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Exploring designers' cognitive abilities in the concept product design phase through traditional and digitally-mediated design environments

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Abstract

This study explores design strategies that designers adapt in different design environments and assesses cognitive load associated with acquiring, comprehending, and implementing strategies in concept product design phase. The findings from qualitative and quantitative analyses show that the traditional design environment exhibits a greater intrinsic load, thereby fostering a greater diversity of ideas, design strategies, and solutions. The digitally-mediated design environment demonstrates extraneous load, resulting in a tendency towards similarity in ideas, design strategies, and solutions.

Keywords: design education, design strategy, cognitive ability, digital design, design learning

1. Introduction

The concept design phase in product design is commonly recognized as the stage where designers seek inspiration to generate a variety of ideas that prompt the development of innovative solutions for pre-existing problems (Vinker et al., 2023; Goncalves et al., 2014). The process of concept design encompasses the identification of problems, the generation of ideas through innovative problem-solving techniques, and the production of initial solution drafts. The concept design solutions related to the problem are substantially influenced by the environment in which they are produced (Ranscombe and Zhang, 2021; Camba et al., 2018). Nevertheless, it is possible to generate innovative design concepts in both traditional and digital design environments. The traditional design environment is characterized by manual sketching using pen and paper, as well as in-person collaboration. In contrast, the digital design environment relies on digital sketching using a shared whiteboard and remote collaboration (Tang et al., 2011; Stones and Cassidy, 2007). It is critical to distinguish between these two environments and how they affect the design process. There exists a limited number of studies that delve into the actions of designers in both traditional and digital media, and research on comparing traditional and digital media through the utilization of design protocols is notably scarce. An illustration of this may be seen in the study conducted by Bilda and Demirkan (2003), where protocol analyses were employed to examine design activity and the reactions to media transitions regarding the fundamental cognitive abilities of designers. Based on their empirical investigation involving six designers, they discovered that traditional media, such as design activities conducted on paper, offer greater benefits compared to digital media in terms of generating alternative solutions and achieving a more comprehensive understanding of the design problem, particularly during the first stages of the design process. Stones and Cassidy (2007) conducted a study that examined the utilization of paper-based and computer-based tools to assess the synthesis tactics employed by designers when utilizing both mediums. They discovered that in the context of early design thinking, traditional media were shown to facilitate creative thinking, but digital media appeared to impede the creative process for a significant number of designers. The examination of ideation processes in paper-based and digital mediums indicates that paper may provide a more extensive framework for reinterpretation, hence facilitating the generation of innovative ideas. Conversely, digital tools may impose limitations on the ability to reinterpret, potentially constraining the generation of innovative ideas (Stones and Cassidy, 2010). Upon analyzing the influence exerted by various media on the design process, it was determined that the transition from traditional to digital environment did not yield a substantial change in the number of design segments. The study conducted by Tang et al. (2011) and Maldini (2016) found that both traditional and digital environments exhibited similar degrees of complexity and cognitive engagement during the design process. Likewise, digital tools have the potential to foster a more convergent problem-solving approach, yet they do not inherently restrict the expansion of ideas or impede the pace of development. Designers apply different strategies, such as formal interpretation and abstraction, to integrate components from both tangible and intangible artistic assets (Stones and Cassidy, 2007). Digital tools are preferred for stakeholder communication because they can effectively transmit information while retaining managed ambiguity. Its use to generate ideas is limited. The primary question of this study is how designers adapt their design strategies while involved in concept product design in both traditional and digital environments, and how these environments influence their cognitive abilities. Thus, the objective is to explore design strategies that designers adapt in different design environments and to assess the cognitive load associated with acquiring, comprehending, and implementing strategies during the concept product design phase.

2. Literature review

There is a growing inquiry into the potential adverse effects of incorporating digital tools into the engineering design process, particularly concerning its impact on creativity. Hanna and Barber (2001) and Lawson (2005) have advocated for the necessity of conducting an empirical investigation to examine a diverse array of obstacles to creativity in design that arise from the utilization of digital tools. Robertson and Radcliffe (2009) found that the utilization of CAD tools at the first stages of the design process has a detrimental impact on designers' capacity to engage in creative design. This phenomenon is attributed to the occurrence of premature design fixation and constrained ideation. Notwithstanding this, the utilization of digital tools enables the facilitation of design collaboration by streamlining the processes of visual concept creation, sharing, and modification to a certain degree (Frich et al., 2021). In addition, the combination of digital tools and textile crafting abilities has demonstrated that manual crafting fosters the development of creative thinking and imparts a profound emotional quality to the design output. However, additional investigation is required to comprehend its impact on creativity and the potential evolution of digital tools to facilitate this process (Treadaway, 2007). There is a need to investigate designers' strategies to solve design problems in both traditional and digital media, in order to ascertain their impact on designers' cognitive abilities during the concept design phase.

