq. 2, where LD represents link density, N_{link} represents the number of links, and N_{idea} represents the number of ideas.

$$LD = \frac{N_{link}}{N_{idea}} \tag{2}$$

4. Results

4.1. Design outcomes

4.1.1. Quantity of Ideas

Main Effects As depicted in Fig. 5.a, the main effects of texts and images on idea quantity were not significant. On average, groups exposed to product texts and scene images generated the most ideas in Rapid Divergence, whereas those provided with concept texts and scene images produced the highest number of ideas in the In-depth Divergence Phase.

Interaction Effects Fig. 5.b reveals a significant interaction effect on idea quantity during Rapid Divergence ($H(4,63) = 3.165, p = .031$). When presenting product images, the group with product texts generated a significantly larger quantity of ideas compared to the

Table 6
Interaction effect analysis results of participant ratings.

Phase	Novelty		Practicality		Diversity	
	H	p	H	p	H	p
Rapid Divergence	0.928	0.452	4.367	**0.004***	1.531	0.204
In-depth Divergence	0.144	0.965	3.831	**0.008***	0.194	0.941
Convergence	0.777	0.544	2.121	0.089	/	

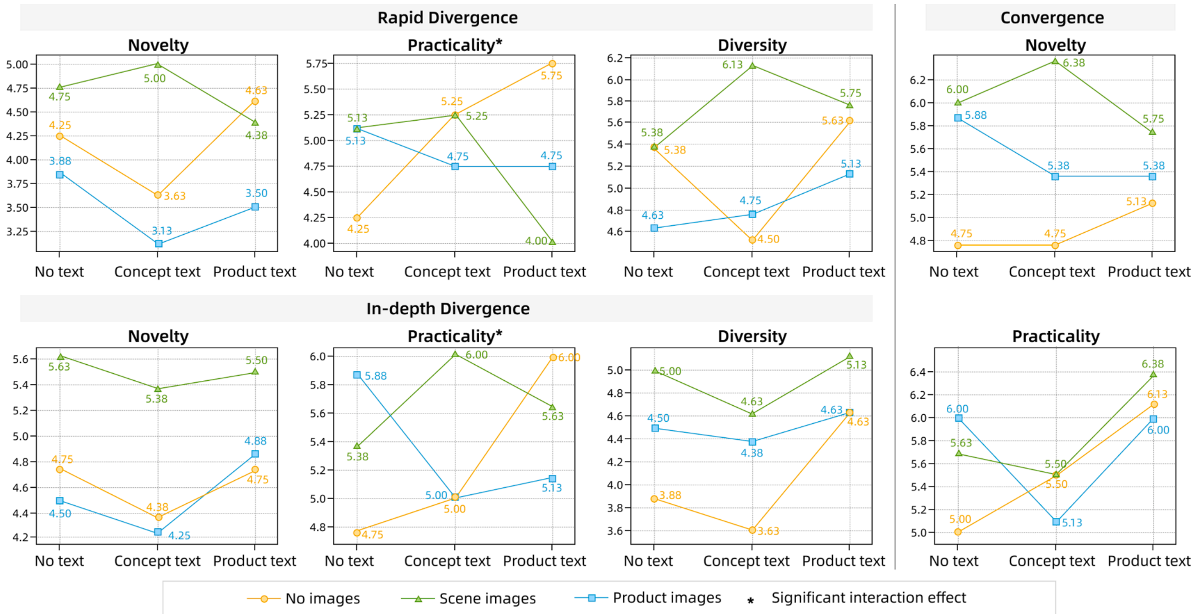

Fig. 7. Visualization of interaction effect analysis results (participant ratings).

group with concept texts ($p = .029$), indicating a reciprocal effect of texts' and images' fidelities on the quantity of generated ideas. The interaction effect during the In-depth Divergence Phase was not statistically significant ($H(4, 63) = .984, p = .407$).

4.1.2. Participant Ratings

This section presents participant ratings along with excerpts from interviews. P_1^2 denotes the second participant in the first group.

Main Effects As shown in Table 5 and Fig. 6, in Rapid Divergence, a significant main effect of visual stimuli was observed on novelty, with novelty of groups exposed to scene images significantly surpassed those without images ($p = .041$) and with product images ($p = .001$). P_5^3 and P_3^6 mentioned that scene images evoked memories and unresolved issues from various sports scenarios, stimulating them to conceive unique ideas. Conversely, participants with product images (e.g., P_2^4) felt constrained by the specific products depicted in the images. Besides, groups with scene images were significantly more diverse than those with product images ($p = .004$), mainly because a single scene image could prompt participants to think of various related products. For instance, based on the image of a playground, P_4^4 conceived multiple ideas like smart insoles and pre-run stretching equipment.

For In-depth Divergence, images' influence on novelty remained significant. Groups exposed to scene images demonstrated higher novelty compared to those without images ($p = .005$) and with product images ($p = .003$). Scene images prompted participants to explore novel ideas by envisioning different scenarios of a specific concept. For instance, P_5^2 first conceived a VR fitness device, and by combining this idea with the image of a swimming pool, she generated the idea of swimming AR glasses.

In Convergent, images still impacted novelty significantly. Ideas generated in groups with scene images ($p < .001$) and product images ($p = .002$) were notably more novel than those without images. Participants integrated details from product images into their proposals (e.g., P_2^8, P_4^5, P_6^2), while scene images helped them (e.g., P_1^5) break free from initial ideas and consider practical requirements. Furthermore, practicality scores were significantly higher when scene images were provided compared to no images ($p = .013$) and product images ($p = .041$). Scene images encouraged participants to consider the necessity of existing functionalities based on the scene, leading to the elimination of impractical features.

Interaction Effects As presented in Table 6 and Fig. 7, significant interaction effects were observed for practicality during two divergence phases. In Rapid Divergence, the impact of images with different fidelities on practicality was influenced by the fidelities of accompanying texts, and vice versa. For example, despite higher practicality in groups with scene or product images compared to those

Table 7
Main effect analysis results of expert ratings. Dimensions using the multi-factor ANOVA are represented by the F-value, while dimensions using the Scheirer-Ray-Hare test are represented by the H-value.

Phase	Modality	Novelty		Practicality		Diversity	
		H/F	p	H/F	p	H/F	p
Rapid Divergence	Text	1.980	0.139	0.106	0.900	3.238	**0.046***
	Image	6.662	**0.001***	2.546	2.044	3.361	**0.041***
In-depth Divergence	Text	3.542	**0.030***	2.351	0.097	0.153	0.322
	Image	1.587	0.206	1.407	0.246	3.282	**0.044***
Convergence	Text	0.485	0.618	0.149	0.862	/	
	Image	0.947	0.393	0.192	0.825		

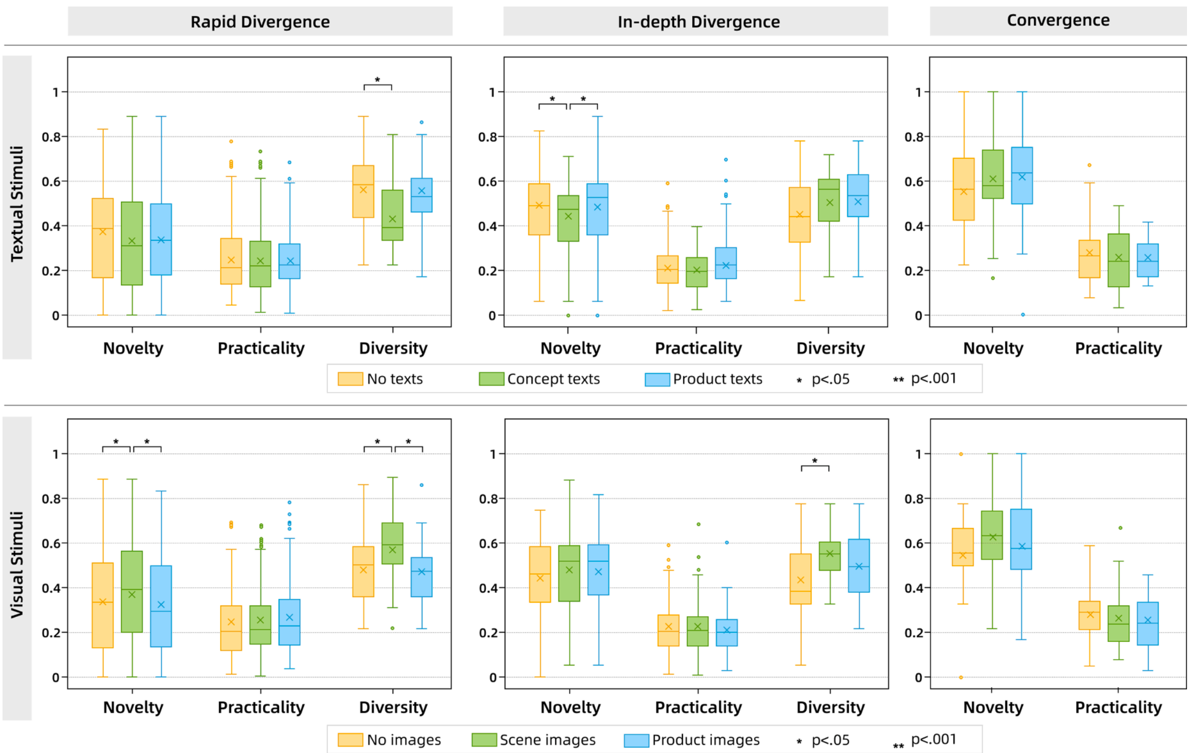

Fig. 8. Visualization of main effect analysis results (expert ratings).

without images, the presence of product texts led to significantly higher practicality in groups without images when compared to those with product images ($p = .043$) and scene images ($p = .001$). For In-depth Divergence, when presenting concept texts, the practicality of groups with scene images significantly surpassed groups without images ($p = .042$). Although no significant interaction effects in other dimensions, there was a clear mutual influence between the fidelities of texts and images in Fig. 7.

