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An empirical study of cognitive load and constraint-driven innovation in the early phase of product design within a digitally mediated medium

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ABSTRACT

Digitally mediated design mediums have revolutionized product design, but their cognitive impact during early concept design stages remains unclear. This study employs cognitive load theory (CLT) and constraint-driven cognition to examine how traditional (TD) and digitally mediated (DM) mediums influence cognitive load, problem-solving, and design outcomes. A quasi-experimental study with 16 design students, divided into TD and DM groups, used two distinct design tasks. Results revealed three key findings. First, the DM medium imposed a significantly higher extraneous cognitive load due to attentional fragmentation and interface management, consuming working memory resources critical for creative synthesis. Second, a fundamental strategic divergence emerged: the TD group engaged in problem-driven cognition through material constraints, yielding higher conceptual novelty (63% vs. 25%) and five times more sustainability considerations. The DM group used solution-driven strategies, leading to more derived outcomes. Third, the cognitive impact was task-dependent; digital tools reduced intrinsic load for well-defined mechanical tasks but offered no advantage for open-ended aesthetic tasks. This study suggests design mediums function as active cognitive environments, not neutral tools. A reevaluation of design education and practice is essential, promoting digital metacognition, retaining tactile skills, and developing hybrid processes that leverage the distinct cognitive benefits of each medium.

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KEYWORDS
Traditional medium; digitally mediated medium; cognitive load; concept design; product design

1. Introduction

The evolution of the design medium into a predominantly digital environment has fundamentally transformed product design, offering powerful new tools for problem-solving, idea generation, and knowledge acquisition (Cross, 2021; Marion & Fixson, 2021; Tatipala et al., 2021). This digital transition represents a fundamental shift in the designer's cognitive environment, providing both opportunities and new

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challenges. As design is fundamentally a cognitive process, the design medium constitutes an integrated environment of tools and representations that actively mediates design cognition (Cascini et al., 2022; Kim & Kim, 2015; Tufail et al., 2024). Based on previous studies (e.g., Bilda & Demirkan, 2003; Jukes et al., 2010), a design medium that employs non-digital, tactile tools, such as pens, paper, and physical models, and supports direct manipulation is referred to as a traditional design medium (TD). Conversely, a medium that comprises software and hardware, such as CAD, digital sketchpads, web browsers, and AI platforms, which require interface mediation and provide access to extensive information networks, can be described as a digitally mediated medium (DM). In this context, a TD medium can be understood as a cognitive and practical environment that is disconnected from the digital resource network. Digital environments, referred to as DM mediums, provide unprecedented access to resources and transform traditional design practices (Bilda & Demirkan, 2003; Mortati et al., 2023). Therefore, they facilitate the development of integrated environments that digitally mediate cognition (Cascini et al., 2020, 2022).

Designers increasingly rely on digital tools to perform tasks and develop strategies (Safin, 2016). These digital mediations offer significant learning opportunities through simulations, crowdsourced information, and global trends (Broadbent et al., 2020; Burdick & Willis, 2011; Costa et al., 2020; Cramp, 2015), improving access to learning resources and promoting self-regulated learning (Cramp & Lamond, 2016). Although DM mediums provide potentials for creativity, they can hinder cognition due to competing stimuli (Bennett et al., 2008; Cezar & Maçada, 2023; Frederiksen et al., 2020). Research indicates that TD mediums, such as sketching, are associated with improved problem engagement and creative thinking (Bilda & Demirkan, 2003; Stones & Cassidy, 2007, 2010), constituting a vital aspect of the 'designerly way of knowing' (Cross, 2010). On the other hand, digital tools can facilitate complexity and convergent problem-solving (Tang et al., 2011; Feeman et al., 2018), although they may also result in premature fixation and derived outcomes (Casais, 2020; Robertson & Radcliffe, 2009; Stones & Cassidy, 2010). Context influences these outcomes, with research indicating that digital tools improve form innovation in certain tasks (Barbieri & Muzzupappa, 2024). Digital sketching provides confidence but presents trade-offs between fidelity and effort (Evans & Aldoy, 2016; Ranscombe & Zhang, 2021). While facilitating rapid prototyping, digital tools may lead to split attention (Budinoff et al., 2024; Camba et al., 2018; Richey et al., 2012), highlighting the need for strategic integration (Novica et al., 2023).

Despite foundational protocol studies (e.g., Bilda & Demirkan, 2003; Stones & Cassidy, 2007), significant gaps remain in understanding cognitive load within modern DM environments. The design landscape has evolved with generative AI (Fang et al., 2025), new interfaces (Pearson, 2020), and 'data thickening' (Mortati & Cautela, 2025). A major problem is the insufficient use of digital tools in early conceptual phases, forcing disjointed tool-switching that disrupts cognitive flow (Al-Rqaibat et al., 2025). Although mixed-media are being examined (Shih et al., 2017), the cognitive costs of task asymmetry in complex digital resources are inadequately studied. This shift requires a move from earlier methods (Hanna & Barber, 2001; Lawson, 2005; Mitchell et al., 2003) to investigating 'digital design thinking' with new metrics (Oxman, 2017). Furthermore, addressing innovation challenges requires digital empathy and organized processes to foster collaboration in remote and AI-assisted settings, despite tool constraints on creativity (Patricio et al., 2024).

Thus, the digital transformation has produced a novel cognitive environment for designers. To systematically examine its specific cognitive demands and implications, we utilize cognitive load theory (CLT) as our main theoretical basis throughout this study.

1.1. Cognitive load theory in design

CLT provides the basis for understanding the cognitive demands within this new cognitive environment. It explains the dynamics by suggesting that the abundance of information often increases extraneous load while potentially reducing the germane load essential for schema development (Sweller, 2011, 2022; Wickens & Carswell, 2021). The DM medium offers extensive information libraries and advantages (Mortati et al., 2023), but it also fosters dependency and presents cognitive challenges by increasing extraneous load through split attention across interfaces and multitasking (Kirschner, 2002; Sweller et al., 2019). This excess of stimuli can overwhelm working memory, diminish concentration, and result in superficial decisions (Bennett et al., 2008; Li, 2017; Skulmowski & Xu, 2022).

CLT provides a robust framework for understanding the cognitive demands of design, explaining how working memory is overwhelmed by competing information (Sweller, 2022). CLT categorizes load into three types: intrinsic (inherent to the task's complexity), extraneous (imposed by unnecessary and distracting information), and germane (the effort of constructing schemas) (Sweller, 2022). The time-constrained design process relies on limited working memory (Wickens & Carswell, 2021), and overload can cause fragmented decisions (Kirschner, 2002). This is critical, as an abundance of digital information poses an overload risk, negatively affecting outcomes (Renjith, 2017). Furthermore, limited working memory impacts creativity, where overload undermines ideation (Bilda & Gero, 2007) and underload hinders performance (De Jong, 2010; Krieglstein et al., 2022).

Early design phases significantly influence creativity (Sun & Yao, 2012), involving motivation, cognition, and expertise (Chen et al., 2022). Digital tools may overload working memory via multitasking and fragmentation (Frederiksen et al., 2020; Kirschner, 2002), while traditional constraints might boost germane processing. However, causal relationships between cognitive load, creativity, and outcomes show contradictions. Some studies find reduced load aids divergent thinking (Hancock et al., 2021; Redifer et al., 2019), while others show experts use higher load for better outcomes (Sun et al., 2014) and higher creativity (Calpin & Menold, 2023), with one study finding only a weak negative link to performance (Zimmerer & Matthiesen, 2021). Such evidence suggests the application of CLT in design remains limited (Howard et al., 2008), particularly concerning load dimensions in early concept design phases (Nelson & Menold, 2020). DM mediums enhance flexibility but risk overload (Schmitt et al., 2021). Skulmowski and Xu (2022) thus propose 'cognitive load alignment' to strategically match tools to tasks, acknowledging extraneous load's task-specificity. As design is a knowledge-dependent problem-solving activity (Wickens & Carswell, 2021), understanding the impact of cognitive load in DM mediums is critical.

Understanding cognitive load, however, constitutes only part of the whole situation. The medium's impact on cognitive load directly shapes the designer's fundamental strategies throughout the design process.

1.2. Design cognition and strategy

The iterative design process is a cognitive activity involving navigation of complex knowledge resources (Da Silva et al., 2020; Muratovski, 2021). While designers historically relied on physical references and internal knowledge (De Rooij et al., 2021; Kim & Kim, 2015), effective use of digital resources now requires new skills and cognitive frameworks for knowledge acquisition and problem definition (Hattie & Donoghue, 2016; O'Neil, 2014). Research identifies distinct cognitive strategies, such as Kruger and Cross's (2006) problem-driven and solution-driven, which yield different creative outcomes. The strategies employed with digital tools significantly impact the design process (Marion & Fixson, 2021), and constraint's role in design reasoning continues to be clarified (Ashrafganjouei & Gero, 2021). These strategic and cognitive shifts are particularly critical in the concept design phase, where inspiration transforms into innovation (Gonçalves et al., 2014; Vinker et al., 2023).