Cognitive psychologists propose that individuals engaged in learning activities may experience extraneous cognitive load as a result of excessive knowledge or an overwhelming amount of learning materials (Sweller, 2010; Sweller, 2011; DeStefano and LeFevre, 2007; Bennett et al., 2008). Numerous researchers contend that the use of digital media to retrieve knowledge can lead to a cognitive overload, hence exerting a detrimental impact on learning activities. However, design often relies on digitally mediated environments; thus, designers must develop digital media-based design strategies in learning to tackle problems. Thus, a digitally-mediated design environment will not only enable digital sketching but also provide designers with simple access to a large range of learning materials, reduce research time, and offer many learning opportunities to gain critical knowledge to solve design problems. Furthermore, designers employ diverse learning methodologies to tap into pertinent prior information, which can be utilized to address intricate challenges encountered throughout the design process. These strategies are defined as behavioral or cognitive processes that facilitate the encoding of information in a manner that enhances knowledge integration and retrieval, hence establishing structured plans of action to effectively accomplish a certain design task. The present state of digital media offers designers a wide array of digital tools and abundant knowledge resources. However, this abundance can lead to information overload, as designers face challenges in effectively managing copious amounts of information while meeting design objectives within given timeframes. From this standpoint, it is imperative to investigate the phase of concept design and the cognitive load within the design process.

3. Research approach

We conducted a series of design experiments where the participants were assigned the task of designing a concept design for a flower lamp. Subsequently, we conducted an empirical investigation to examine their design activities while evaluating their cognitive abilities using a cognitive load component scale formulated by Naismith et al. (2015) and adapted by Michalski et al. (2023) at the end of each experiment. In addition, we classified and mapped the factors that indicate cognitive load effects based on the qualitative statements provided by participants at the end of the experiment sessions (De Jong, 2010). The design task, experimental setup, and technique were carried out as follows.

3.1. Design participants

This study recruited a sample of 12 design participants majoring in product design in a Master of Design program at the design school of our institute. The participants consisted of an equal number of males (n=6) and females (n=6), with ages ranging from 25 to 30 years. They possessed a range of experience in product design, spanning from two to five years. This approach aimed to provide significant insights into the strategies employed by designers in adapting to multiple design environments. The participants were evenly distributed into two distinct groups: one group was required to complete the design activities in traditional and another in digitally mediated environments. Before participating in the design experiments, the participants provided their informed consent. This study received approval from the institutional review board (IRB) of our institute with reference number HSEARS20221103005.

3.2. Design tasks

An individual engaged in learning may experience cognitive overload as a result of an excessive amount of redundant information present in the big data environment (de Silva and Maçada, 2023). Given this notion, we hypothesized that designers' cognitive abilities are impaired as a result of cognitive overload caused by the abundance of digitally disseminated knowledge and excessive access to digital information. To investigate cognitive abilities, we assessed three distinct forms of cognitive loads that are believed to be present during a learning activity, as suggested by cognitive psychology literature (Sweller, 2011). Based on this, we assumed that three cognitive outcomes would be assessed based on the participants' design activities. First, intrinsic cognitive load is the mental work required to process certain information during a design activity. Second, extraneous load is the cognitive effort required to retrieve distributed or unclear information. Thirdly, using working memory to build and automate schema creates a germane load. This type of load helps design activity because participants can construct a schema that addresses the interrelated parts of intrinsic cognitive load in learning about the design problem. Thus, a cognitive load encompasses characteristics associated with prior information stored in long-term memory. Previous research has demonstrated that the distribution of working memory resources towards tasks that require a substantial germane cognitive load has a notable influence on overall learning performance (Sweller, 2010). To examine and evaluate the concept product design activities performed by the participants, a set of design tasks was created with two specific objectives (Lee et al., 2016) in a problem-based learning (designing) environment (Jalani and Sern, 2015). Firstly, by assigning relatively straightforward tasks, it was anticipated that participants would be able to complete design activities more effectively, thereby increasing their intrinsic and germane cognitive loads. Secondly, by assigning more challenging tasks, participants would encounter difficulties in achieving the design objectives, thereby maximizing the extraneous cognitive load. In this study, participants were instructed to engage in a design task involving the concept design of a blossoming flower lamp. The task required them to determine an appropriate level of difficulty and to envision a transformation scenario in which the flower lamp would bloom upon being powered on. The determination of the difficulty level was based on the establishment of the requisite number of moveable elements in a concept design of a flower lamp capable of transformation. In the design phase, an object including a solitary movable element was classified as an elementary level of complexity. Consequently, the quantity of movable components was augmented to introduce sufficient complexity into the design process, thereby facilitating the development of an optimal transformable prototype design. Upon completing the main design task, participants were instructed to do the subtasks on either a digital or physical paper, after which the investigator requested them to verbally elucidate each subtask. The design brief is provided in Table 1.

Table 1. The design brief for the blossoming flower lamp concept design

Main design task	You must design a lamp in the shape of a flower. The lamp must be transformable, when turned on, it will blossom like a flower. The lamp will have moveable petals which will unfold in the shape of a flower
Requirements	The lamp must resemble a flower
	The lamp must have at least four movable petals
	Ensure a unique and pleasant design
	You can try as many designs, just keep track of the time
	You are permitted / not permitted to use any data sources or digital aid (Internet, CAD)
Subtasks	After completing the main task, explain the following components of the concept design on a physical paper/digital paper, and explain each of them verbally:
	a. Main idea behind the design
	b. The thought process at each stage
	c. How did you handle issues that arose throughout the design process?

3.3. Experiment setup and measures

The experiments were conducted in a design laboratory located within our local design institute, wherein two distinct design environments were prepared for the participants. First, the participants were situated within a traditional design environment, wherein they were provided exclusively with guide notes on the flower lamp design and typical design implements such as pencils, erasers, sharpeners, A4 and A3 paper sheets, and other essential tools. They were expressly forbidden from utilizing any type of digital tools, including internet connectivity and computer-aided design (CAD) software and smartphones, they were allowed to discuss with their peers in the experiment. Second, the experiment implemented a digitally mediated design environment wherein participants were equipped with digital resources for engaging in digital design activities. These resources encompassed laptops or computers, tablets and digital sketch pads, internet connectivity and remote discussion with peers, and pertinent design software. The participants were granted unrestricted access to digital resources, such as the Internet and computer-aided design (CAD) tools. The design environments are depicted in Figure 1.