4.1.3. Expert Ratings

According to Kendall's W test, the consistency coefficients of expert ratings were close to or greater than 0.6 ($p < .001$), indicating a relatively strong consistency in the ratings from experts.

Main Effects As shown in Table 7 and Fig. 8, in the Rapid Divergence Phase, texts' main effect was significant in diversity, with groups lacking texts showing notably higher diversity compared to those with concept texts ($p = .019$). The main effect of images was significant in novelty and diversity, with groups exposed to scene images demonstrating significantly higher novelty and diversity compared to those without images ($p_{novelty} = .007, p_{diversity} = .044$) and with product images ($p_{novelty} = .001, p_{diversity} = .019$).

For In-depth Divergence, the main effect of texts was significant in novelty, with groups exposed to concept texts exhibiting significantly lower novelty compared to groups without texts ($p = .020$) and groups with product texts ($p = .041$). The main effect of images was significant in diversity, with groups exposed to scene images showing significantly higher diversity compared to those without images ($p = .014$). However, in the Convergence Phase, neither the main effects of texts nor images were significant.

Interaction Effects Results of the interaction effect analysis are presented in Table 8 and Fig. 9. During In-depth Divergence, a significant interaction effect was observed in practicality. Specifically, when presenting product images, the practicality of the group

Table 8
Interaction effect analysis results of expert ratings. Dimensions using the multi-factor ANOVA are represented by the F-value, while dimensions using the Scheirer-Ray-Hare test are represented by the H-value.

Phase	Novelty		Practicality		Diversity	
	H/F	p	H/F	p	H/F	p
Rapid Divergence	1.471	0.210	1.006	0.404	0.422	0.793
In-depth Divergence	1.488	0.205	3.298	**0.011***	0.589	0.672
Convergence	2.630	**0.043***	0.498	0.738	/	

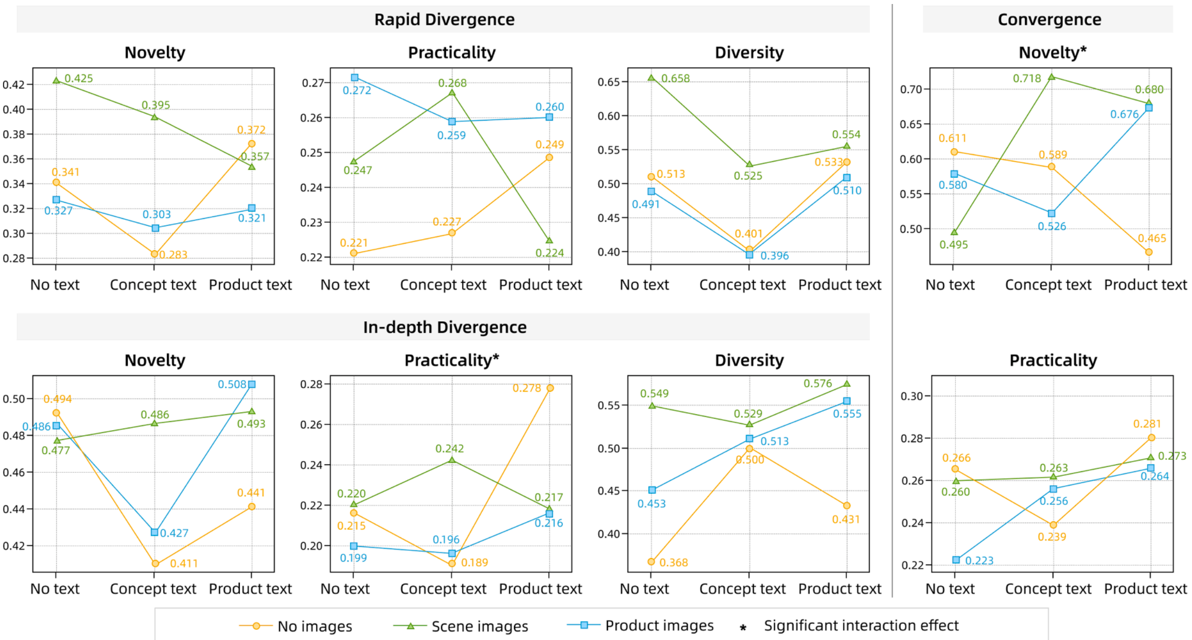

Fig. 9. Visualization of interaction effect analysis results (expert ratings).

with product texts significantly surpassed that of the group with concept texts ($p = .024$). Similarly, in the Convergence Phase, the novelty dimension exhibited a significant interaction effect. While the interaction effects in other dimensions were not significant, there was evident interplay between texts and images as depicted in Fig. 9. For example, during Rapid Divergence, scene images' effectiveness in enhancing practicality was affected by the fidelity of texts.

4.2. Design process

4.2.1. Behavior Coding

Fig. 10 illustrates the distribution of behavior types across groups throughout the three design phases. We primarily focus on differences in time allocation for the five behavior types within each phase and variations in time allocation of each behavior across the stages. It is worth noting that behavior coding data only reflects the behavioral tendencies of participants exposed to different creative stimuli. The time proportions do not directly correlate with the creativity of design outcomes. Key findings from the behavior coding are summarized as follows:

Task Analysis (A) During Rapid Divergence, participants without stimuli (G9) allocated more time to task analysis due to difficulties in "defining the design task's scope" (P_9^1). During In-depth Divergence, the time spent on task analysis significantly decreased across all groups, indicating minimal impact from different stimuli on the time allocated for task analysis.

Idea Generation (G) G1 and G5 spent a higher proportion of time on idea generation in Rapid Divergence and Convergence, while G3 exhibited a higher proportion during In-depth Divergence. Participants reported being more focused on generating ideas when presented with scene images (i.e., G1, G3, G5), noting that "seeing scene images makes me think more fluently, as they provide real product usage scenarios" (P_1^1). Additionally, the time for idea generation increased across all groups as the design process progressed.

Idea Evaluation (E) During Rapid Divergence, all groups engaged less in idea evaluation, while in the subsequent phase all groups exhibited a noticeable increase in the time proportion. G4 and G9 had the highest time proportion for evaluating ideas. The rich details in product texts and images led G4's participants to "make more detailed comparisons between my own ideas and those in the creative stimuli" (P_4^3). Conversely, participants in G9 spent more time evaluating ideas because they "struggle to optimize ideas with low