This effect is critical during the concept design phase, where initial ideas are synthesized into coherent solutions (Gonçalves et al., 2014; Vinker et al., 2023). As the iterative design process involves navigating complex knowledge resources (Da Silva et al., 2020; Muratovski, 2021) and the strategies used impact outcomes (Marion & Fixson, 2021), the immediate access offered by DM mediums can, paradoxically, hinder creative thinking, potentially reducing novelty and constraining solutions (Budinoff et al., 2024; Casais, 2020).

DM mediums shape learning strategies, the cognitive, metacognitive, and motivational strategies that enhance knowledge acquisition (Boekaerts, 1997; Hattie & Donoghue, 2016; O'Neil, 2014). This includes management strategies for accessing digital resources (Dignath et al., 2008), which is crucial given designers' dependence on online repositories (Cross, 2021; Muratovski, 2021). Designers formulate such strategies to locate and evaluate materials for defining complex problems, thereby informing their overall design strategy (O'Neil, 2014). However, a lack of comparative studies on strategy development within DM mediums creates uncertainty about adaptation to digital information structures.

In the DM medium, the design activity is regarded as the fundamental cognitive processes of problem framing, ideation, and synthesis to develop an innovative solution through design strategies (Donoghue, Hattie & Donoghue, 2016; O'Neil, 2014). Moreover, information management practice is considered a subset of design activity related to sourcing, filtering, and organizing external information (e.g., online searches, database navigation, and file management) through management strategies (Dignath et al., 2008). This division facilitates an analysis of how the DM medium reallocates cognitive effort from the former to the latter.

As design is inherently cognitive, the medium influences cognition. TD mediums aid tactile iteration and problem definition (Bilda & Demirkan, 2003; Da

Silva et al., 2020; Stones & Cassidy, 2007), whereas engineering studies suggest CAD tools can negatively impact creativity by promoting premature fixation (Hanna & Barber, 2001; Lawson, 2005; Mitchell et al., 2003). This tension underscores the need to understand strategy development in modern design environments.

The ultimate implications of these cognitive and strategic interactions are assessed by their influence on constraint-driven innovation, indicating a specific empirical gap.

1.3. Constraint-driven innovation and research gap

This study is placed within the context of constraint-driven innovation. In concept design, constraints such as novelty, feasibility, and sustainability are not simply limitations but important drivers that shape the creative process (Wang et al., 2018). Constraint-driven innovation suggests that by addressing these constraints, designers can concentrate their cognitive efforts, narrow the solution space to feasible regions, and promote novel outcomes (Fu et al., 2024). The design medium inherently influences this interaction. TD mediums may enhance problem engagement and iteration (Bilda & Demirkan, 2003; Stones & Cassidy, 2007), potentially boosting creative thinking and deeper constraint negotiation. Conversely, digital tools, while enabling complexity, can lead to premature design fixation and derived outcomes (Casais, 2020; Robertson & Radcliffe, 2009; Stones & Cassidy, 2010). This highlights a critical tension: digital tools enhance convergent problem-solving (Feeman et al., 2018; Ranscombe & Zhang, 2021), yet they risk distancing the designer from the fundamental constraints that drive innovation.

Current studies have addressed related issues by investigating the cognitive-affective aspects of creativity, fixation mechanisms, and the influence of digital tools. Sudha and Premkumar (2025) show that creativity is substantially influenced by affective-conative resources, suggesting a digital interface can provoke frustration that reduces these resources and increases cognitive load. This interaction aligns with the fixation model of Nguyen and Zeng (2017), where fixation emerges from a divergence between perceived and anticipated fitness, shaped by 'affect' and 'perceived workload.' Digital tools such as CAD can generate an 'illusion of completeness' (Vasantha et al., 2014), increasing the cognitive load of change and causing premature fixation, thereby limiting reinterpretation. The regulation of cognitive load through tool design and training is also critical; Prabhu et al. (2023) demonstrate that a modular educational strategy manages intrinsic and extraneous load to enhance self-efficacy and schema construction more effectively than traditional lectures.

While studies like Wang et al. (2023) map the landscape of digital prototyping tools, and others like Kim and Maher (2023) highlight the potential of AI co-creative platforms to enhance ideation novelty and diversity, they do not explicitly measure the associated cognitive costs, strategic adaptations, or risks of new cognitive dependencies. A close examination of these perspectives uncovers a specific gap: the lack of a controlled, comparative study employing CLT to explicitly examine the causal relationship from design medium (TD vs. DM) to cognitive load, strategy adoption, and subsequently to constraint-driven design outputs.

Previous research has not simultaneously and empirically investigated this integrated process.

1.4. Study objectives and research questions

Given the apparent advantages of digital resources, concerns have emerged over their potential to induce cognitive overload, possibly hindering creative cognition (Bennett et al., 2008; Budinoff et al., 2024; Casais, 2020; Kirschner, 2002). However, a thorough empirical analysis is needed to transcend this assumption. While professional design practice often involves a seamless integration of TD and DM mediums, a controlled, comparative examination is required to isolate their distinct cognitive effects. This study systematically separates TD and DM as distinct cognitive environments to establish a clear experimental comparison. Therefore, this study combines CLT with design cognition through a conceptual framework and posits that the design medium (TD vs. DM) influences a designer's cognitive load distribution, which in turn shapes the adoption of design strategies and ultimately impacts design outcomes. This study is guided by the following research questions (RQs):

RQ1: How do TD and DM design mediums affect designers' extraneous, intrinsic, and germane cognitive load during the concept design process?

RQ2: What distinct problem-solving strategies develop among designers using TD versus DM mediums?

RQ3: How do the constraints and benefits of each medium impact the novelty, feasibility, and sustainability of design outcomes?

2. Materials and methods

2.1. Design participants

Sixteen master's students in product design (aged 25–30, with 2–5 years of experience) were recruited. The cohort consisted of 6 female and 10 male participants, evenly distributed into a TD group ($n = 8$) and a DM group ($n = 8$). The TD group had expertise in hand drawing and physical prototyping, while the DM group specialized in digital tools like CAD and UI/UX software. Participants provided informed consent, were assigned codes (TD1-TD8, DM1-DM8), and the study was approved by the institutional review board (IRB reference: HSEARS20221103005).

2.2. Conceptual framework and study design

This study is guided by a conceptual framework (see Figure 1) that integrates CLT with design cognition, positing that design mediums serve as active cognitive environments that manipulate cognitive load, subsequently influencing problem-solving strategies and

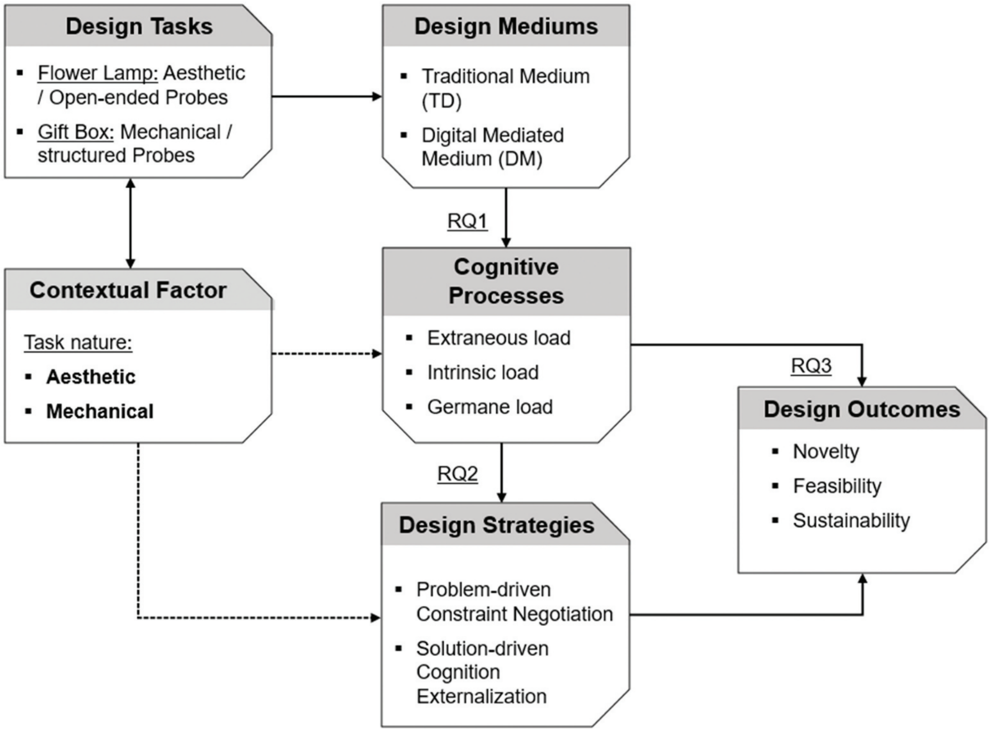

Figure 1. Conceptual framework with the research questions and cognitive load and design cognition integration.

ultimately shaping design outcomes. A quasi-experimental, between-subjects protocol study was conducted, comparing TD and DM mediums. The between-subjects design, in which each participant engaged with only one medium, was selected to prevent learning effects or strategy transfer that might arise if the same participants utilized both mediums, thereby confounding the measurement of each medium's individual cognitive impact.

To test the assumption that a medium's cognitive influence is task-dependent, we chose two different concept design tasks: an open-ended aesthetic task (flower lamp) and a structured mechanical task (gift box).