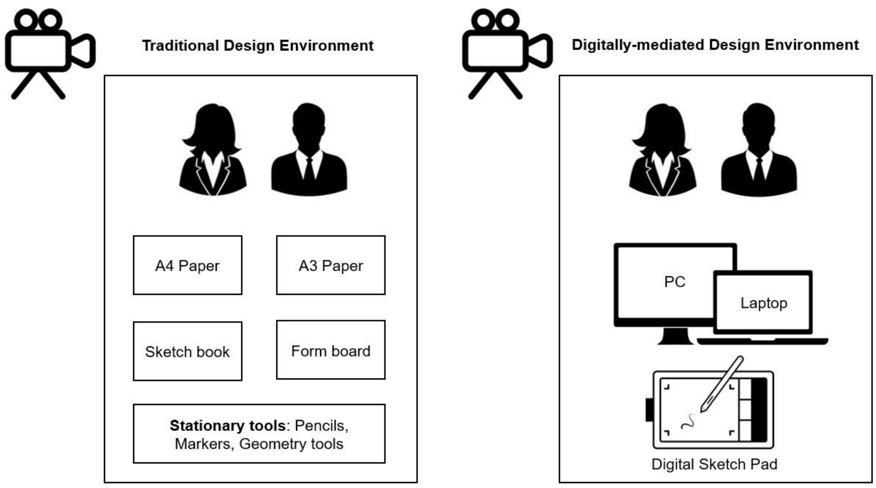

Figure 1. Design environments for design experiments

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Throughout the experiments, we gathered data on participant design behaviour employing a video camera. Furthermore, we obtained, sketches and audio recordings of responses to questions about the concept design of a flower lamp from the participants involved in the experiments. Subsequently, we proceeded to gather the participants' subjective responses to cognitive abilities after completing all the tasks and verbal responses to the subtasks. The subjective response measures from the cognitive load component scale, a six-item inventory encompassed two items for each intrinsic load, extraneous load, and germane load. The scale employs a five-point Likert scale that spans from "1 = not all of the case" to "5 = completely the case" (Naismith et al., 2015).

3.4. Data collection and analysis

The textual contents of the subtasks provided by the participants on the paper sheets, along with their verbal explanations, were transcribed, subjected to qualitative analysis and interpretation, and presented as the qualitative results. In addition, we conducted an analysis of the qualitative statements recorded on the paper sheets in order to identify indicators that signify the presence of cognitive load effects. The factors that contribute to cognitive load are natural complexity (NC), element interactivity (EI) associated with intrinsic load, split attention effect (SAE), modality effect (ME), redundancy effect (RE), expertise reversal effect (ERE) mapped to extraneous load, and effective cognitive load (ECL), and schema construction (SC) are linked to germane load (de Jong, 2010; Sweller, 2010).
For the quantitative analysis, a two-factor multivariate analysis of variance (MONOVA) test was run to measure the effects of the independent variable, design environment with two levels (traditional design environment and digitally mediated design environment) on the dependent variables, the three types of cognitive load (Intrinsic load, extraneous load, germane load). Post hoc analyses using the least significant difference (LSD) test were performed to investigate the differences in the cognitive load types between the two levels of the independent variable.

4. Results and design insights

4.1. Participants' design activities in the traditional design environment

The basic idea behind the concept design of a flower lamp, the thought process, resolving design-related issues, and concept sketching of the product design were the four key components of the participants' design activities. The observation revealed that the participants had different methods for allocating their time. Notably, some of them took a long time to read the design brief and thoroughly consider possible concepts before starting the drawing step. This strategy resulted in fewer changes being made to their original sketches later on. On the other hand, some participants took a quicker approach, devoting less time to preliminary thought and drawing right away. These participants made several revisions to their initial design concepts as they iterated on them over time. Notwithstanding these differences, every participant had a clear emphasis on careful thought, frequently halting during the drawing process to engage in deeper thinking stages. The following subsections detail the participants' contributions to the flower lamp's concept design:

4.1.1. Main idea

The participants' reports showed that the central theme was creating a lamp inspired by the natural beauty and behaviour of flowers. It emphasized a blend of aesthetics and functionality, focusing on an eco-friendly design with features like solar energy and natural mimicry of flower behavior. As Participant P1 notes "I am designing a flower-shaped electrical soft and adjustable lamp that can take the shape of different flowers". Participant P2 notes "I am trying to consider a real flower's shape and behavior that is similar to a real flower function".

4.1.2. Thought process

The thought process revolved around a deep appreciation and emulation of natural elements. The participants' approach was to balance simplicity and complexity, ensuring the lamp was both aesthetically pleasing and functionally relevant. The design decisions were guided by the desire to

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maintain a floral form and create a unique visual experience. As Participant P3 notes "I want to combine nature and technology to define the form and functions and explore its unique opportunities. Participant P2 notes "I want the bulb to be enclosed in the petals so when turned it on, the light will be revealed".

4.1.3. Handling issues

The issues were addressed through a blend of creativity and practicality. The participants mentioned overcoming design challenges like petal movement and light automation based on sunlight. Solutions involved incorporating technology like sensors and motors while keeping the design user-friendly and environmentally conscious. As Participant P4 notes "I am resolving how to make the petals moveable. Maybe I can use a sensor to detect the brightness of the light and use motors to control the petals' movement".