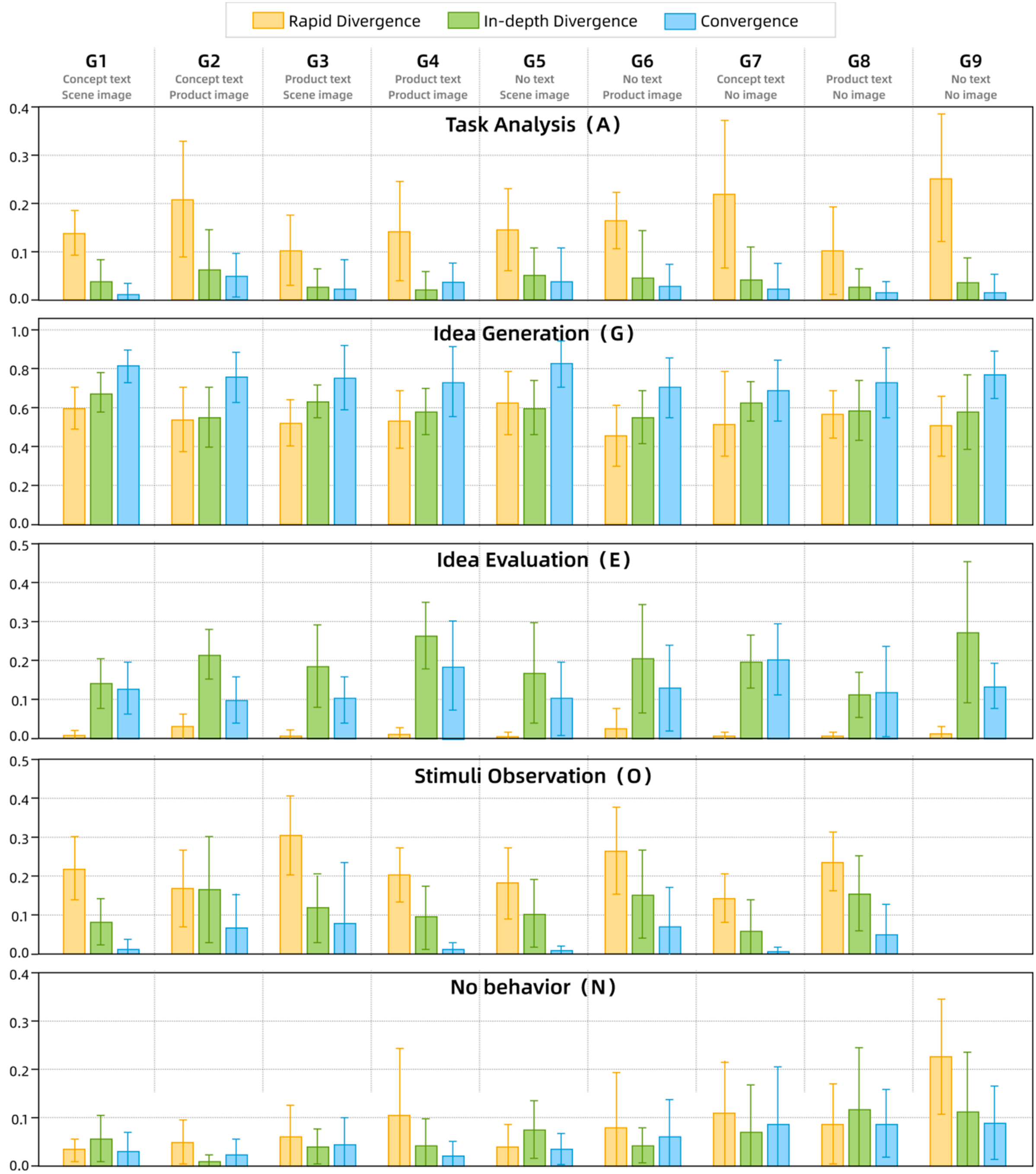

Fig. 10. Behavior coding results.

practicality" (P_9^3). In the Convergence Phase, the time proportion for idea evaluation decreased for all groups, with no clear commonality among groups with higher time proportions (i.e., G4, G7).

Stimulus Observation (O) In the first phase, participants in G3, G6, and G8 spent the highest proportion of time viewing stimuli, but there was no apparent commonality in the stimuli among the groups. For In-depth Divergence, groups with product images (i.e., G2, G6) allocated more time to viewing stimuli. Although all groups allocated less time to stimulus observation in Convergence, groups exposed to product solutions (G2, G3, and G6) spent a relatively higher proportion of time observing stimuli.

No Behavior (N) No observable behavior is likely indicative of a mental stagnation state. In Rapid Divergence, the time proportion for no behavior was lower in G1-G8 than in G9, suggesting that creative stimuli facilitated the progression of conceptual design. However, in the following two phases, G7-G9 exhibited a higher proportion of no behavior, indicating that texts alone were

Group	Text Type	Image Type	Link density between solutions and stimuli					
			Total	P	I	N	A	T
1	Concept text	Scene image	0.69	0.00	0.01	0.18	0.00	0.50
2	Concept text	Product image	0.62	0.00	0.10	0.00	0.05	0.47
3	Product text	Scene image	0.75	0.04	0.37	0.17	0.13	0.04
4	Product text	Product image	0.54	0.03	0.35	0.02	0.03	0.11
5	No text	Scene image	0.51	0.00	0.00	0.50	0.00	0.01
6	No text	Product image	0.49	0.01	0.24	0.02	0.07	0.15
7	Concept text	No image	0.54	0.00	0.00	0.03	0.00	0.50
8	Product text	No image	0.61	0.02	0.38	0.01	0.11	0.09
9	No text	No image	/					

Fig. 11. Link density between ideas and stimuli (darker color means higher density).

Group	Text Type	Image Type	Link density in Rapid Divergence						Link density in In-depth Divergence						Link density in Convergence					
			Total	P	I	N	A	T	Total	P	I	N	A	T	Total	P	I	N	A	T
1	Concept text	Scene image	1.37	0.15	0.15	0.01	0.01	0.89	3.01	0.05	1.02	0.22	0.51	1.21	8.50	0.00	3.75	0.25	2.00	2.50
2	Concept text	Product image	1.14	0.39	0.39	0.00	0.12	0.63	2.38	0.02	0.85	0.00	0.49	1.01	7.71	0.00	3.14	0.00	2.29	2.29
3	Product text	Scene image	1.33	0.67	0.67	0.03	0.18	0.09	3.22	0.02	1.87	0.24	0.81	0.28	7.75	0.00	5.00	0.50	1.88	0.38
4	Product text	Product image	0.98	0.53	0.53	0.01	0.07	0.30	2.68	0.14	1.42	0.03	0.76	0.34	5.38	0.00	3.25	0.00	1.75	0.38
5	No text	Scene image	1.05	0.09	0.09	0.03	0.00	0.21	2.04	0.05	0.46	0.79	0.51	0.23	5.75	0.00	1.63	1.00	2.63	0.50
6	No text	Product image	0.99	0.46	0.46	0.02	0.10	0.38	2.49	0.00	1.15	0.10	0.73	0.50	6.38	0.00	3.88	0.00	1.25	1.25
7	Concept text	No image	1.07	0.22	0.22	0.00	0.03	0.74	2.35	0.03	0.58	0.03	0.78	0.93	5.63	0.13	1.50	0.00	1.88	2.13
8	Product text	No image	1.14	0.54	0.54	0.00	0.17	0.37	3.26	0.09	1.83	0.00	0.89	0.44	6.25	0.13	4.38	0.00	1.38	0.38
9	No text	No image	0.39	0.05	0.05	0.00	0.02	0.33	1.66	0.00	0.60	0.00	0.80	0.26	3.88	0.00	1.75	0.00	1.63	0.50

Fig. 12. Link density in three design phases (darker color means higher density).

insufficient. In comparison, the combination of texts and product images (G2, G4) resulted in a lower proportion of no behavior.

4.2.2. Linkograph

Links between ideas and stimuli Comparing different groups' link density (see Fig. 11), primary findings include: (1) Groups exposed to both texts and scene images (G1, G3) demonstrated the highest link density, suggesting enhanced inspiration for idea generation. (2) Groups with product texts (i.e., G3, G4, G8) exhibited the highest density in parallel links, incremental links, and alternative links, indicating the tendency to generate ideas by directly paraphrasing, modifying, or supplementing the product texts in the stimuli. (3) Groups exposed to scene images (i.e., G1, G3, G5) showed the densest new idea links, indicating that scene images aid in recalling problems related to the design task and generating solutions based on them. (4) Groups with concept texts (i.e., G1, G2, G7) exhibited the densest tangential links, as abstract concepts from texts encourage participants to conceptualize solutions from a cognitive and theoretical perspective.

Link diversity refers to the variety of link types generated by participants, with higher link diversity indicating stimuli's greater effectiveness in inspiring diverse thinking patterns. As illustrated in Fig. 11, participants in G3, G4, G6, and G8 produced all five types of links, indicating higher link diversity.

Density of links across three phases As depicted in Fig. 12, a higher link density suggests that existing solutions have inspired more new ideas, while a higher parallel link density indicates more repetition and a lack of innovation. Therefore, a high overall link density with a low parallel link density suggests the generation of more valuable ideas. Additionally, a high density of tangential links represents the generation of more novel ideas in divergence phases but may indicate a lack of design focus in the Convergence Phase (Hatcher et al., 2018).

In the Rapid Divergence Phase, G1 exhibited the highest overall link density and tangential link density, while G3 showed a relatively high overall link density and the highest parallel link density. Overall, providing concept texts and scene images (G1) led to the generation of more novel and valuable ideas. During the In-depth Divergence Phase, G1, G3, and G8 had the highest overall link density. Specifically, G1 had the highest tangential link density, G3 had a relatively low parallel link density, and G8 had a higher parallel link density. Overall, combinations of scene images with texts effectively stimulated idea generation. For the Convergence Phase, G1-G3 had the highest overall link density, but G1 and G2 also exhibited high tangential link density, indicating a lack of focus in their design process.