2.2.1. Flower Lamp (aesthetic/open-ended) design task

This task probed a synthetic, ill-defined problem space. The organic form-finding was intended to increase intrinsic and germane cognitive load for schema development while reducing reliance on preexisting digital templates.

2.2.2. Gift box (mechanical/structured) design task

This task probed an analytical, well-defined problem space. It was designed to test if digital resources reduce intrinsic load by providing predefined mechanisms and whether this advantage is offset by an increase in extraneous load, as proposed by our conceptual framework.

Table 1. Design tasks and research purpose alignment.

Research Purpose	Research Question	Data collection
Cognitive load (Extraneous, Intrinsic, Germane)	RQ1	Self-reported cognitive load scale; Verbal protocols indicating frustration/effort; Activity logs showing multitasking (DM group)
Design strategy (Problem-driven and solution-driven)	RQ2	Coded verbal protocols; Analysis of activity logs (search queries vs. sketching time)
Design outcomes and constraint-driven innovation (Novelty, Feasibility, Sustainability)	RQ3	Analysis of final concepts and descriptions; Protocol analysis for constraint mentions; Frequency counts of features

The two tasks were intentionally chosen to represent different perspectives on a spectrum that includes ill-defined to well-defined problems. This was necessary to move beyond a generic 'TD vs. DM' comparison and to empirically test the assumption, fundamental to our framework, that a medium's cognitive influence differs by task characteristics. In other words, this enabled us to determine whether digital tools reduce intrinsic load (task's nature) for well-defined problems while leaving ill-defined problems unaffected. The identical problem constraints (the blossoming of the flower lamp and the automatic opening of the gift box) for both groups may suggest that the observed differences stem from the influence of each medium on cognitive engagement. Moreover, the tasks were explicitly designed to elicit phenomena relevant to our research questions. Table 1 outlines this alignment, mapping each task characteristic to specific questions and data collection methods.

2.3. Experiment setup and tools

The experiments were conducted in controlled design labs. The TD group was provided exclusively with physical tools: guide notes, pencils, paper, erasers, and other necessary implements. They were restricted from using any digital tools or internet access.

The DM group was provided with a comprehensive digital workspace to replicate a modern design environment. This included the following components.

- Hardware: Laptops/PCs, tablets, and digital sketchpads (e.g., Wacom).
- Software: CAD (SolidWorks, Fusion 360), digital sketching (Adobe Illustrator, Procreate), and access to generative AI platforms.
- Resources: Unrestricted internet access for inspiration, tutorials, image libraries, and component databases.

The decision to provide high-fidelity tools like CAD during the early concept stage models the resource-rich digital environments of modern practice, where a full suite of tools is constantly available. This continuous access fundamentally alters the cognitive environment; the ability to instantly verify a mechanism or search for inspiration introduces cognitive loads and strategic temptations absent in traditional settings. Consequently, this study investigates the cognitive effects of this prevalent digital reality, rather than debating the appropriateness of specific tools. Tools for remote communication (e.g., Zoom, Teams) were excluded to maintain a focus on individual cognition.

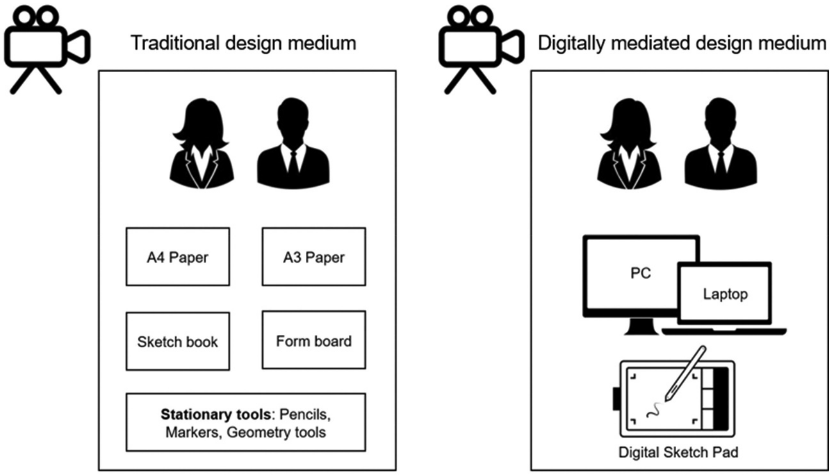

Figure 2. Experiment setups for TD and DM groups.

The decision to provide unrestricted internet access to the DM group, while restricting it for the TD group, is fundamental to the study's design. It implements the fundamental difference we aim to assess: the cognitive and strategic implications of being integrated within a vast, readily accessible digital information network rather than relying on internal knowledge and physical manipulation. This setup allowed us to isolate the phenomenon of digital resource dependence and its implications for concept design.

The experimental setup is illustrated in Figure 2.

2.4. Design tasks and procedure

Participants underwent a 15-minute briefing followed by a 90-minute design phase. The TD group used physical booklets and low-fidelity prototypes, while the DM group used digital tools and web resources. All participants were instructed to think aloud during the design process. Upon task completion, cognitive load was assessed via a self-reported scale, and digital activity logs were captured for the DM group. Final design outputs were collected from all participants.

The design tasks incorporated specific constraints to create a uniform, reproducible foundation for both groups (Dorst, 2015). This ensured that any differences in cognitive load, strategy, or outcome could be more accurately attributed to the design medium itself, rather than to variable interpretations of an open-ended brief. The central focus is therefore not on the constraints' existence but on how the features of TD and DM mediums influence a designer's cognitive and strategic adaptation to them. Figure 3 illustrates design briefs.

2.5. Data collection

Data were collected across three streams aligned with the conceptual framework.

Design brief: Flower lamp design concept

Main 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 must have moveable petals that can be unfolded in the shape of a flower.

Design requirements:

- *The lamp must resemble a flower.*
- *The lamp must have at least four movable petals.*
- *Ensure a unique and pleasant design.*
- *Try as many designs; just keep track of the time.*
- *Use any data source or digital assistance for the design process (only for the DM group)*

Sub tasks: (write down the following components of the design process)

1. *Main idea behind the proposed design*
2. *The design approaches at each stage*
3. *How did you handle issues that arose in the design process?*

Design brief: Gift box design concept

Main task

You must design a gift box that opens by being lifted from the sides. The design can be either simple or complex; just ensure that it is visually appealing. The moment the recipient grabs the box from the left and right sides, it automatically opens its upper cover.

Design requirements:

- *It must be opened by lifting from the sides.*
- *Ensure a unique and pleasant design.*
- *Try as many designs; just keep track of the time.*
- *Use any data source or digital assistance for the design process (only for the DM group).*

Sub tasks: (write down the following components of the design process)

1. *Main idea behind the proposed design*
2. *The design approaches at each stage*
3. *How did you handle issues that arose in the design process?*

Figure 3. Design brief: flower lamp and gift box design concepts.

2.5.1. Design outcomes

The outcomes include sketches and concept descriptions from both groups. The TD group's submissions of sketchbooks containing handwritten notes and acquired the DM group's digital sketches and document files.

2.5.2. Process data

The data include video and audio recordings of think-aloud protocols of both groups, and the DM's group digital activity logs (timestamps, search queries, and tool usage).

2.5.3. Cognitive load measurement

Cognitive load was measured using a validated 9-item scale, adapted from Naismith et al. (2015), Michalski et al. (2023), and Leppink et al. (2014). This scale consists of three subscales, each containing three items, which measure intrinsic, extraneous, and germane load. This scale is used as a standard self-report tool for assessing the individual subjective experience associated with each load component (see Appendix B for cognitive load scale). Participants rated each item using a 9-point scale (0 = not at all the case, 10 = completely the case) to reflect on their retrospective perception.

2.6. Data analysis

A mixed-method analysis was conducted that included quantitative and qualitative data analysis. This analytical approach was specifically formulated based on the pathways defined in our conceptual framework, using quantitative methods to assess the cognitive load assumptions (RQ1) and applying qualitative coding to map the emergent design strategies (RQ2) and their subsequent outcomes (RQ3).

Table 2. Thematic codes for qualitative analysis.

Category	Code	Definition
Inspiration	Organic reference	Drawing inspiration from nature or physical objects
	Digital sourcing	Using online platforms for inspiration
	Derived outcome	A concept closely mirrored a commonly found online solution
Strategy	Problem-driven	Focusing on user needs and core problem constraints
	Solution-driven	Adding features based on available digital content
	Iterative refinement	Evidence of repeated questioning and improvement
Cognition	Material engagement	Considering physical properties and feasibility
	Feasibility overlooked	Proposing solutions without considering production
Outcomes features	Novelty Usefulness Sustainability	New forms or unique functional integrations, feasible and eco-friendly materials, energy considerations

2.6.1. Quantitative analysis

A multi-variate analysis of variance (MANOVA) test was performed to compare cognitive load dimensions (intrinsic, extraneous, germane) between the TD and DM groups, with design medium (TD and DM) as the independent variable. Univariate tests along with Tukey post hoc comparison tests were performed to assess the impact of each design medium on the cognitive load dimensions of each group. All statistical tests were performed using IBM SPSS Statistics 25 software.