4.1.4. Sketching

The participants' sketches in the traditional design environments are presented in Figure 2 as an example.

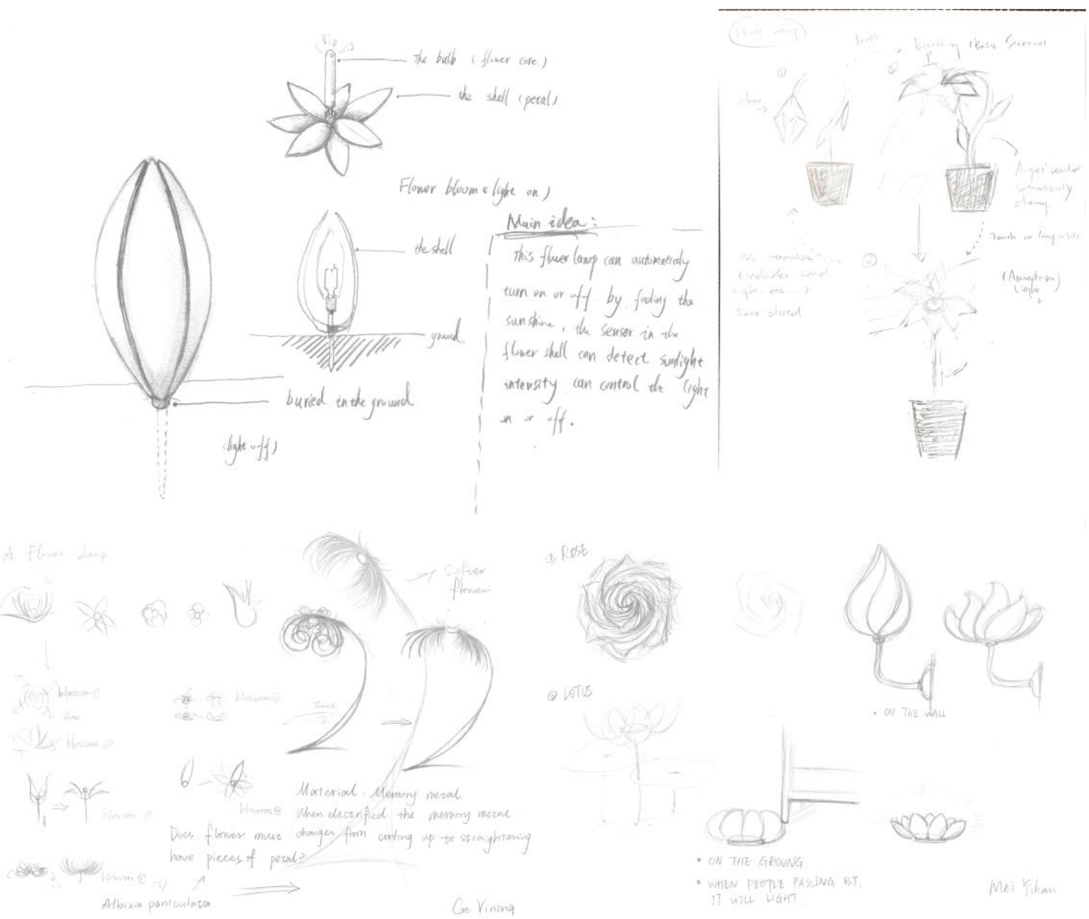

Figure 2. Examples of sketches from participants' activities in the traditional design environment

4.2. Cognitive load indicators in qualitative statements the traditional design environment

Based on the qualitative statements of the participants in the traditional design environment, we found several statements related to intrinsic load (f = 22), extraneous load (f = 6), and germane load (f = 13). The complex nature or difficulty of the contents in the design task caused a high cognitive load concerning intrinsic and germane loads, while the extraneous load was lower as compared to the other loads in the same design environment, which indicates that the processing of unnecessary and unproductive information was not redundant and dispersed (See Table 2). As the extraneous load is low, the statements related to intrinsic load and germane load indicated that participants with a high level of initial information on the flower lamp's main idea and handling issues were able to combine the elements of complex information with their existing design knowledge and manipulate the schema development in the working memory. In particular, the natural complexity of the flower lamp concept design-related information understood and used in the design process indicated intrinsic cognitive load (Sweller, 2010). It was also shown via design task element interactivity. The main idea, thought process, and management of transformable design difficulties during flower blossoming drove the flower lamp design. In the traditional design environment, there were no external sources of information, therefore the split attention effect was zero. However, peer discussion among the participants increased it and added extraneous load. The design task encouraged participants to use their prior knowledge of the concept design's main idea and thought processes to develop a schema, increasing the germane load (de Jong, 2010).