		Group	1	2	3	4	5	6	7	8	9
		Type of Text	Concept	Concept	Product	Product	No	No	Concept	Product	No
		Type of Image	Scene	Product	Scene	Product	Scene	Product	No	No	No
Rapid Divergence	Quantity	-	8.13	6.50	8.88	9.25	7.00	7.63	8.25	7.00	6.38
	Participant Ratigns	Novelty	5.00	3.13	4.38	3.50	4.75	3.88	3.63	4.63	4.25
		Practicality	5.25	4.75	4.00	4.75	5.13	5.13	5.25	5.75	4.25
		Diversity	6.13	4.75	5.75	5.13	5.38	4.63	4.50	5.63	5.38
	Expert Ratings	Novelty	0.395	0.303	0.357	0.321	0.425	0.327	0.283	0.372	0.341
		Practicality	0.268	0.259	0.224	0.260	0.247	0.272	0.227	0.249	0.221
		Diversity	0.525	0.396	0.554	0.510	0.658	0.491	0.401	0.533	0.513
In-depth Divergence	Quantity	-	5.13	4.63	5.00	5.38	5.88	4.75	5.38	4.50	4.00
	Participant Ratigns	Novelty	5.38	4.25	5.50	4.88	5.63	4.50	4.38	4.75	4.75
		Practicality	6.00	5.00	5.63	5.13	5.38	5.88	5.00	6.00	4.75
		Diversity	4.63	4.38	5.13	4.63	5.00	4.50	3.63	4.63	3.88
	Expert Ratings	Novelty	0.486	0.427	0.493	0.508	0.477	0.486	0.411	0.441	0.494
		Practicality	0.242	0.196	0.217	0.216	0.220	0.199	0.189	0.278	0.215
		Diversity	0.529	0.513	0.576	0.555	0.549	0.453	0.500	0.431	0.368
Convergence	Participant Ratings	Novelty	6.38	5.38	5.75	5.38	6.00	5.88	4.75	5.13	4.75
		Practicality	5.50	5.13	6.38	6.00	5.63	6.00	5.50	6.13	5.00
	Expert Ratings	Novelty	0.718	0.526	0.680	0.676	0.495	0.580	0.589	0.465	0.611
		Practicality	0.263	0.256	0.273	0.264	0.260	0.223	0.239	0.281	0.266

Highest Rating … Lowest Rating

Fig. 13. Creative stimuli's influence on design outcomes, with numbers representing the average score. For the same phase and dimension, the color indicates the rank of the average score, with deeper blue indicating higher average scores and deeper yellow indicating lower average scores.

5. Discussion

5.1. Creative Stimuli's multifaceted influence on design outcomes

The experiment's findings suggest the essential to provide students with differentiated creative stimuli at various design phases. To facilitate the comparison among the performances of different stimulus combinations across phases and dimensions, quantitative data are summarized in Fig. 13.

Firstly, the participant and expert ratings are somewhat inconsistent. For instance, during Convergence, G5's participants perceived their ideas as highly novel, contrary to expert opinions. This could be due to the subjective nature of creativity, which is influenced by individual preferences despite the availability of well-recognized evaluation metrics. Such difference should be taken seriously, as design students' and experts' perceived creativity of design proposals are both pivotal in a product's transition from concept to realization (Dell'Era et al., 2020). Some creative stimuli can inspire students to generate ideas recognized by professionals, but according to the Creative Flow Theory, students' own perception in the design process affects their motivation and enthusiasm in subsequent development and refinement processes (Csikszentmihalyi et al., 2014). Conversely, students may feel inspired by certain stimuli yet receive limited recognition from experts. Through a comprehensive assessment combining student and expert perspectives, we aim to identify creative stimulus combinations mutually recognized by both parties. Such consensus is crucial in real design processes, as students' perception of creativity impacts their creative motivation, and expert evaluations influence the feasibility and market acceptance of design proposals.

Combining both participant and expert ratings (Fig. 13), G1 performed well overall in Rapid Divergence. G1's students can recall past experiences through scene images and then combine concept texts to envision possible product forms. Meanwhile, students can associate possible product types through concept texts to consider these products' problems in actual settings based on scene images. For In-depth Divergence, G1 and G3 performed better because scene images trigger students' inspiration through contextualization (Thrash et al., 2014), help them review overlooked issues in their ideas, expand the usage scenarios of the ideas, and optimize the ideas based on actual usage experiences. Additionally, G1's concept texts further promoted divergent thinking among students, while G3's product texts helped students supplement the functional details of their design proposals. In Convergence, students in G3 and G4 performed better as they tended to extract specific functions from product texts and integrate them into their own design proposals, thereby realizing the extension of inspiration according to the transmission model (Thrash and Elliot, 2004). The simultaneous presence of product texts and images (G4) further helped students envision the form, appearance, and structure of a product. Revisiting prior research on the timing of stimuli introduction (Damadzic and Medeiros, 2022), our findings further revealed that whether stimuli are constraints or triggers evolves over phases. For instance, while G3's scene images predominantly acted as triggers to facilitate idea iteration during In-depth Divergence, these images tended to serve more as constraints in Convergence to help students filter out more practical ideas with consideration of real usage scenarios.

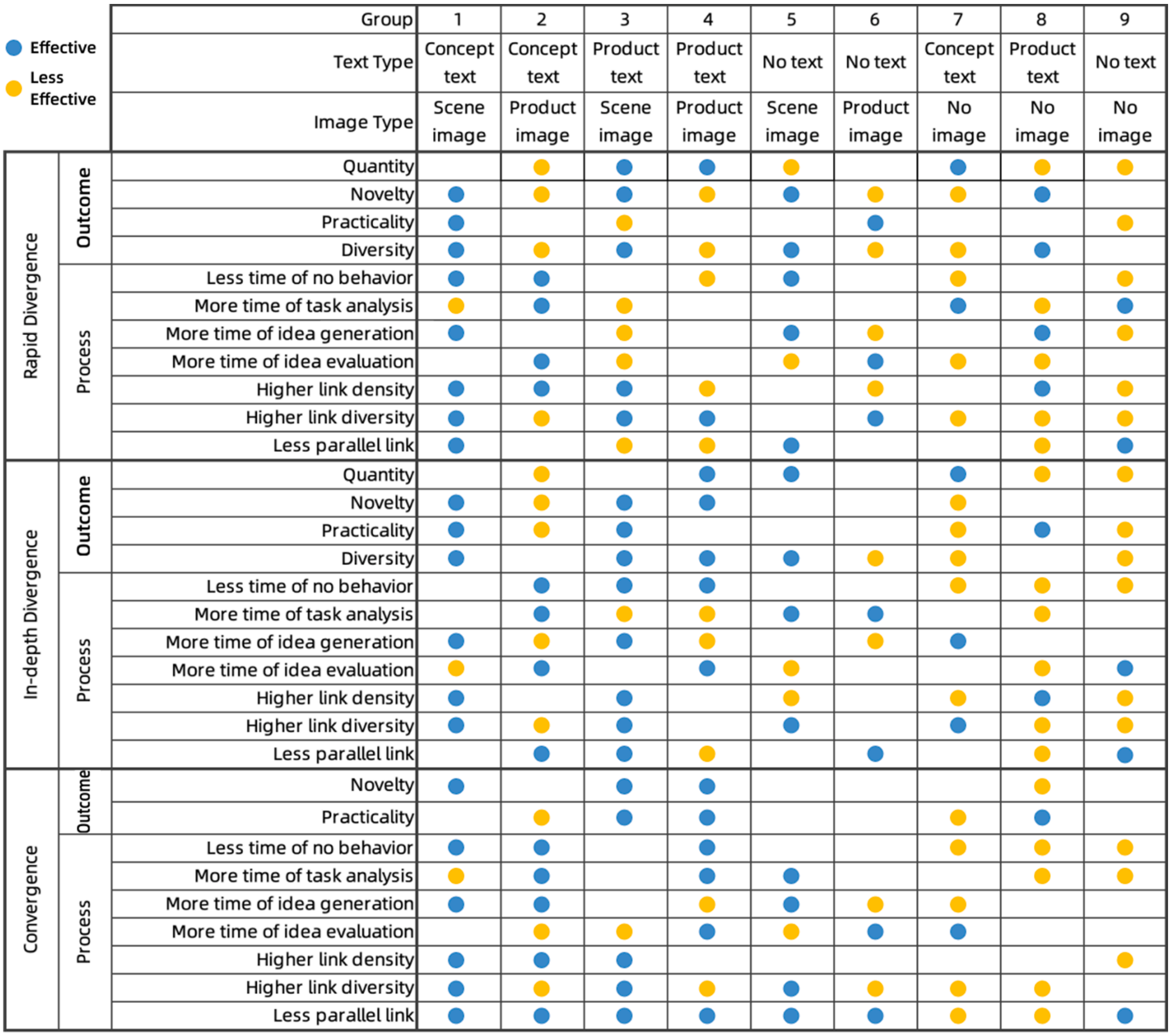

Fig. 14. Different stimulus combinations' performance in design outcomes and process.