2.6.2. Qualitative analysis

Verbal protocols were transcribed thoroughly and categorized into statements representing a single thought or action. Two researchers separately coded a 20% sample utilizing NVivo and the codebook (see Table 2), obtaining an inter-coder reliability (Cohen's kappa) of 0.85. Discrepancies were resolved through discussions, subsequent to which one researcher finalized the categorization. This structured process enabled consistent identification of themes related to strategies and outcomes.

3. Results

3.1. Cognitive load differences across TD and DM mediums

Using the first pathway of our conceptual framework, we examined the different impacts of design mediums on cognitive load dimensions. The framework predicted that DM medium would increase extraneous load while exhibiting task-dependent effects on intrinsic load. To address RQ1, we analyzed the cognitive load dimensions across the two design mediums. The MANOVA test indicated a significant overall effect of the design medium on cognitive load (Wilks' $\Lambda = 0.866$, $F(3, 164) = 8.436$, $p < .001$). Univariate analyses showed that this effect was attributed to significant increases in extraneous cognitive load ($F(1, 166) = 23.732$, $p < .001$) within the DM medium, with mean scores significantly higher ($M = 4.5$, SD = 2.32) compared to the TD medium ($M = 3.0$, SD = 1.61). This pattern confirms that digital resources increased significant extraneous load through interface complexity and navigational demands. Neither intrinsic nor germane load exhibited medium-related differences in the overall analysis, suggesting

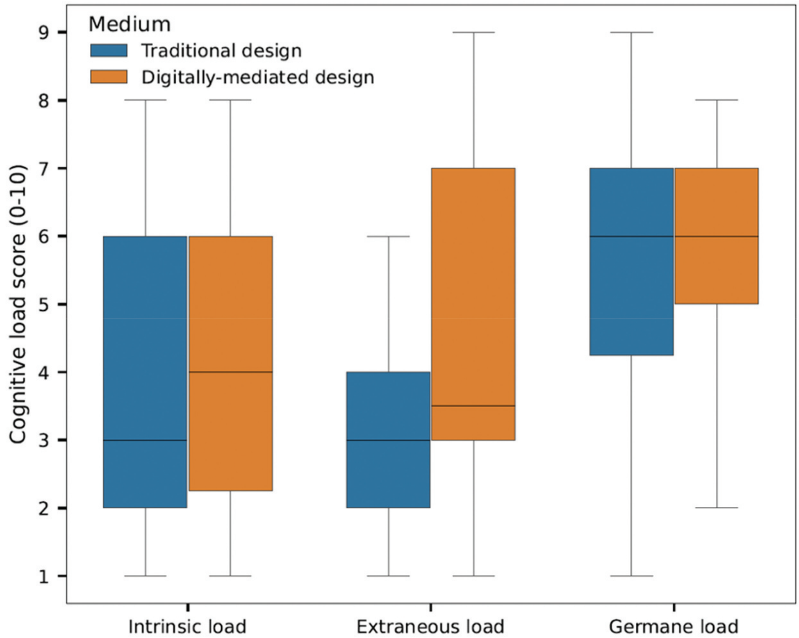

Figure 4. Cognitive load in the flower lamp concept design tasks.

a consistent perception of core content difficulty and knowledge integration across different design mediums.

The analysis of individual design tasks revealed a more detailed insight. For the flower lamp concept, the multivariate effect was significant (Wilks' $\Lambda = 0.881$, $F(3, 80) = 3.585$, $p = 0.017$), primarily influenced by extraneous load ($F(1, 82) = 10.877$, $p = 0.001$). The DM group had a significantly increased extraneous load ($M = 4.67$, $SD = 2.63$) compared to the TD group ($M = 3.10$, $SD = 1.62$) (see Figure 4). This indicates that for open-ended, aesthetic tasks, the DM medium's primary cognitive impact is an increase in extraneous load without alleviating the intrinsic challenge.

The gift box design task revealed a significant multivariate effect (Wilks' $\Lambda = 0.802$, $F(3, 80) = 6.597$, $p < 0.001$) with a twofold impact: the DM medium reduced intrinsic load ($F(1, 82) = 4.805$, $p = 0.031$) while increasing extraneous load ($F(1, 82) = 13.165$, $p < 0.001$) (see Figure 5). This result indicates a cognitive trade-off specific to well-defined mechanical tasks, where digital tools simplify the core geometric challenge (lower intrinsic load) but impose new interface-related demands (higher extraneous load).

3.1.1. Extraneous load

The quantitative results showed that the DM medium consistently increased extraneous load across all design tasks (overall: +50%, flower lamp: +51%, gift box: +51%). Largest effect sizes observed: $\eta^2 = 0.125$ (overall), $\eta^2 = 0.117$ (flower lamp). These results were strongly supported by the qualitative outcomes; the DM group demonstrated tool-dependent cognition: frequent platform switching ('searched Pinterest, Google, Etsy'), interface management burden (' . . . drawing on Wacom tablet is slow'), and information

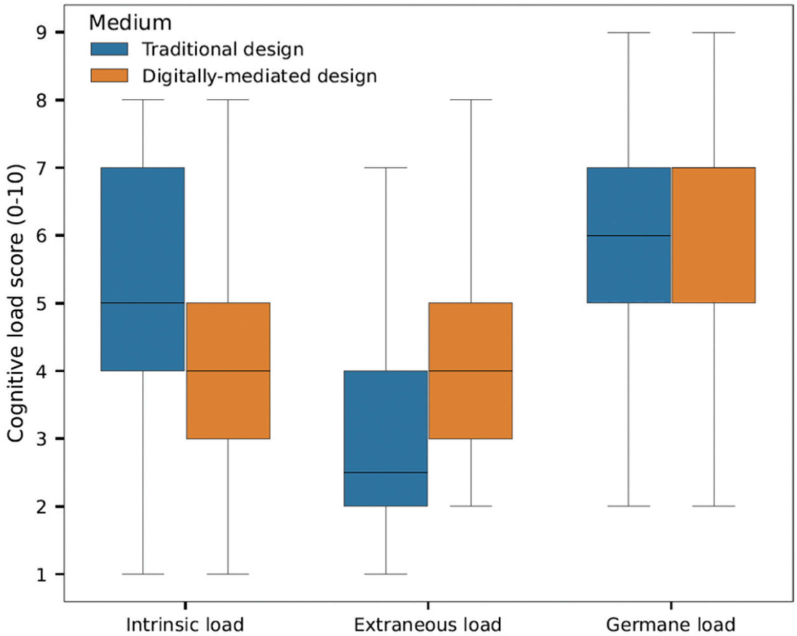

Figure 5. Cognitive load in the gift box concept design tasks.

fragmentation ('combined 5 internet sources'). This indicates that digital tools introduce a consistent transactional overhead that consumes working memory.

3.1.2. *Intrinsic load*

Digital tools reduced the intrinsic load for the gift box design (–29%) but not for the flower lamp design. The TD medium maintained higher intrinsic demand across tasks. In the gift box concept design (mechanically complex), digital tools simplified core challenges through instant access to mechanism templates (' . . . found origami structures online') and simulation capabilities (' . . . tested box opening in CAD'). In the flower lamp concept design (aesthetically complex), organic inspiration resisted digital simplification: ' . . . Nature's complexity can't be Googled' (TD4), and ' . . . Digital references made tulip design more confusing' (DM2). This supports the finding that digital tools reduce intrinsic load only for tasks with definitive solution spaces, preexisting digital templates.

3.1.3. *Germane load*

The TD group consistently reported in a higher germane load (gift box: +23%, flower lamp: +22%), though these differences were not statistically significant in the MANOVA

Table 3. Germane load dimensions in the traditional and digitally mediated design medium.

Germane load Dimension	TD medium	DM medium
Schema building	TD8's iterative cake box refinement	DM5's copied piano-key mechanism
Deep processing	"*What if?*" explorations (TD4)	"*Searched and pasted*" (DM3)
Knowledge integration	Mechanical customization (TD5)	Sensor add-ons without integration (DM4)

test. However, qualitative analysis of the germane load dimensions indicated significant differences in the allocation of cognitive resources for schema construction (see Table 3).

The TD medium enhances mental model representation through manual illustration and physical prototyping, fostering embodied knowledge and deeper constraint engagement. In contrast, DM medium showed significantly lower novel concept development (−62%) and higher derived solutions (+73%), suggesting that while the effort devoted to learning (germane load) may be similar, the quality and depth of the resulting cognitive schemas differ significantly between mediums.

3.2. *Emergent design strategies in TD and DM mediums*

In accordance with the framework's mediating pathway from cognitive load to design strategy, the results identified distinct problem-solving strategies emerging from the cognitive environments of each medium. To address RQ2, the design strategies were analyzed that emerged in each medium. In flower lamp design, the TD group emphasized physical mechanics: 71% employed user scenario simulation, and 57% integrated sustainability (e.g., TD1's solar-powered motors, TD3's brightness-sensing petals). This reflects a problem-driven strategy focused on core requirements. The DM group, however, prioritized abstract sensory objectives (71%), with trend mining replacing core exploration in 57% of protocols. Digital borrowing dominated as DM4 used Google for floral shapes, DM5 added video displays, and DM7 implemented automation. This indicates a solution-driven strategy introduced by digital inspiration rather than problem analysis.