4.3. Participants' design activities in the digitally-mediated design environment

The participants' design activities were divided into four main parts: the main idea behind the concept design of a flower lamp, the thought process, handling issues related to the design, and concept sketching of the product design in a digitally mediated design environment. The observation notes showed that participants exhibited a consistent behavior pattern. Upon receiving the design briefs, they immediately turned to the internet to search for similar design concepts. This approach indicated a reliance on existing external sources, raising questions about the extent to which participants leveraged their internal cognitive abilities. Unlike their counterparts in the traditional design environment, who allocated substantial time to contemplation, participants in this environment expended this time conducting online searches. During the sketching process, they intermittently paused; however, rather than engaging in introspection, they frequently returned to the internet for design inspiration or reference. The participants' activities on the flower lamp concept design in the digitally mediated design environment are presented in the following subsections:

4.3.1. Main idea

The participants' qualitative reports showed that the main theme was the creation of a highly interactive, digital flower lamp with dynamic features. This lamp was not just about illumination but also about providing an immersive experience with elements like music synchronization, shape-shifting for brightness control, and thematic inspirations from movies and music. As Participant P7 notes "At the same time, let the shape of the lamp change into different ranges to adjust the brightness". Participant P9 notes "I think the main idea of the flower lamp should be inspired by the movie, Avatar". Regarding the music synchronization, Participant P10 notes "My main idea is to create a flower-like lamp that will bloom in cold water at Christmas with random music". Participant P11 notes "My main idea came from an umbrella, using a telescopic mechanism to control the movement of the petal".

4.3.2. Thought process

The thought process was highly user-centric and innovation-driven. There was a focus on understanding user needs and expectations to create a product that stands out in the market. The participants' design practice aimed at solving usability problems in a novel way, offering features that go beyond traditional lighting to include emotional and sensory experiences. As Participant P12 notes "I want to design individual petals to connect to the bulb and design the movements". Participant P12 notes "First, I searched some interesting flower shapes on the internet and thought about the lightning and heating and also how to scent the candle. Then the lamp I looked at the lamp that looked like a flower and got the aid".

4.3.3. Handling issues

Participants showed a more technologically driven approach to problem-solving. Complex issues like creating a responsive and interactive environment were tackled through advanced mechanisms like a telescopic umbrella mechanism for petal movement, scent emission, and visual-audio synchronization.

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The solutions are more about enhancing user engagement and experience. As Participant P7 notes “How to make petals moveable? The problem was solved by using an umbrella telescopic mechanism”. Regarding user engagement and experiences, Participant P8 notes “From solving pain points to providing users with itch points, to thinking about immersion in continuous use”.

4.3.4. Sketching

The participants' sketching activities in the digitally mediated design environments are presented in Figure 3 as an example.

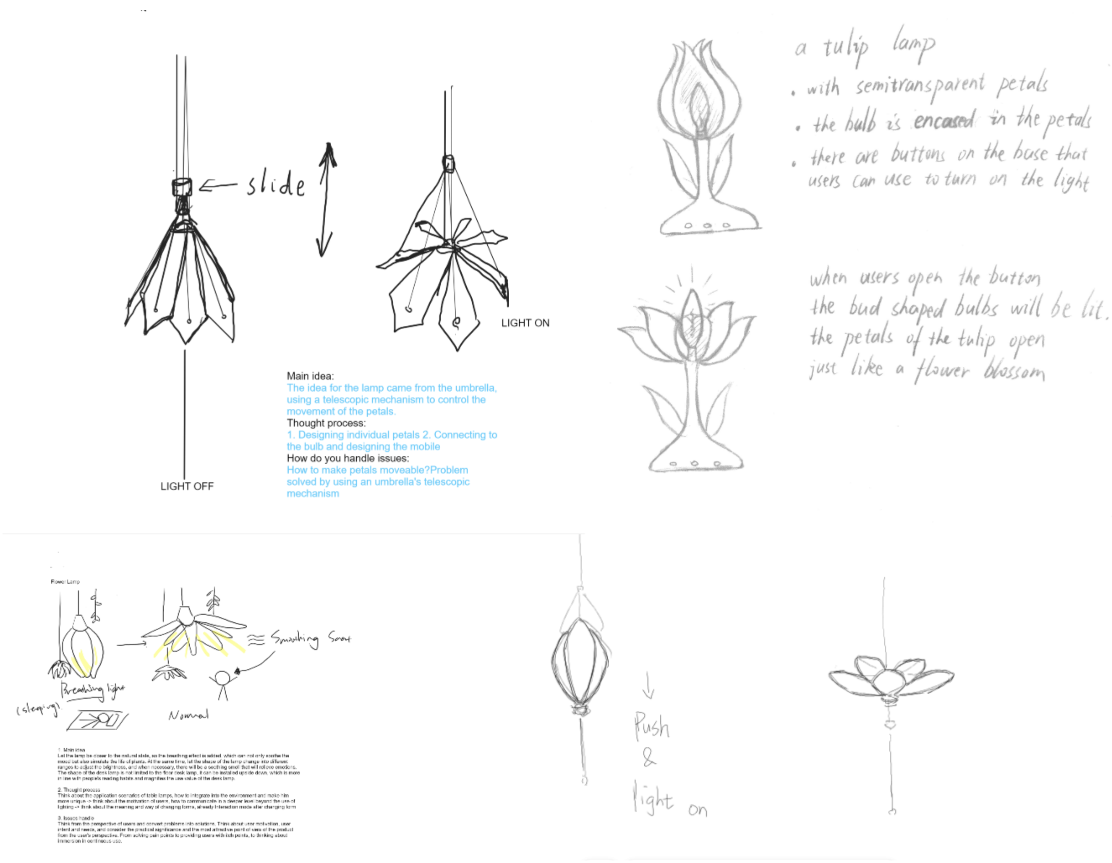

Figure 3. Examples of sketches from participants' activities in the digitally-mediated design environment