Furthermore, we observe subtle changes in the effectiveness of creative stimuli as the conceptual design progresses. As students delve deeper, they require more specific and concrete stimuli, and the assistance of abstract stimuli gradually diminishes. For example, the combination of concept texts and scene images (G1) performed well in both divergent phases but scored lower in practicality during Convergence, while the combination of product texts and product images (G4) showed a contrary tendency. This finding illustrates that presenting stimuli as constraints in later design phases does not necessarily have negative effects as indicated by prior work (Medeiros et al., 2017), with the specific impact largely depending on stimuli's types. We also find that the blank control group (G9) generally underperformed in the first two phases, but in Convergence, G9's expert ratings surprisingly surpassed most groups. This is possibly because students' ideas were already well-formed during Convergence, and thus the influence of creative stimuli on the novelty and practicality was minimal.

Moreover, there is no stimulus combination with absolute superiority, and multimodal stimuli do not necessarily always outperform unimodal stimuli. For instance, in Rapid Divergence, the group presenting only product images (G8) performed better than the two groups with multimodal creative stimuli (G2, G4), suggesting that the fidelity of texts and images in multimodal stimuli need to be aligned to achieve better results. For example, concept texts should appear with scene images because students struggle to directly convert concept texts into ideas when they are displayed alone or with products images. Scene images help students comprehend the relatively abstract concept texts and provide them with a direction for conceptualization. Although product images have a similar effect, students are more inclined to view concept texts as an explanation of product images and may not diverge further based on the concepts, thus leading to lower creativity in G2.

5.2. Stimuli for creative outcomes or process

Different stimulus combinations' impact on design outcomes and the design process is illustrated in Fig. 14, distinguishing between effective (blue) and less effective (yellow) combinations. For outcomes, effective combinations exceed the median in both expert and participant ratings, while less effective combinations fall below the median. Regarding the design process, the time allocation and link density for each group are ranked, with the first four deemed effective and the last four considered less effective.

The varied performance of the same combination underscores the importance of considering design objectives comprehensively and selecting appropriate stimulus combinations. While previous work mostly focuses on stimuli's effects on the creativity of outcomes, these effective stimuli may not be suitable from the perspective of the design process. Overall, no single stimulus combination can simultaneously address all aspects of design outcomes and process. Particularly, there is a certain negative correlation among the time allocations for various design behaviors. Future research can integrate findings in Fig. 14 and select creative stimuli based on actual design objectives. Specifically:

- Rapid Divergence: G1's stimuli enhance design outcomes' creativity and facilitate most process indicators, albeit reducing time spent on task analysis. To facilitate task analysis, options include providing no stimuli, concept texts alone, or both concept texts and product images.
- In-depth Divergence: stimuli in both G1 and G3 foster creativity in design outcomes but may affect the time allocation for task analysis and idea evaluation. To increase time allocation of task analysis without compromising design outcomes, using scene images alone could be considered. Moreover, combining product texts and images enhances idea quantity, novelty, and diversity while facilitating idea evaluation, albeit at reducing the time for task analysis and idea generation.
- Convergence: stimuli from G3 and G4 enhance creativity in design outcomes but lead to less time for idea evaluation and idea generation, respectively. To facilitate these process indicators, considering the combination of concept texts and scene images may be beneficial.

5.3. Necessity of dynamically providing creative stimuli

This study reveals the varying effects of creative stimulus combinations on different conceptual design phases, underscoring the necessity to dynamically provide creative stimuli throughout the design process. First, the provided stimuli should be catered to the specific design phases. For instance, the experiment findings suggest providing a combination of scene images and concept texts during Rapid Divergence and transitioning to more concrete product-related stimuli during Convergence. Second, the term "dynamic" here also implies the provision of stimuli that align with specific design tasks. Given that current creativity stimulation tools (Darzentas et al., 2019; Lomas et al., 2021) commonly provide stimuli of fixed content and fidelity, a potential avenue for future research is how to dynamically adjust and provide creative stimuli based on different design tasks. Furthermore, educators are suggested to adjust the types of presented creative stimuli based on education objectives. For instance, according to the behavior coding, concept texts and product images are suitable for students weak in task analysis, encouraging them to allocate more time to this process.

In addition, the provided types of stimuli should also adjust with students' state. We notice that students' openness attitude for more active information acquisition, in addition to being aroused by the difficulty they encountered as the prepared mind theory (Seifert et al., 1995) suggested, can also be invoked by the external stimuli. For example, the behavior coding reveals that the group with scene images and product texts (G3) spent most time observing stimuli in Rapid Divergence and demonstrated a high link density. This is possibly because the scene images brought students in a non-focused state (Liu et al., 2022), preparing them for absorbing and integrating the information from the provided stimuli. From this view, dynamically providing stimuli serve as the supplement to the prepared mind theory, which stimulates students in stuck through inspiration triggers while remains students open-minded to external information even when they do not encounter difficulties. To achieve this, it is essential to establish a dynamic mechanism for presenting the most beneficial creative stimuli according to students' current state, which demands further investigation and experimentation.

5.4. Limitations and future work

Given the scope of this paper, our research also has some limitations. First, this study only considered the modality and fidelity of creative stimuli, without exploring other factors like semantic distance, novelty, and quantity. While we have explained our reasons for prioritizing modality and fidelity of creative stimuli in Section 3.1, future work could further investigate how other characteristics of creative stimuli, influence conceptual design building upon the methodology and conclusion of this study.

Apart from that, this study only involved stimuli in modalities of texts and images, without including other types such as sketches, 3D models, and videos. High-fidelity product images, compared to sketches, provide more detailed information on materials, shapes, and structures of a product, offering richer stimuli for students. Although sketches are important materials for students to engage in reflective dialogues, high-fidelity images remain commonly used in most research (Paay et al., 2023; Vasconcelos et al., 2017) and better align with students' prevalent demand. While videos and 3D models have been proven effective, their limited availability may not meet the diverse requirements of design tasks. However, some existing research (Kwon et al., 2023) has begun constructing datasets for 3D model creative stimuli, opening avenues for future studies across various modalities.

Moreover, the impact of creative stimuli on creativity exhibits individual differences. As inspiration derives from individuals' reaction to the stimuli rather than the stimulation itself (Thrash et al., 2014), the effectiveness of creative stimuli is influenced by the student's information utilization capabilities, professional background, and design thinking process. While this study provided recommendations for stimulus combinations at different design phases through a comparative experiment, these suggestions may not universally apply to all students. Future research should clarify the differential effects of creative stimuli on individuals and provide more targeted creative stimuli based on these differences.

Additionally, the complexity of conceptual design highlights some aspects worth further exploration. Firstly, in early design phases, students often need to conduct extensive information retrieval and screening, so the quantity of stimuli in the experiment may not fully meet their needs. Despite that, our experiment rigorously controlled for irrelevant variables and included a blank control group, and the number of stimuli provided aligns with quantities in previous research (Chan et al., 2011; Paay et al., 2023), which guaranteed the reliability of results. Future studies could assess the impact of larger stimulus quantities on students' performance. Secondly, this study was conducted under experimental conditions, which may differ from real-world design scenarios. However, controlling for irrelevant variables in the real world is challenging, making it difficult to rigorously compare different stimulus combinations' effects. Based on our findings, future research could validate these creative stimulus combinations' effectiveness in more realistic design scenarios through methods such as design workshops and field experiments.

6. Conclusion

This study aims to explore how creative stimuli of distinct modalities and fidelities impact different conceptual design phases, fostering more suitable application of creative stimuli in conceptual design. To achieve this, we conducted a 3×3 experiment with 72 design students, assessing stimuli's influence on design outcomes through measures including quantity, novelty, practicality, and diversity, as well as on design process using behavior coding and linkograph analysis. This research has three primary contributions.

Firstly, our investigation into design outcomes reveals creative stimuli's multifaceted influence and reflects on their variations in different design phases and combinations, which extends prior work that mostly focuses on a certain design phase and stimulus type. We also observe mutual influence between the fidelity of texts and images, for instance, combining concept texts with scene images and product images sometimes yielding contradictory effects. Revisiting the Memi C framework, this finding further illustrates that episodic memory and semantic memory are not isolated. Conversely, they may either promote or inhibit each other, depending on the type of stimuli.

Secondly, we have elucidated how different stimulus combinations affect students' behavior and cognitive patterns, as evident by behavior coding and linkograph analysis. For instance, concrete stimuli may limit students' in-depth task analysis early in the design process, while impacting students' time allocation for idea generation and evaluation. This finding could assist design educators in preparing appropriate types of stimuli based on their educational objectives. We also find that scene images are more effective in prompting students to generate ideas from the design problem (more new idea links), while concept texts stimulate students to discover new solutions through cognitive association (more tangential links).

Thirdly, by synthesizing creative stimuli's impact on both design outcomes and process, we emphasize the necessity of dynamically providing stimuli during conceptual design. This research highlights that there are no universally applicable stimuli in the conceptual design process, and their effectiveness depends on factors including the design objectives and current design phase. As a supplement to the prepared mind theory, dynamically providing stimuli based on students' state is also essential to keep them open-minded for external information. These insights provide practical evidence and directions for future research and underscore the need for tailored stimulus strategies in design education.