For gift box design, the TD group leveraged constraint-based iteration: 79% featured material-driven innovation (TD1's multi-functional box), and 64% used scenario-based validation (TD4's theme-driven forms). Their strategy was defined by a deep engagement with the problem's physical and user constraints. The DM group relied on digital scaffolding: DM3 admitted 'search[ing] Google and copy[ing] answers' and DM2 refined search algorithms, demonstrating a strategy of externalizing the problem-solving process.'

The strategies manifested in different approaches to ideation and problem refinement. The TD group showed a focus on function first (like TD3's solar sensor) inspired by real examples (TD2's Arco Castiglioni reference, TD5's sunflower concept) and awareness of production (TD3's 3D-printing question, TD8's cost assessment). The DM group aimed for feature-first expansion (like DM1's mood-changing lamp) using digital inspirations (DM1's Plants vs. Zombies, DM7's Avatar) and prioritizing experiential curation (DM1's multisensory journey) but overlooked feasibility (DM7's sci-fi petal dispersal, DM8's ' . . .

Table 4. Critical observations in both groups design activities.

Observation	Explanation
Digital dependency	DM group showed a 73% higher incidence of unverified solution adoption (e.g., "copy the answers" DM3) versus TD group' hands-on experimentation.
Cognitive strategy	TD group adopted problem-solving (evidenced by mechanical descriptions), while DM group externalized cognition through tools (search engines, digital references).
Innovation outcomes	Digital tools expanded solution possibilities but reduced novel recombination: only 25% of the participants in the DM group demonstrated conceptual innovations versus 63% in the TD group.
Feature integration	The TD group incorporated 5× more environmental considerations (e.g., solar power, material choices) despite the DM group's advanced technical capabilities.

breathing effects'). These differences in the strategy formulation are summarized in Table 4, which highlights the fundamental cognitive and behavioral divergence between the TD and DM groups.

The digital activity logs of the selected participants in the DM group demonstrated their design processes, searching strategies, and problem-solving activities; they are presented in Supplementary Material A.

3.3. The influence of medium on design outcomes

The framework's final pathway proposed that medium-induced cognitive and strategic differences would result in measurable outcome differences, particularly through different interactions with constraints. Regarding RQ3, the qualitative analysis revealed a direct link between medium, strategy, and outcome. The TD group demonstrated organic, constraint-driven innovation, emphasizing material feasibility, tactile interaction, and sustainability through iterative hands-on refinement and prototyping. Conversely, the DM group produced broader but more derived concepts, integrating multisensory features and crowdsourcing but often overlooking core requirements like manufacturability and sustainability. Their outcomes were characterized by feature-complexity but lower conceptual novelty and feasibility.

This divergence is evident in the conceptual origin of their ideas. The TD group's flower lamp concepts were predominantly organic (87%) (13 out of 15 revenant protocols) inspired by specific flora like sunflowers, tulips, and lotuses), with 63% emphasizing environmental integration. TD3 integrated sunlight-responsive automation (' … the flower lamp can autonomously activate/deactivate using sunlight'), while TD4 demonstrated solution-oriented pragmatism.

The DM group expanded conceptual boundaries digitally: DM1 and DM5 pursued cross-domain integration (e.g., breathing effects combined with music), DM2 referenced pop culture (Avatar-inspired petal dispersal), and DM6 designed abstract sensory experiences (e.g., unfolding in cold water) but this often resulted in concepts that were technologically ambitious yet physically ungrounded. The flower lamp concept design sketches by the TD and DM group are presented in Figure 6.

For gift box design, the TD group prioritized psychological surprise (TD1: ' … simple designs maximize surprise'), anthropomorphic interaction (TD2's Pokémon-style touch-activated box), and mechanical simplicity (TD3's dowel-lock mechanism).

The DM group emphasized technological innovation: 64% incorporated multisensory feedback, 29% embedded intelligence (e.g., emotion-sensing), and adaptive functionality (DM1's size-adjustable box). Participants sketches for the gift box concept design in the TD and DM group are presented in Figure 7.

Overall, the conceptual framework describes specific cognitive mechanisms by which design mediums influence design outcomes. The DM medium increases extraneous cognitive load due to its complex interface and abundant information resources, leading to solution-driven strategies that prefer external curation over deep problem engagement. This strategic shift results in outcomes with higher feature complexity but lower conceptual novelty and sustainability.

The framework demonstrates a task-dependent mediation: for mechanical tasks with clearly defined solution spaces, digital resources can reduce intrinsic load,

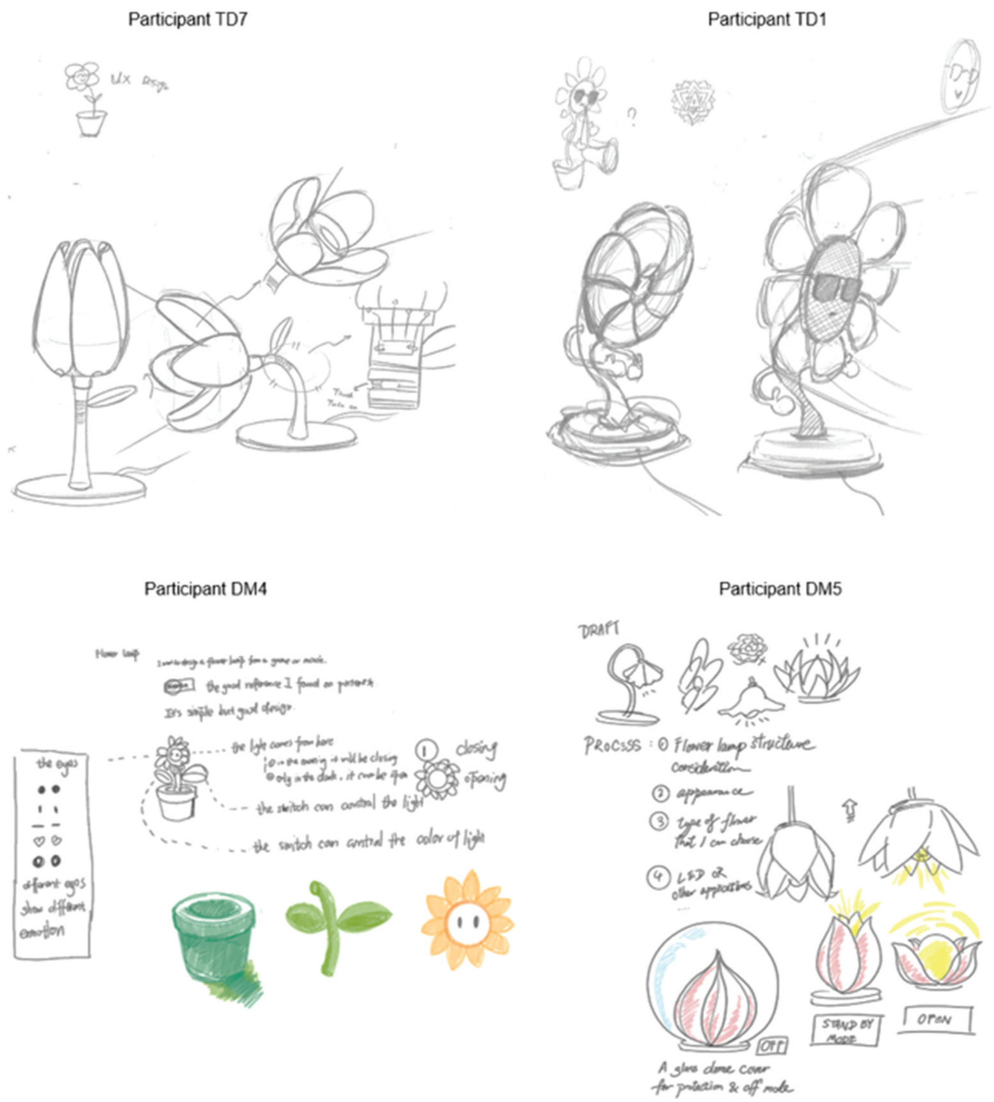

Figure 6. Representative sketches for flower lamp concept design (TD and DM).

potentially enhancing specific elements of the design process. However, in the context of open-ended aesthetic tasks, this benefit disappears while the extraneous load cost remains. The TD medium, with lower extraneous load and deeper engagement with physical constraints, consistently promotes problem-driven strategies that result in more innovative, feasible, and sustainable outcomes across task types. The framework reveals the differences across mediums and the fundamental cognitive and strategic mechanisms that lead to different creative pathways (see Figure 8).