4.4. Cognitive load indicators in qualitative statements the digitally-mediated design environment

The qualitative responses provided by the participants in the digitally mediated design environment revealed several notes on intrinsic load (f = 17), extraneous load (f = 16), and germane load (f = 12). The intricate nature or challenging aspects of the information inside the design assignment resulted in a significant cognitive load. The extraneous load in the digitally mediated design environment was found to be much higher than the extraneous load in the traditional design environment, as evidenced by the data presented in Table 2. This suggests that the processing of irrelevant and unproductive information was excessive and scattered in the digitally mediated design environment, in contrast to the more focused and efficient processing observed in the traditional design environment. Due to the relatively high extraneous load in this particular environment, the cognitive load experienced by participants surpasses their mental resources, resulting in a failure of the learning process and rendering their design activities ineffective within the digitally mediated design environment. Specifically, the intrinsic cognitive load was high due to the natural complexity and element interactivity, resulting in a successful initiation of understanding regarding the main idea. Nevertheless, the occurrence of both the split

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attention effect and the redundancy effect during the learning process was also high in numbers, resulting in an increased extraneous load (Sweller, 2010). This suggests that the learning was not focused on the main idea and handling issues of the flower lamp design, but rather on acquiring irrelevant knowledge about product design. Table 2 indicates that the intrinsic load indicators were notably higher in numbers, particularly for the main idea in the digitally-mediated design environment. Consequently, the participants were expending a substantial amount of cognitive resources to process the main idea of the flower lamp design. Conversely, the extraneous load indicators were high in numbers, indicating a decrease in germane load (de Jong, 2010). This hindered the participants' ability to understand, analyze, and handle the main idea of the flower lamp design.

Table 2. Cognitive load indicators in qualitative statements in the traditional design environment and digitally-mediated design environment

Traditional Design Environemnt					Digitally-mediated Design Environment					
Intrinsic Load		Extraneous Load	Germane Load		Intrinsic Load		Extraneous Load			Germane Load
NC	EI	SAE	ECL	SC	NC	EI	SAE	RE	ERE	SC
M1	I1	G8	I6	T1	M2	M1, T1	I1	T4	G8	T2
M2	T2, I2, T2	G9		M4, I4, T4	M3	I3	I2	I7		T3
T3	M3, I3	I10, G10		M5, I5	M4	I4	I5	T9		T5, I5
M6, T6	T5	G11		T7, I7, G7	M5, T5	M5	I6			T6
M7	I9	G12		T8	M6	M7	I8			T7
M8, I8				T10	M8	M12	M9, I9, G9			T8
M9				T11	M9		T10			T9
M10					M10		T11, I11			I10, T10
M11, I11					M11		I12			T11
M12, I12										T12
14	8	6	1	12	10	7	12	3	1	12
22		6	13		17		16			12

*Statements on the main idea (M1 to M12)
*Statements on the thought process (T1 to T12)
*Statements on the handling issues (I1 to I11)
*Statements on the peers' discussion (G1 to G12)

4.5. Quantitative analysis results

A two-factor multivariate analysis of variance (MANOVA) was conducted to examine the impact of the design environment on cognitive load. The results of the test indicated a statistically significant difference between the traditional design environment and digitally mediated design environment in terms of their combined cognitive load, $F(3, 44) = 4.06$, $p = 0.012$; Wilks' $\Lambda = 0.783$, $\eta 2 = 0.21$. The test of the between-subjects analysis revealed a significant difference between the two environments in terms of the impact on intrinsic load, $F(1, 46) = 4.05$, $p = 0.049$; $\eta 2 = 0.081$) and extraneous load ($F(1, 46) = 5.853$, $p = .020$; $\eta 2 = 0.113$). Nevertheless, the study did not find any statistically significant difference between the two design environments in terms of germane load, $F(1, 46) = 1.42$, $p = 0.239$; $\eta 2 = 0.030$).

To evaluate a significant difference in the cognitive load experienced by participants in the design environments, a post hoc analysis was conducted utilizing the Least Significant Difference (LSD) test. A significant difference was found in the scores of intrinsic cognitive load and extraneous cognitive load between the participants in the traditional design environment and digitally mediated design environment. The intrinsic cognitive load score in the traditional design environment (2.5 ± 0.93) was shown to be greater compared to the digitally mediated design environment (2 ± 0.78). The extraneous cognitive load observed in the traditional design environment (3 ± 1.04) was lower than in the digitally mediated design environment (3.7 ± 0.85). This result suggests that the design tasks performed by the participants in the traditional design environment are more effective than the design tasks performed in the digitally mediated design environment. Figure 4 illustrates the observed patterns of cognitive load score fluctuations in response to variations in the design environment.

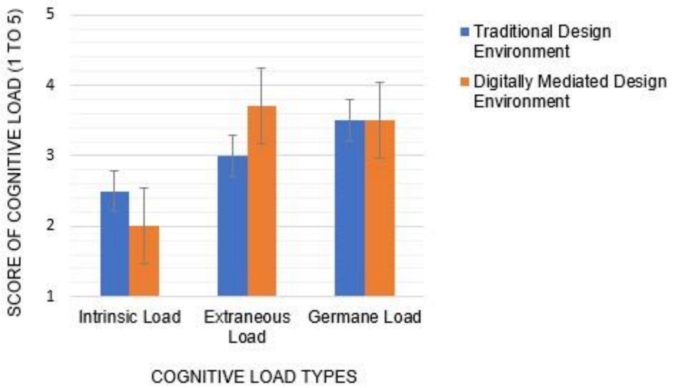

Figure 4. Cognitive Load scores in traditional and digitally-mediated design environments