CRediT authorship contribution statement

Pei Chen: Writing – original draft, Writing – review & editing. **Zhuoshu Li:** Writing – review & editing, Writing – original draft, Visualization, Project administration, Data curation, Conceptualization. **Yexinrui Wu:** Methodology, Investigation, Formal analysis, Data curation. **Hongbo Zhang:** Writing – review & editing. **Jiaxuan Zhou:** Investigation, Data curation. **Lingyun Sun:** Supervision, Funding acquisition.

Acknowledgments

This work was supported by the National Key R&D Program of China (2022YFB3303301).

Appendix A. Creative Stimuli Provided in Experiment

Fig. A.1 depicts the eight sets of creative stimuli provided to participants in the experiment. For G1-G8, each set of stimuli is combined according to the specified fidelity of texts and images in each group.

No.	Text Stimuli		Image Stimuli	
	Concept Text	Product Text	Scene Image	Product Image
1	Exercising thr-ough jumping	A cordless jump rope with adjustable rope length, featuring ball-shaped weights on the handles to increase resistance and enhance fat-burning effects. It has fun-ctions such as timing and counting, and can record exercise data for each session.		
2	Adapting to personalized exercise needs	An intelligent fitness mirror with a wide-angle camera for posture capture, AI-powered movement guidance, and adaptive training content.		
3	Transmitting signals from people to devices	A wearable fitness tracker that monitors heart rate, distance, and other metrics in real-time, and alerts the user in case of abnormal data.		
4	Training core strength for abdominals	A smart ab roller with assistance for crunches and planks, featuring an inte-grated braking and rebound system. Designed with a tire-like tread pattern for secure, non-slip performance.		
5	Alleviating muscle fatigue after exercise	A wearable vibrating heating device with adhesive backing, allowing attachment to various body parts. Controlled via smartphone for customizable vibration and heating modes.		
6	Utilizing equipment to drive human movement	A smart treadmill with excellent shock absorption and noise reduction, capable of adjusting speed according to the runner's stride frequency. Foldable for easy storage when not in use.		
7	Achieving shaping goals through waist fat reduction	A smart hula hoop with multiple vibration modules for fat burning. Features detachable modules that can be adjusted in number to fit various body types.		
8	Engaging in certain outdo-or activities indoors	A smart exercise bike that offers music playback and beat-synced cycling. It allows for the setting of various resistances and automatically adjusts resistance based on the user's workout intensity.		

Fig. A1. Creative stimuli provided in experiment.

Appendix B. Design Solution Sheets

Fig. B.1-B.3 show the design solution sheet in Rapid Divergence, In-depth Divergence, and Convergence, respectively. Each design solution sheet includes an introduction of the design task and the design requirements in this phase.

Rapid Divergence Group_____ Participant No._______ Name________

For many people, exercise is an activity that relieves stress and strengthens the body. Your task is to design an exercise aid for fitness enthusiasts to help them improve their exercise results or experience, and the product should meet the following requirements:
(1) Ensure exercise safety and avoid potential risks; (2) Be easy to use and operate, with a low learning curve.

You have 12 minutes to brainstorm design ideas based on the design task. During this time, you need to come up with as many design proposals as possible without considering too many details of the proposals.

Idea 1	Idea 2	Idea 3	Idea 4
Idea 5	**Idea 6**	**Idea 7**	**Idea 8**
Idea 9	**Idea 10**	**Idea 11**	**Idea 12**

Fig. B1. Design solution sheet in Rapid Divergence.

In-depth Divergence Group_____ Participant No._______ Name________

For many people, exercise is an activity that relieves stress and strengthens the body. Your task is to design an exercise aid for fitness enthusiasts to help them improve their exercise results or experience, and the product should meet the following requirements:
(1) Ensure exercise safety and avoid potential risks; (2) Be easy to use and operate, with a low learning curve.

You have 12 minutes to further develop the ideas from the previous stage. You can choose to refine, iterate, or further expand upon some of the proposals.

Idea 1 from________	Idea 2 from________	Idea 3 from________	Idea 4 from________
Idea 5 from________	**Idea 6** from________	**Idea 7** from________	**Idea 8** from________
Idea 9 from________	**Idea 10** from________	**Idea 11** from________	**Idea 12** from________

Fig. B2. Design solution sheet in In-depth Divergence.

Convergence

Group_________ Participant No_________ Name_________

For many people, exercise is an activity that relieves stress and strengthens the body. Your task is to design an exercise aid for fitness enthusiasts to help them improve their exercise results or experience, and the product should meet the following requirements:
(1) Ensure exercise safety and avoid potential risks;
(2) Be easy to use and operate, with a low learning curve.

You have 8 minutes to converge on a final design solution. You can iterate, combine, or refine the proposals from the previous two stages, taking into account the novelty and practicality of the solutions, and generate a final design proposal.

Design Solution

(caption on next page)

Fig. B3. Design solution sheet in Convergence.

Data availability

Data will be made available on request.

References

Agogué, M., Kazakçi, A., Hatchuel, A., Le Masson, P., Weil, B., Poirel, N., & Cassotti, M. (2014). The impact of type of examples on originality: Explaining fixation and stimulation effects. *The Journal of Creative Behavior, 48*(1), 1–12. https://doi.org/10.1002/jocb.37

Alipour, L., Faizi, M., Moradi, A. M., & Akrami, G. (2018). A review of design fixation: research directions and key factors. *International Journal of Design Creativity and Innovation, 6*(1-2), 22–35. https://doi.org/10.1080/21650349.2017.1320232

Benami, O., & Jin, Y. (2008). *Creative Stimulation in Conceptual Design* (pp. 251–263). https://doi.org/10.1115/DETC2002/DTM-34023

Benedek, M., Beaty, R. E., Schacter, D. L., & Kenett, Y. N. (2023). The role of memory in creative ideation. *Nature Reviews Psychology, 2*(4), 246–257. https://doi.org/10.1038/s44159-023-00158-z

Borgianni, Y., Rotini, F., & Tomassini, M. (2017). Fostering ideation in the very early design phases: How textual, pictorial and combined stimuli affect creativity. *DS 87-8 Proceedings of the 21st International Conference on Engineering Design (ICED 17) Vol 8: Human Behaviour in Design, Vancouver, Canada, 21-25.08.2017*, 139–148. ISBN: 9781904670964

Broek, J. J., Sleijffers, W., Horváth, I., & Lennings, A. F. (2000). Using physical models in design. *Proceedings of 3rd international conference on computer-aided industrial design and conceptual design*.

Chan, J., Dow, S. P., & Schunn, C. D. (2015). Do the best design ideas (really) come from conceptually distant sources of inspiration? *Design Studies, 36*, 31–58. https://doi.org/10.1016/j.destud.2014.08.001

Chan, J., Fu, K., Schunn, C., Cagan, J., Wood, K., & Kotovsky, K. (2011). On the Benefits and Pitfalls of Analogies for Innovative Design: Ideation Performance Based on Analogical Distance, Commonness, and Modality of Examples. *Journal of Mechanical Design, 133*(081004). https://doi.org/10.1115/1.4004396

Chiu, I., & Shu, L. H. (2012). Investigating effects of oppositely related semantic stimuli on design concept creativity. *Journal of Engineering Design, 23*(4), 271–296. https://doi.org/10.1080/09544828.2011.603298

Crilly, N. (2015). Fixation and creativity in concept development: The attitudes and practices of expert designers. *Design Studies, 38*, 54–91. https://doi.org/10.1016/j.destud.2015.01.002

Csikszentmihalyi, M. (1996). *Creativity: The work and lives of 91 eminent people*. HarperCollins.

Csikszentmihalyi, M. (1997). Flow and the psychology of discovery and invention. *HarperPerennial, New York, 39*, 1–16.

Csikszentmihalyi, M., Csikszentmihalyi, M., Abuhamdeh, S., & Nakamura, J. (2014). *Flow and the foundations of positive psychology: The collected works of Mihaly Csikszentmihalyi*. Springer.

Czikszentmihalyi, M. (1990). *Flow: The psychology of optimal experience*. New York: Harper & Row.