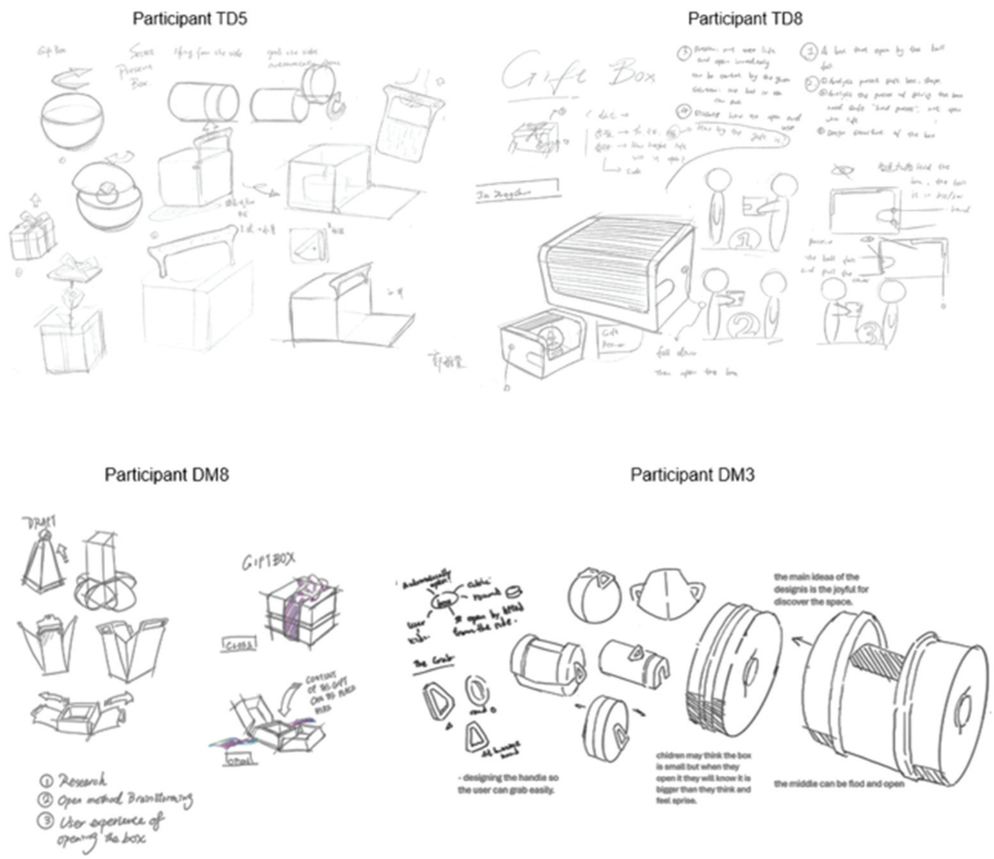

Figure 7. Representative sketches for gift box concept design (TD and DM).

4. Discussion

Based on the conceptual framework, the results revealed multiple pathways from the medium environment through cognitive processes to creative outcomes, with the nature of the task serving as a key moderating factor. The study explored the cognitive and strategic impacts of design mediums using CLT and constraint-driven cognition. The results addressed the three research questions, indicating that the design medium functions as an active participant rather than a neutral medium, influencing cognition, strategy, and design outcomes.

4.1. Cognitive load dynamics in TD versus DM mediums

The results of RQ1 reveal the dynamics of cognitive load, demonstrating the observed patterns and trade-offs among intrinsic, extraneous, and germane loads across the two mediums and task types. The DM medium induces a significant extraneous cognitive load, thereby supporting CLT within a modern design context (Kirschner, 2002; Sweller et al., 2019). The DM group demonstrated a substantially higher extraneous cognitive load compared to the TD group, with mean increases of +1.57 points for the flower lamp

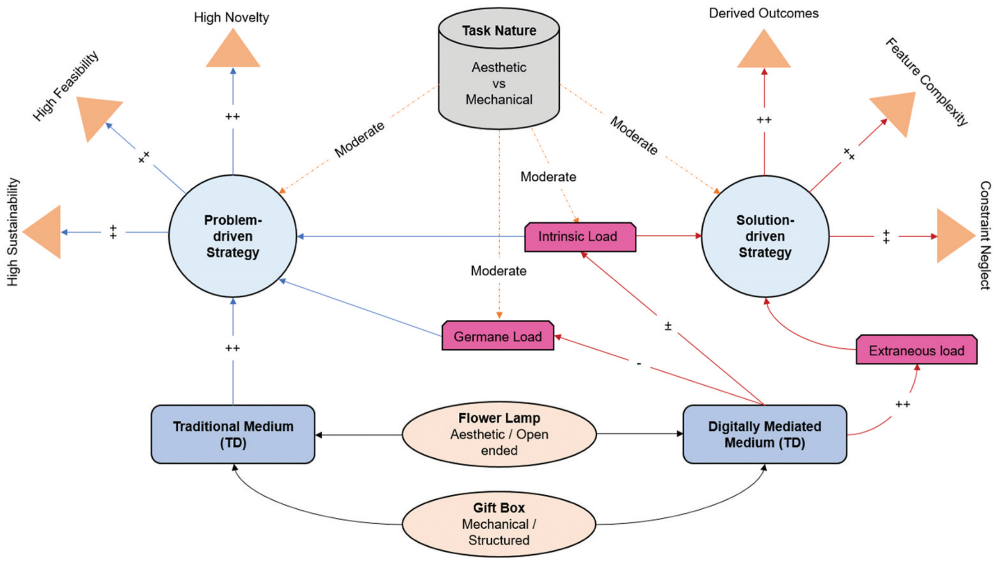

Figure 8. The cognitive-mediation framework with predicted pathways, influencing cognitive process through design mediums.

concept and +1.42 points for the gift box concept. This finding aligns with Cezar and Maçada (2023), who found that excessive information and online stimuli increase extraneous load and disorganize attention. This cognitive load can also be interpreted in view of affective resources; as Sudha and Premkumar (2025) suggest, digital interfaces may induce frustration that reduces the conative resources necessary for sustained creative exploration. This increased cognitive load manifested through three primary mechanisms: attentional fragmentation, indicated by frequent tool-switching in activity logs (e.g., DM6's 43 distinct search queries within 44 minutes), and interface management issues, explicitly observed in verbal protocols (e.g., DM4's remark, '... drawing on a digital tablet is not useful for controlling lines'). Information overload, leading to a 73% increase in unverified solution adoption relative to the TD group. These mechanisms support Hawlitschek and Joeckel (2017), who found that extraneous load increases distractions and non-essential processing. The resulting cognitive demands reduce the limited working memory resources essential for creative synthesis, corroborating Stones and Cassidy's (2007) findings on how digital interfaces can hinder deep creative thinking and are consistent with Shanmugasundaram and Tamilarasu's (2023), who identified challenges from attentional fragmentation. This situation illustrates the core challenge for designers: the digital medium offers an exceptional repository of resources while simultaneously imposing a continuous demand for cognitive management, whether the tools are actively used or merely available as options.

However, the finding of a context-dependent intrinsic load is crucial. The decrease in intrinsic load for the DM group in the structured gift box task (−29%) confirms Howard et al. (2008) finding that digital tools can reduce geometric complexity. Nevertheless, this advantage was task-specific and disappeared in the open-ended aesthetic task of designing a flower lamp, a point captured by TD4's statement that ' ... nature's complexity cannot be Googled.' This result challenges the presumption of universal digital effectiveness and supports Chandrasekera et al. (2025) claim that AI-based tools must contextualize innovations within human culture and history to foster true creativity.

This task-specific efficacy has been confirmed by other studies; for instance, Barbieri and Muzzupappa (2024) found that generative design tools improved form invention, while Kim and Maher (2023) indicated that AI offering conceptually similar inspirations can enhance novelty. However, these advantages appear tied to structured tasks or specific AI interactions, contrasting with the broad, less-structured digital environment in our study, which resulted in a net increase in cognitive load. Finally, while germane cognitive load (associated with learning) remained statistically significant across both groups, qualitative protocol analysis revealed significant differences in its application. The TD group employed iterative ' … What if?' questioning to resolve constraints, whereas the DM group engaged in fragmented feature collecting without functional integration (e.g., DM8's underdeveloped 'breathing effect, scent, video' concepts). The observed cognitive load patterns support the framework's first assumption regarding the task-dependent nature of digital tools' effectiveness. The finding that digital tools reduce intrinsic load for mechanical tasks but not for aesthetic tasks highlights the inadequate nature of standard guidelines for digital tool efficacy.

4.2. Emergent problem-solving strategies

The results for RQ2 indicate a fundamental strategic divergence influenced by the medium, providing strong support for Bilda and Demirkan's (2003) assertion that traditional media facilitate problem-driven cognition. In the TD group, material-led iteration was the most common method, with 79% using constraint-based physical prototyping (for example, TD3's elegant dowel locking mechanism). Through scenario-based validation, 64% of participants demonstrated deep user empathy (e.g., TD5: ' … consider users' … fundamental needs') and incorporated sustainability considerations at a rate five times greater than the DM group. The implementation of these problem-driven strategies led to a significant increase in solution novelty, with 63% of TD innovations being conceptual, compared to 25% in the DM group. Conversely, the DM medium effectively externalized cognition, transforming the designer's primary role from problem-solver to solution-curator (Casais, 2020). This corresponds with Wang et al. (2023), who found that designers increasingly use digital tools to communicate interactive and environmental qualities, indicating a broader industry shift toward solutions-driven processes. The DM group's strategy featured cross-domain integration, crowd-sourced validation (71% engaged in trend mining, e.g., DM4 ' … searching for gift box design examples'), and technical expansion (14% of DM solutions addressed manufacturability, contrasting with the TD group's constant emphasis on feasibility). This strategic difference elucidates the innovation gap and corroborates Robertson and Radcliffe's (2009) concerns over premature fixation in digital processes.