5. Conclusions and design impact

This study explores designers' cognitive abilities and design activities in traditional and digitally mediated design environments using a flower lamp concept product design example. Designers thought more and iterated less in the traditional design environment because they engaged with the design brief. The designers prioritized aesthetics, utility, eco-friendliness, and natural beauty in the flower lamp design. The intrinsic cognitive load was higher in the traditional design environment, implying deeper task processing with less distraction. Designers used internet resources more in digitally mediated workplaces, demonstrating a distinct approach to creativity and problem-solving. The digitally mediated design environment developed interactive, technology-driven concept design ideas with music synchronization and dynamic user experiences. However, the split attention effect and overwhelming information availability in the wider internet search increased extraneous cognitive load, indicating a greater degree of distraction or dispersion of attention, possibly due to online information and external stimuli (de Silva and Maçada, 2023). Each participant had a unique sketch and approach to the design problem in the traditional design environment, but in the digitally mediated environment, their sketches were similar. This may be because the participants heavily depended on the internet, where they searched for flower designs and lamps after reading the design requirements, which constituted the basis of their concept design and fixed their design ideas (Robertson and Radcliffe, 2009). Participants in the traditional design environment focused on the design brief and deep thinking rather than drawing and outside ideas. Quantitative results show that intrinsic and extraneous cognitive loads change significantly between the design environment. Comparatively, the traditional design environment increased intrinsic cognitive load, suggesting deeper cognitive engagement with design tasks. The digitally mediated environment had more extraneous cognitive load, indicating more distractions or non-essential cognitive processing (Hawlitschek and Joeckel, 2017). These findings may indicate that the design environment strongly affects cognition, creativity, and design output.

The examination of the impact of traditional and digitally mediated design environments on designers' activities and cognitive load during the concept design phase presents a multifaceted area of study characterized by varying viewpoints and potential consequences for design practice and education. The

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traditional design environment often highlights the tactile and intuitive characteristics of sketching, which are believed to facilitate the development of visual-spatial understanding, improve issue conceptualization, and encourage diverse thinking. The traditional media seems to endorse a wide range of solutions, indicating that it effectively handles designers' cognitive load in a way that promotes the generation of innovative ideas in the early concept design phases. In addition, the practice of conventional sketching fosters the development of reinterpretation and the origination of innovative ideas, both of which are crucial during the initial phases of concept design. Sketching can also inspire designers and allows them to refine and revise those innovative ideas to generate more concepts due to its iterative, cyclical, and dialectic aspects (Schembri et al., 2015). The digitally mediated design environment underscores the benefits of technology in enhancing the process of generating ideas, indicating that digital tools have the potential to yield more structured outcomes and facilitate a more focused approach to problem-solving. These tools are often admired for their ability to enhance clarity, speed, and ease of modification, which can enable effective communication with stakeholders and may alleviate unnecessary cognitive burdens, allowing designers to focus their cognitive resources on pertinent areas of the design work (Ates and Koroglu, 2024).

This study is subject to several limitations, such as the insufficient sample size to establish the quantitative outcomes of cognitive load. The design tasks were solely derived from the concept design phase, so lessening both the design outcomes and the study's impact. Subsequent research will be undertaken to enlist a significant number of participants who will engage in design activities centered around a real product design scenario. These participants will have the opportunity to extensively utilize digital resources and 3D design tools to enhance the results of cognitive load. However, the study design has the capacity to investigate various types of product design other than concept design, such as form factor, the working principle and functions of product design. Future research will examine the correlation between the cognitive abilities, design creativity and the design outcomes.

The design landscape is transitioning from analog to digital. Nevertheless, the current design tools do not align with the design process, thus requiring modifications to the tools and adjustments to the design process. This is necessary to ensure that the effectiveness of the design process is either maintained or enhanced in a digital environment. Hence, there is a need for advanced design approaches as the design process frequently begins with obsolete design approaches that are ill-suited for the digitally-mediated design environment. Due to the widespread usage of digital tools today, the design environment will soon be fully digitally transformed (Bohemia et al., 2013). Despite the widespread usage of digital media, design education has not been well prepared due to a lack of research on the digital design process. This research established a novel research viewpoint on the development of design methods for a digitally mediated environment to address designers' cognitive abilities in the early design phase.

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References

Ateş, H. and Köroğlu, M., (2024). "Online collaborative tools for science education: Boosting learning outcomes, motivation, and engagement". Journal of Computer Assisted Learning. https://doi.org/10.1111/jcal.12931

Bennett, S., Maton, K. and Kervin, L., (2008). "The 'digital natives' debate: A critical review of the evidence." British journal of educational technology, 39(5), pp.775-786. https://dx.doi.org/10.1111/j.1467-8535.2007.00793.x

Bilda, Z. and Demirkan, H., (2003). "An insight on designers' sketching activities in traditional versus digital media". Design studies, 24(1), pp.27-50. https://dx.doi.org/10.1016/S0142-694X(02)00032-7

Bohemia, Erik & Cruickshank, Leon & Kovacevic, Ahmed & Blythe, Mark & Fain, Nusa. (2013). "Brief Encounters: Exploring Digital Technologies in New Design Practice." https://dx.doi.org/10.13140/2.1.2078.6888

D. Camba, Jorge & Kimbrough, Mark & Kwon, Eunsook. (2018). "Conceptual product design in digital and traditional sketching environments: a comparative exploratory study." Journal of Design Research. 16. 131. 10.1504/JDR.2018.10014195.

da Silva Cezar, B.G. and Maçada, A.C.G., (2023). "Cognitive Overload, Anxiety, Cognitive Fatigue, Avoidance Behavior and Data Literacy in Big Data environments". Information Processing & Management, 60(6), p.103482. https://doi.org/10.1016/j.ipm.2023.103482