Dahl, D. W., & Moreau, P. (2002). The Influence and Value of Analogical Thinking during New Product Ideation. *Journal of Marketing Research, 39*(1), 47–60. https://doi.org/10.1509/jmkr.39.1.47.18930

Damadzic, A., & Medeiros, K. (2022). The balancing act: An empirical study introducing and removing constraints in idea generation. *Psychology of Aesthetics, Creativity, and the Arts, 16*(4), 665. https://doi.org/10.1037/aca0000355

Darzentas, D., Velt, R., Wetzel, R., Craigon, P. J., Wagner, H. G., Urquhart, L. D., & Benford, S. (2019). Card Mapper: Enabling Data-Driven Reflections on Ideation Cards. *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems* (pp. 1–15). https://doi.org/10.1145/3290605.3300801CHI '19

Dell'Era, C., Magistretti, S., Cautela, C., Verganti, R., & Zurlo, F. (2020). Four kinds of design thinking: From ideating to making, engaging, and criticizing. *Creativity and innovation management, 29*(2), 324–344. https://doi.org/10.1111/caim.12353

Design Council (2005). The Double Diamond Process Model. https://www.designcouncil.org.uk/our-resources/the-double-diamond/.

Dybvik, H., Abelson, F. G., Aalto, P., Goucher-Lambert, K., & Steinert, M. (2022). Inspirational Stimuli Improve Idea Fluency during Ideation: A Replication and Extension Study with Eye-Tracking. *Proceedings of the Design Society, 2*, 861–870. https://doi.org/10.1017/pds.2022.88

Eckert, C., Stacey, M., & Earl, C. (2005). References to past designs. *Studying Designers '05*, 3–21.

Eysenck, H. J. (1994). The measurement of creativity. *Dimensions of creativity* (pp. 199–242).Cambridge, MA, US

Ezzat, H., Agogué, M., Le Masson, P., Weil, B., & Cassotti, M. (2020). Specificity and Abstraction of Examples: Opposite Effects on Fixation for Creative Ideation. *The Journal of Creative Behavior, 54*(1), 115–122. https://doi.org/10.1002/jocb.349

Farh, J.-L., Lee, C., & Farh, C. I. (2010). Task conflict and team creativity: a question of how much and when. *Journal of applied psychology, 95*(6), 1173. https://doi.org/10.1007/s10490-021-09771-z

Fernandes, R. B., & Ogliari, A. (2018). Enhancing creativity through Biological Stimuli during new products ideation. *International Journal for Innovation Education and Research, 6*(10), 332–350. https://doi.org/10.31686/ijier.vol6.iss10.1200Number: 10

Fu, K., Chan, J., Cagan, J., Kotovsky, K., Schunn, C., & Wood, K. (2013). The Meaning of "Near" and "Far": The Impact of Structuring Design Databases and the Effect of Distance of Analogy on Design Output. *Journal of Mechanical Design, 135*(021007). https://doi.org/10.1115/1.4023158

Goldschmidt, G., & Sever, A. L. (2011). Inspiring design ideas with texts. *Design Studies, 32*(2), 139–155. https://doi.org/10.1016/j.destud.2010.09.006

Goldschmidt, G., & Tatsa, D. (2005). How good are good ideas? Correlates of design creativity. *Design Studies, 26*(6), 593–611. https://doi.org/10.1016/j.destud.2005.02.004

Gomes, M. G., Ogliari, A., Fernandes, R. B., & Marques, K. O. (2022). Evaluation of physical models as creative stimuli in conceptual design of products. *Design Studies, 81*, Article 101119. https://doi.org/10.1016/j.destud.2022.101119

Gonçalves, M., Cardoso, C., & Badke-Schaub, P. (2012). *Find Your Inspiration: Exploring Different Levels of Abstraction in Textual Stimuli*.

Gonçalves, M., Cardoso, C., & Badke-Schaub, P. (2014). What inspires designers? Preferences on inspirational approaches during idea generation. *Design Studies, 35*(1), 29–53. https://doi.org/10.1016/j.destud.2013.09.001

Gonçalves, M., & Cash, P. (2021). The life cycle of creative ideas: Towards a dual-process theory of ideation. *Design Studies, 72*, Article 100988. https://doi.org/10.1016/j.destud.2020.100988

Guilford, J. P. (1956). The structure of intellect. *Psychological Bulletin, 53*(4), 267–293. https://doi.org/10.1037/h0040755

Hatcher, G., Ion, W., Maclachlan, R., Marlow, M., Simpson, B., Wilson, N., & Wodehouse, A. (2018). Using linkography to compare creative methods for group ideation. *Design Studies, 58*, 127–152. https://doi.org/10.1016/j.destud.2018.05.002

Haught-Tromp, C. (2017). The green eggs and ham hypothesis: How constraints facilitate creativity. *Psychology of Aesthetics, Creativity, and the Arts, 11*(1), 10. https://doi.org/10.1037/aca0000061

Herring, S., Jones, B., & Bailey, B. (2009). Idea Generation Techniques among Creative Professionals. *2009 42nd Hawaii International Conference on System Sciences* (pp. 1–10). https://doi.org/10.1109/HICSS.2009.241ISSN: 1530-1605

Holyoak, K. J., & Koh, K. (1987). Surface and structural similarity in analogical transfer. *Memory & Cognition, 15*(4), 332–340. https://doi.org/10.3758/BF03197035

Howard, T. J., Culley, S. J., & Dekoninck, E. (2008). Describing the creative design process by the integration of engineering design and cognitive psychology literature. *Design Studies, 29*(2), 160–180. https://doi.org/10.1016/j.destud.2008.01.001

Howard, T. J., Dekoninck, E. A., & Culley, S. J. (2010). The use of creative stimuli at early stages of industrial product innovation. *Research in Engineering Design, 21*(4), 263–274. https://doi.org/10.1007/s00163-010-0091-4

Huang, L., Gino, F., & Galinsky, A. D. (2015). The highest form of intelligence: Sarcasm increases creativity for both expressers and recipients. *Organizational Behavior and Human Decision Processes, 131*, 162–177. https://doi.org/10.1016/j.obhdp.2015.07.001

Jansson, D. G., & Smith, S. M. (1991). Design fixation. *Design Studies, 12*(1), 3–11. https://doi.org/10.1016/0142-694X(91)90003-F

Kang, H. B., Amoako, G., Sengupta, N., & Dow, S. P. (2018). Paragon: An Online Gallery for Enhancing Design Feedback with Visual Examples. *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems* (pp. 1–13). https://doi.org/10.1145/3173574.3174180CHI '18

Kazakci, A. O., Gillier, T., Piat, G., & Hatchuel, A. (2015). Brainstorming vs. creative design reasoning: a theory-driven experimental investigation of novelty, feasibility and value of ideas. *Design computing and cognition'14* (pp. 173–188). Springer. https://doi.org/10.1007/978-3-319-14956-1_10

Kim, E., & Kim, K. (2015). Cognitive styles in design problem solving: Insights from network-based cognitive maps. *Design Studies, 40*, 1–38. https://doi.org/10.1016/j.destud.2015.05.002

Koronis, G., Casakin, H., & Silva, A. (2021). Crafting briefs to stimulate creativity in the design studio. *Thinking Skills and Creativity, 40*, Article 100810. https://doi.org/10.1016/j.tsc.2021.100810

Koronis, G., Silva, A., Siang, J. K. K., & Yogiaman, C. (2022). A study on the link between design brief structure and stimulus fidelity to optimize novelty and usefulness. *AI EDAM, 36*, Article e5. https://doi.org/10.1017/S0890060421000378

Kulkarni, C., Dow, S. W., & Klemmer, S. R. (2012). Early and Repeated Exposure to Examples Improves Creative Work. *Annual Meeting of the Cognitive Science Society*. https://doi.org/10.1007/978-3-319-01303-9_4

Kwon, E., Rao, V., & Goucher-Lambert, K. (2023). Understanding inspiration: Insights into how designers discover inspirational stimuli using an ai-enabled platform. *Design Studies, 88*, Article 101202. https://doi.org/10.1016/j.destud.2023.101202

Liu, Q., Chen, J., Wang, W., & Qin, Q. (2021). Conceptual Design Evaluation Considering Confidence Based on Z-AHP-TOPSIS Method. *Applied Sciences, 11*(16), 7400. https://doi.org/10.3390/app11167400

Liu, W., Dempo, A., Kimura, T., Kawashima, T., & Shinohara, K. (2022). Effects of the presence of a cell phone and exposure to natural environments on remote associates task performance. *Scientific Reports, 12*, 9507. https://doi.org/10.1038/s41598-022-13634-y

Liu, Y. C., Chakrabarti, A., & Bligh, T. (2003). Towards an 'ideal' approach for concept generation. *Design Studies, 24*(4), 341–355. https://doi.org/10.1016/S0142-694X(03)00003-6

Lomas, J. D., Karac, M., & Gielen, M. (2021). Design Space Cards: Using a Card Deck to Navigate the Design Space of Interactive Play. *Proceedings of the ACM on Human-Computer Interaction, 5*, 227:1–227:21. https://doi.org/10.1145/3474654

Malaga, R. A. (2000). The effect of stimulus modes and associative distance in individual creativity support systems. *Decision Support Systems, 29*(2), 125–141. https://doi.org/10.1016/S0167-9236(00)00067-1