Patricio et al. (2024) highlight the significance of managing this strategic shift, suggesting that effective digital collaboration requires structured processes and 'digital empathy' to bridge communication gaps and reduce the cognitive and strategic fragmentation observed in our DM group. While digital tools facilitated the extension of integrated features (e.g., DM5's piano-key gift box), they also resulted in derivative outcomes, exemplified by DM6's near-replication of an existing IKEA lamp. These results corroborate Fleury et al. (2021) and Kosmadoudi et al. (2013), indicating that simplified design environments enhance creative performance by reducing external stimuli. The digital activity logs indicated that digital tools both enhance and fragment cognition, corroborating Richey et al.'s (2012) theory that an abundance of resources can inconsistently narrow solution spaces. This heterogeneity indicates that digital tools require strategic curation, which design education currently lacks. As Gupta et al. (2024) suggest regarding generative AI in instructional design, educators must develop comprehensive strategies to encourage tool use without compromising creative outcomes.

4.3. Impact on design outcomes and constraint negotiation

The main results for RQ3 provide strong evidence for a constraint-driven interpretation of the observed outcomes. The TD group's process demonstrated effective innovation driven by constraints (Fu et al., 2024; Wang et al., 2018). Their deep engagement, iterative questioning, and emphasis on feasibility show a cognitive cycle of identifying, negotiating, and addressing constraints (e.g., TD3's dowel-lock mechanism and TD1's solar-power integration). This deep engagement with material and mechanical constraints supports Bilda and Demirkan's (2003) claim that traditional media helps define problems and prevents the infinite increase of design convergence space (Fu et al., 2024). The result was more innovative and production-aware outcomes, with the TD group achieving 63% solution novelty compared to 25% in the DM group and integrating five times more sustainability considerations, thereby preventing premature fixation (Robertson & Radcliffe, 2009). This finding has direct implications for design education. Prabhu et al. (2023) showed that a modular educational strategy effectively regulates cognitive load to improve learning, indicating that similar structured approaches could be developed to help students manage the cognitive demands of digital tools while maintaining the advantages of deep constraint engagement.

Conversely, the DM group's increased extraneous load and solution-oriented approach frequently resulted in the neglect of fundamental constraints. The availability of unlimited digital information broadened the solution space; however, in the absence of immediate physical and material constraints, it led to several misleading solutions (Fu et al., 2024). Thus, the primary advantage of the DM medium, infinite information, ironically resulted in more derived and less substantive outcomes due to a lack of deep constraint engagement.

5. Conclusions

This study presents empirical evidence that design mediums serve as active cognitive environments rather than neutral tools, significantly influencing designers' cognitive load, problem-solving strategies, and creative outcomes. An empirical investigation guided by CLT and constraint-driven cognition reveals the following three main results:

First, the results demonstrate that the DM medium imposes a significant extraneous cognitive load through attentional fragmentation, interface management, and information overload, validating CLT in current design contexts. This load consumes working memory resources essential for creative synthesis, supporting previous concerns about digital tools hindering deep creative thinking. However, this cognitive cost is balanced by digital tools' capacity to reduce intrinsic load for well-defined mechanical tasks, though this advantage disappears for open-ended aesthetic tasks where 'nature's complexity cannot be Googled.'

Second, the study reveals a fundamental strategic divergence: TD medium fosters problem-driven cognition through material engagement and constraint negotiation, while DM medium promotes solution-driven approaches that externalize cognition and risk premature fixation. This strategic difference accounts for the significant outcome gap, as the TD medium produces substantially higher conceptual novelty (63% compared to 25%) and five times more sustainability considerations.

Finally, the results provide empirical evidence for constraint-driven innovation, showing that traditional constraints focus creative efforts and limit infinite solution spaces; however, an abundance of digital tools often leads to derived outcomes because constraints are frequently overlooked.

5.1. Theoretical and practical implications

This study offers significant theoretical contributions. First, it empirically validates cognitive load dynamics in design mediums, clarifying discrepancies in prior load-creativity research (Calpin & Menold, 2023; Redifer et al., 2019) by demonstrating the task-dependent effectiveness of tools. By defining 'digital dependency' via activity logs, it provides evidence corroborating Marion and Fixson's (2021) concerns about the decline of deep problem exploration. The results indicate that digital mediation externalizes cognition (Casais, 2020), reallocating mental effort from the problem space to the solution space. Incorporating CLT expands insights from expertise-load research (Sun et al., 2014) into medium comparisons, necessitating a reconsideration of digital tool integration.

For design education, curricula must extend beyond technical training to teach digital metacognition, such as using 'search quotas' to optimize cognitive resources. Developing tactile skills through hand sketching and physical prototyping is essential to preserve constraint-driven innovation (Schembri et al., 2015), countering traditional skill loss and complete digitalization (Aldoy & Evans, 2021). Assessment frameworks should incorporate load-aware cognitive efficiency metrics alongside solution quality.

For practice, professionals should implement hybrid approaches: traditional ideation for open-ended tasks and digital execution for mechanical tasks. To reduce the DM medium's high extraneous load, practices should restrict concurrent tools and use sequential processes. Digital tools need integrated sustainability guidelines to address identified deficiencies. Despite cognitive costs, digital tools should be strategically used for their advantages in producing organized outcomes, enhancing clarity, accelerating processes, facilitating modifications, and improving stakeholder communication (Ateş & Köroğlu, 2024).

5.2. Limitations and future work

This study's results should be considered within its limitations, which outline clear directions for future research. First, the sample size of 16 participants, although appropriate for an in-depth mixed-methods protocol study involving comprehensive verbal analysis, limits the statistical power and generalizability of quantitative results, such as the MANOVA results. The size of this sample exemplifies a common trade-off in design cognition research, prioritizing depth of process data over scope. Therefore, the current sample size is typical for foundational cognitive studies that emphasize rich qualitative process data, and it was appropriate to uncover different and consistent patterns in cognitive load and strategy across the two groups. However, further study with larger samples will be needed to validate the effect sizes of the changes in cognitive load. Secondly, the inclusion of student participants presents a limitation, which implies that the cognitive strategies observed in their design processes may differ from those of expert designers. However, master's students with 2–5 years of experience represent emerging designers who are actively developing their cognitive strategies with modern digital tools. Their processes are thus important for understanding the formative influence of design mediums and for guiding educational practice. Third, the strict separation of TD and DM mediums, while methodologically necessary for isolating their specific cognitive effects, does not reflect the cohesive nature of professional practice. This controlled separation was crucial for establishing the baseline causal effects of each medium and thus providing a clear foundation for future studies on hybrid workflows. The specific characteristics of the two design tasks may not represent the full spectrum of design problems. The selected tasks, while not detailed, effectively demonstrated the fundamental difference between open-ended aesthetic and structured mechanical problems, enabling us to highlight the critical role of task types as moderators, which is an important result of this study. Future research should employ multimodal methods (EEG, eye-tracking) for real-time cognitive measurement and explore these cognitive and strategic patterns across a variety of tasks and domains. Building on this foundation, subsequent studies can develop effective educational strategies and design processes that optimize the cognitive benefits of both traditional and digital mediums.

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References

Aldoy, N., & Evans, M. (2021). An investigation into a digital strategy for industrial design education. *International Journal of Art & Design Education*, *40*(1), 283–302. https://doi.org/10.1111/jade.12334

Al-Rqaibat, S. A., Bataynah, R., & Al-Nusair, S. (2025). Impact of implementing digital tools in the basic design studios on the students' design process in the following years. *International Journal of Technology and Design Education*, 1–25. https://doi.org/10.1007/s10798-025-10029-8

Ashrafganjouei, M., & Gero, J. S. (2021). Exploring the effect of a visual constraint on students' design cognition. *AI EDAM*, *35*(1), 3–19. https://doi.org/10.1017/S0890060420000335

Ateş, H., & Köroğlu, M. (2024). Online collaborative tools for science education: Boosting learning outcomes, motivation, and engagement. *Journal of Computer Assisted Learning*, *40*(3), 1052–1067. https://doi.org/10.1111/jcal.12931

Barbieri, L., & Muzzupappa, M. (2024). Form innovation: Investigating the use of generative design tools to encourage creativity in product design. *International Journal of Design Creativity and Innovation*, *12*(3), 163–182. https://doi.org/10.1080/21650349.2024.2336972

Bennett, S., Maton, K., & Kervin, L. (2008). The 'digital natives' debate: A critical review of the evidence. *British Journal of Educational Technology*, *39*(5), 775–786. https://doi.org/10.1111/j.1467-8535.2007.00793.x

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

Bilda, Z., & Gero, J. S. (2007). The impact of working memory limitations on the design process during conceptualization. *Design Studies*, *28*(4), 343–367. https://doi.org/10.1016/j.destud.2007.02.005

Boekaerts, M. (1997). Self-regulated learning: A new concept embraced by researchers, policy makers, educators, teachers, and students. *Learning and Instruction*, *7*(2), 161–186. https://doi.org/10.1016/S0959-4752(96)00015-1

Broadbent, J., Panadero, E., Lodge, J. M., & de Barba, P. (2020). Technologies to enhance self-regulated learning in online and computer-mediated learning environments. In M. J. Bishop, J. Elen, E. Boling, & V. Svihla (Eds.), *Handbook of research in educational communications and technology*. Springer.