De Jong, T., (2010). “Cognitive load theory, educational research, and instructional design: Some food for thought.” Instructional science, 38(2), pp.105-134. https://doi.org/10.1007/s11251-009-9110-0
DeStefano, D. and LeFevre, J.A., (2007). “Cognitive load in hypertext reading: A review”. Computers in human behavior, 23(3), pp.1616-1641. http://dx.doi.org/10.1016/j.chb.2005.08.012
Frich, J., Nouwens, M., Halskov, K. and Dalsgaard, P., (2021), May. “How digital tools impact convergent and divergent thinking in design ideation”. In Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems (pp. 1-11). https://dx.doi.org/10.1145/3411764.3445062
Gonçalves, M., Cardoso, C. and Badke-Schaub, P. (2014), “What inspires designers? Preferences on inspirational approaches during idea generation”, Design Studies, Elsevier BV, Vol. 35 No. 1, pp. 29–53. https://doi.org/10.1016/j.destud.2013.09.001
Hanna, R. and Barber, T., (2001). “An inquiry into computers in design: attitudes before–attitudes after.” Design studies, 22(3), pp.255-281. https://doi.org/10.1016/S0142-694X(00)00029-6
Hawlitschek, A. and Joeckel, S., (2017). “Increasing the effectiveness of digital educational games: The effects of a learning instruction on students’ learning, motivation and cognitive load.” Computers in Human Behavior, 72, pp.79-86. https://doi.org/10.1016/j.chb.2017.01.040
Jalani, N.H. and Sern, L.C., (2015). “The example-problem-based learning model: applying cognitive load theory.” Procedia-Social and Behavioral Sciences, 195, pp.872-880. https://dx.doi.org/10.1016/j.sbspro.2015.06.366
Lawson, B., (2005). “Oracles, draughtsmen, and agents: the nature of knowledge and creativity in design and the role of IT.” Automation in construction, 14(3), pp.383-391. https://doi.org/10.1016/j.autcon.2004.08.005
Lee, H., et al. (2016). “Difficulties in transformable design and its causes.” DS 84: Proceedings of the DESIGN 2016
Maldini, I., (2016). “Attachment, durability and the environmental impact of digital DIY.” The Design Journal, 19(1), pp.141-157. https://doi.org/10.1080/14606925.2016.1085213
Michalski, C., Cowan, M., Bohinsky, J., Dickerson, R. and Plochocki, J.H., (2023). “Evaluation of cognitive load for a mixed reality anatomy application.” Translational Research in Anatomy, 31, p.100247. https://doi.org/10.1016/j.tria.2023.100247
Naismith, L.M., Cheung, J.J., Ringsted, C. and Cavalcanti, R.B., (2015). “Limitations of subjective cognitive load measures in simulation-based procedural training.” Medical education, 49(8), pp.805-814. https://dx.doi.org/10.1111/medu.12732
Ranscombe, C. and Zhang, W. (2021) “What Motivates And Discourages Designers To Use Digital Sketching? Comparing Its Use To Externalise Ideas Versus Communicating With External Stakeholders”, Proceedings of the Design Society, 1, pp. 3441–3450. https://dx.doi.org/10.1017/pds.2021.605.
Robertson, B.F. and Radcliffe, D.F., (2009). “Impact of CAD tools on creative problem solving in engineering design.” Computer-aided design, 41(3), pp.136-146. https://doi.org/10.1016/j.cad.2008.06.007
Schembri, M., Farrugia, P., Wodehouse, A.J., Grierson, H. and Kovacevic, A., (2015). “Influence of sketch types on distributed design team work”. CoDesign, 11(2), pp.99-118. 10.1080/15710882.2015.1054841
Stones, C. and Cassidy, T., (2007). “Comparing synthesis strategies of novice graphic designers using digital and traditional design tools”. Design studies, 28(1), pp.59-72. https://doi.org/10.1016/j.destud.2006.09.001
Stones, C. and Cassidy, T., (2010). “Seeing and discovering: how do student designers reinterpret sketches and digital marks during graphic design ideation?”. Design studies, 31(5), pp.439-460. https://dx.doi.org/10.1016/j.destud.2010.05.003
Sweller, J., (2010). “Element interactivity and intrinsic, extraneous, and germane cognitive load.” Educational psychology review, 22, pp.123-138. https://doi.org/10.1007/s10648-010-9128-5
Sweller, J., (2011). “Cognitive load theory.” In Psychology of learning and motivation (Vol. 55, pp. 37-76). Academic Press. https://doi.org/10.1016/B978-0-12-387691-1.00002-8
Tang, H.H., Lee, Y.Y. and Gero, J.S., (2011). “Comparing collaborative co-located and distributed design processes in digital and traditional sketching environments: A protocol study using the function–behaviour–structure coding scheme”. Design Studies, 32(1), pp.1-29. https://doi.org/10.1016/j.destud.2010.06.004
Treadaway, C., (2007). “Digital crafting and crafting the digital.” The Design Journal, 10(2), pp.35-48. https://dx.doi.org/10.2752/146069207789272668
Yael Vinker, Andrey Voynov, Daniel Cohen-Or, and Ariel Shamir. (2023). “Concept Decomposition for Visual Exploration and Inspiration.” ACM Trans. Graph. 42, 6, Article 241 (December 2023), 13 pages. https://doi.org/10.1145/3618315