Medeiros, K. E., Watts, L. L., & Mumford, M. D. (2017). Thinking inside the box: Educating leaders to manage constraints. *Handbook of research on creative problem-solving skill development in higher education* (pp. 25–50). IGI Global. https://doi.org/10.4018/978-1-5225-0643-0.ch002

Moral-Bofill, L., Llave, A. L.d.l., & Pérez-Llantada, M. C. (2020). Relationships between high ability (gifted) and flow in music performers: pilot study results. *Sustainability, 12*(10), 4289. https://doi.org/10.3390/su12104289

Moss, J., Kotovsky, K., & Cagan, J. (2007). The influence of open goals on the acquisition of problem-relevant information. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 33*(5), 876–891. https://doi.org/10.1037/0278-7393.33.5.876

Moss, J., Kotovsky, K., & Cagan, J. (2011). The effect of incidental hints when problems are suspended before, during, or after an impasse. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 37*(1), 140–148. https://doi.org/10.1037/a0021206

Nijstad, B. A., & Stroebe, W. (2006). How the Group Affects the Mind: A Cognitive Model of Idea Generation in Groups. *Personality and Social Psychology Review, 10*(3), 186–213. https://doi.org/10.1207/s15327957pspr1003_1

Paay, J., Kjeldskov, J., Bønnerup, M., & Rasenthiran, T. (2023). Sketching and context: Exploring creativity in idea generation groups. *Design Studies, 84*, Article 101159. https://doi.org/10.1016/j.destud.2022.101159

Perkins, D. N. (1997). Creativity's camel: The role of analogy in invention. In *Creative thought: An investigation of conceptual structures and processes* (p. 538). https://doi.org/10.1037/10227-019Washington, DC, US

Perttula, M., & Sipilä, P. (2007). The idea exposure paradigm in design idea generation. *Journal of Engineering Design, 18*(1), 93–102. https://doi.org/10.1080/09544820600679679

Purcell, A. T., & Gero, J. S. (1996). Design and other types of fixation. *Design studies, 17*(4), 363–383. https://doi.org/10.1016/S0142-694X(96)00023-3

Ruiz-Pastor, L., Chulvi, V., Royo, M., & Sampaio, J. N. (2023). Bio-inspired design as a solution to generate creative and circular product concepts. *International Journal of Design Creativity and Innovation, 11*(1), 42–61. https://doi.org/10.1080/21650349.2022.2128886

Sarica, S., Luo, J., & Wood, K. L. (2020). TechNet: Technology semantic network based on patent data. *Expert Systems with Applications, 142*, Article 112995. https://doi.org/10.1016/j.eswa.2019.112995

Sarkar, P., & Chakrabarti, A. (2011). Assessing design creativity. *Design Studies, 32*(4), 348–383. https://doi.org/10.1016/j.destud.2011.01.002

Seifert, C., Meyer, D., Davidson, N., Patalano, A., & Yaniv, I. (1995). Demystification of cognitive insight: Opportunistic assimilation and the prepared- mind perspective. *The nature of insight*, 65–124.

Shi, Y., Wang, Y., Qi, Y., Chen, J., Xu, X., & Ma, K.-L. (2017). IdeaWall: Improving Creative Collaboration through Combinatorial Visual Stimuli. *Proceedings of the 2017 ACM Conference on Computer Supported Cooperative Work and Social Computing* (pp. 594–603). https://doi.org/10.1145/2998181.2998208CSCW '17

Sio, U. N., Kotovsky, K., & Cagan, J. (2015). Fixation or inspiration? A meta-analytic review of the role of examples on design processes. *Design Studies, 39*, 70–99. https://doi.org/10.1016/j.destud.2015.04.004

Song, H. I., Lopez, R., Fu, K., & Linsey, J. (2017). Characterizing the Effects of Multiple Analogs and Extraneous Information for Novice Designers in Design-by-Analogy. *Journal of Mechanical Design, 140*(031101). https://doi.org/10.1115/1.4038565

Srinivasan, V., Song, B., Luo, J., Subburaj, K., Elara, M. R., Blessing, L., & Wood, K. (2018). Does Analogical Distance Affect Performance of Ideation? *Journal of Mechanical Design, 140*(071101). https://doi.org/10.1115/1.4040165

Thagard, P. (2005). *Mind, second edition: Introduction to Cognitive Science*.Google-Books-ID: gjcR1U2HT7kC

Thrash, T. M., & Elliot, A. J. (2003). Inspiration as a psychological construct. *Journal of personality and social psychology, 84*(4), 871. https://doi.org/10.1037/0022-3514.84.4.871

Thrash, T. M., & Elliot, A. J. (2004). Inspiration: core characteristics, component processes, antecedents, and function. *Journal of personality and social psychology, 87*(6), 957. https://doi.org/10.1037/0022-3514.87.6.957

Thrash, T. M., Elliot, A. J., Maruskin, L. A., & Cassidy, S. E. (2010a). Inspiration and the promotion of well-being: tests of causality and mediation. *Journal of personality and social psychology, 98*(3), 488. https://doi.org/10.1037/a0017906

Thrash, T. M., Maruskin, L. A., Cassidy, S. E., Fryer, J. W., & Ryan, R. M. (2010b). Mediating between the muse and the masses: Inspiration and the actualization of creative ideas. *Journal of personality and social psychology, 98*(3), 469. https://doi.org/10.1037/a0017907

Thrash, T. M., Moldovan, E. G., Oleynick, V. C., & Maruskin, L. A. (2014). The psychology of inspiration. *Social and personality psychology compass, 8*(9), 495–510. https://doi.org/10.1111/spc3.12127

Toh, C., & Miller, S. (2014). The impact of example modality and physical interactions on design creativity. *Journal of Mechanical Design, Transactions of the ASME, 136*(9). https://doi.org/10.1115/1.4027639

Tromp, C. (2023). Integrated constraints in creativity: Foundations for a unifying model. *Review of General Psychology, 27*(1), 41–61. https://doi.org/10.1177/10892680211060027

Tromp, C., & Baer, J. (2022). Creativity from constraints: Theory and applications to education. *Thinking Skills and Creativity, 46*, Article 101184. https://doi.org/10.1016/j.tsc.2022.101184

Tromp, C., & Baer, J. (2024). Focusing the search for creative outcomes in stem education: The role of constraints. *Exploring perspectives on creativity theory and research in education* (pp. 23–38). Springer. https://doi.org/10.1007/978-3-031-55416-2

Tromp, C., & Sternberg, R. J. (2022). How constraints impact creativity: An interaction paradigm. *Psychology of Aesthetics, Creativity, and the Arts*. https://doi.org/10.1037/aca0000493

Vasconcelos, L. A., Cardoso, C. C., Sääksjärvi, M., Chen, C.-C., & Crilly, N. (2017). Inspiration and Fixation: The Influences of Example Designs and System Properties in Idea Generation. *Journal of Mechanical Design, 139*. https://doi.org/10.1115/1.4035540

Vasconcelos, L. A., & Crilly, N. (2016). Inspiration and fixation: Questions, methods, findings, and challenges. *Design Studies, 42*, 1–32. https://doi.org/10.1016/j.destud.2015.11.001

Vattam, S., Wiltgen, B., Helms, M., Goel, A. K., & Yen, J. (2011). DANE: Fostering Creativity in and through Biologically Inspired Design. *Design Creativity 2010* (pp. 115–122). https://doi.org/10.1007/978-0-85729-224-7_16

Viswanathan, V. K., & Linsey, J. S. (2013). Role of Sunk Cost in Engineering Idea Generation: An Experimental Investigation. *Journal of Mechanical Design, 135* (121002). https://doi.org/10.1115/1.4025290

Wilson, J. O., Rosen, D., Nelson, B. A., & Yen, J. (2010). The effects of biological examples in idea generation. *Design Studies, 31*(2), 169–186. https://doi.org/10.1016/j.destud.2009.10.003

Xu, J., Chao, C.-J., & Fu, Z. (2020). Research on Intelligent Design Tools to Stimulate Creative Thinking. *Cross-Cultural Design. User Experience of Products, Services, and Intelligent Environments* (pp. 661–672). https://doi.org/10.1007/978-3-030-49788-0_50

Xu, X. T., Xiong, R., Wang, B., Min, D., & Dow, S. P. (2021). IdeateRelate: An Examples Gallery That Helps Creators Explore Ideas in Relation to Their Own. *Proceedings of the ACM on Human-Computer Interaction, 5*, 352:1–352:18. https://doi.org/10.1145/3479496

Yilmaz, S., Daly, S. R., Seifert, C. M., & Gonzalez, R. (2016). Evidence-based design heuristics for idea generation. *Design Studies, 46*, 95–124. https://doi.org/10.1016/j.destud.2016.05.001

Yuan, H., Liu, M., Lu, K., Yang, C., & Hao, N. (2023). The effect of example abstraction on creativity from the perspectives of example modality and generality. *Thinking Skills and Creativity, 47*, Article 101234. https://doi.org/10.1016/j.tsc.2023.101234