Budinoff, H. D., McMains, S., & Shonkwiler, S. (2024). Exploring the impact of design tool usage on design for additive manufacturing processes and outcomes. *Design Science*, *10*, e1. https://doi.org/10.1017/dsj.2023.34

Burdick, A., & Willis, H. (2011). Digital learning, digital scholarship and design thinking. *Design Studies*, *32*(6), 546–556. https://doi.org/10.1016/j.destud.2011.07.005

Calpin, N., & Menold, J. (2023). The cognitive costs of design tasks: Examining cognitive load through verbal and physical indicators. *Journal of Mechanical Design*, *145*(10), 101401. https://doi.org/10.1115/1.4062976

Camba, J. D., Kimbrough, M., & Kwon, E. (2018). Conceptual product design in digital and traditional sketching environments: A comparative exploratory study. *Journal of Design Research*, *16*(1/2), 131–149.

Casais, M. (2020). Facilitating complex knowledge in design education through design tools. In D. Raposo, J. Neves, & J. Silva (Eds.), *Research & education in design: People & processes & products & philosophy* (pp. 3–12). CRC Press.

Cascini, G., Nagai, Y., Georgiev, G. V., Zelaya, J., Becattini, N., Boujut, J. F., Casakin, H., Crilly, N., Dekoninck, E., Gero, J., Goel, A., Goldschmidt, G., Gonçalves, M., Grace, K., Hay, L., Le Masson, P., Maher, M. L., Marjanović, D.Motte, D. . . . Wodehouse, A. (2022). Perspectives on design creativity and innovation research: 10 years later. *International Journal of Design Creativity and Innovation*, *10*(1), 1–30. https://doi.org/10.1080/21650349.2022.2021480

Cascini, G., O'Hare, J., Dekoninck, E., Becattini, N., Boujut, J. F., Guefrache, F. B., Carli, I., Caruso, G., Giunta, L., & Morosi, F. (2020). Exploring the use of AR technology for co-creative product and packaging design. *Computers in Industry*, *123*, 103308. https://doi.org/10.1016/j.compind.2020.103308

Cezar, B. G. D. S., & Maçada, A. C. G. (2023). Cognitive overload, anxiety, cognitive fatigue, avoidance behavior and data literacy in big data environments. *Information Processing & Management*, *60*(6), 103482. https://doi.org/10.1016/j.ipm.2023.103482

Chandrasekera, T., Hosseini, Z., & Perera, U. (2025). Can artificial intelligence support creativity in early design processes? *International Journal of Architectural Computing*, *23*(1), 122–136. https://doi.org/10.1177/14780771241254637

Chen, Y. C., Chang, Y. S., & Chuang, M. J. (2022). Virtual reality application influences cognitive load-mediated creativity components and creative performance in engineering design. *Journal of Computer Assisted Learning*, *38*(1), 6–18. https://doi.org/10.1111/jcal.12588

Costa, L. V., Veloso, A. I., & Martins, F. (2020). Digitally-mediated learning environments and information literacy for active ageing: A pilot study. In S. Cristina & I. Ido (Eds.), *Technology, Innovation, Entrepreneurship and Education: 3rd EAI International Conference, TIE 2019* (pp. - 80–90). Springer, Braga, Portugal.

Cramp, A. (2015). Meaningful dialogue in digitally mediated learning for in-service teacher development. *Technology, Pedagogy and Education*, *24*(1), 1–16. https://doi.org/10.1080/1475939X.2013.822417

Cramp, A., & Lamond, C. (2016). Engagement and kindness in digitally mediated learning with teachers. *Teaching in Higher Education*, *21*(1), 1–12. https://doi.org/10.1080/13562517.2015.1101681

Cross, N. (2010). Understanding Design Thinking. In G. Luca (Ed.), *Notes on doctoral research in design* (pp. 19–37).

Cross, N. (2021). *Engineering design methods: Strategies for product design* (5th ed.). Wiley.

Da Silva, R. H., Kaminski, P. C., & Armellini, F. (2020). Improving new product development innovation effectiveness by using problem solving tools during the conceptual development phase: Integrating design thinking and TRIZ. *Creativity and Innovation Management*, *29*(4), 685–700. https://doi.org/10.1111/caim.12399

De Jong, T. (2010). Cognitive load theory, educational research, and instructional design: Some food for thought. *Instructional Science*, *38*(2), 105–134. https://doi.org/10.1007/s11251-009-9110-0

De Rooij, A., Dekker, E., Slegers, K., & Biskjaer, M. M. (2021). How graphic designers rely on intuition as an ephemeral facility to support their creative design process. *International Journal of Design Creativity and Innovation*, *9*(4), 252–268. https://doi.org/10.1080/21650349.2021.1951358

Dignath, C., Buettner, G., & Langfeldt, H. P. (2008). How can primary school students learn self-regulated learning strategies most effectively?: A meta-analysis on self-regulation training programmes. *Educational Research Review*, *3*(2), 101–129. https://doi.org/10.1016/j.edurev.2008.02.003

Dorst, K. (2015). Frame creation and design in the expanded field. *She Ji: The Journal of Design, Economics, and Innovation*, *1*(1), 22–33. https://doi.org/10.1016/j.sheji.2015.07.003

Evans, M., & Aldoy, N. (2016). Digital design sketching using the tablet PC. *The Design Journal*, *19*(5), 763–787. https://doi.org/10.1080/14606925.2016.1196091

Fang, C., Zhu, Y., Fang, L., Long, Y., Lin, H., Cong, Y., & Wang, S. J. (2025). Generative AI-enhanced human-AI collaborative conceptual design: A systematic literature review. *Design Studies*, *97*, 101300. https://doi.org/10.1016/j.destud.2025.101300

Feeman, S. M., Wright, L. B., & Salmon, J. L. (2018). Exploration and evaluation of CAD modeling in virtual reality. *Computer-Aided Design and Applications*, *15*(6), 892–904. https://doi.org/10.1080/16864360.2018.1462570

Fleury, S., Blanchard, P., & Richir, S. (2021). A study of the effects of a natural virtual environment on creativity during a product design activity. *Thinking Skills and Creativity*, *40*, 100828. https://doi.org/10.1016/j.tsc.2021.100828

Frederiksen, J. G., Sørensen, S. M. D., Konge, L., Svendsen, M. B. S., Nobel-Jørgensen, M., Bjerrum, F., & Andersen, S. A. W. (2020). Cognitive load and performance in immersive virtual reality versus conventional virtual reality simulation training of laparoscopic surgery: A randomized trial. *Surgical Endoscopy*, *34*(3), 1244–1252. https://doi.org/10.1007/s00464-019-06887-8

Fu, X., Zhang, H., Jing, L., Fan, X., Lu, C., & Jiang, S. (2024). A constraint-driven conceptual design approach for product based on function-behavior-structure design process. *Computers & Industrial Engineering*, *189*, 109994. https://doi.org/10.1016/j.cie.2024.109994

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

Gupta, P., Mahajan, R., Badhera, U., & Kushwaha, P. S. (2024). Integrating generative AI in management education: A mixed-methods study using social construction of technology theory. *The International Journal of Management Education*, *22*(3), 101017. https://doi.org/10.1016/j.ijme.2024.101017

Hancock, G. M., Longo, L., Young, M. S., & Hancock, P. A. (2021). Mental workload. In G. Salvendy & W. Karwowski (Eds.), *Handbook of human factors and ergonomics* (5th ed. pp. 203–226). Wiley.

Hanna, R., & Barber, T. (2001). An inquiry into computers in design: Attitudes before-attitudes after. *Design Studies*, *22*(3), 255–281. https://doi.org/10.1016/S0142-694X(00)00029-6

Hattie, J. A. C., & Donoghue, G. M. (2016). Learning strategies: A synthesis and conceptual model. *NPJ Science of Learning*, *1*(1), Article 16013. https://doi.org/10.1038/npjscilearn.2016.13

Hawlitschek, A., & 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*, 79–86. https://doi.org/10.1016/j.chb.2017.01.040

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

Jukes, I., McCain, T., & Crockett, L. (2010). *Understanding the digital generation: Teaching and learning in the new digital landscape*. Corwin.

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

Kim, J., & Maher, M. L. (2023). The effect of AI-based inspiration on human design ideation. *International Journal of Design Creativity and Innovation*, *11*(2), 81–98. https://doi.org/10.1080/21650349.2023.2167124

Kirschner, P. A. (2002). Cognitive load theory: Implications of cognitive load theory on the design of learning. *Learning and Instruction*, *12*(1), 1–10. https://doi.org/10.1016/S0959-4752(01)00014-7

Kosmadoudi, Z., Lim, T., Ritchie, J., Louchart, S., Liu, Y., & Sung, R. (2013). Engineering design using game-enhanced CAD: The potential to augment the user experience with game elements. *Computer-Aided Design*, *45*(3), 777–795. https://doi.org/10.1016/j.cad.2012.08.001

Krieglstein, F., Beege, M., Rey, G. D., Ginns, P., Krell, M., & Schneider, S. (2022). A systematic meta-analysis of the reliability and validity of subjective cognitive load questionnaires in experimental multimedia learning research. *Educational Psychology Review*, *34*(4), 2485–2541. https://doi.org/10.1007/s10648-022-09683-4

Kruger, C., & Cross, N. (2006). Solution driven versus problem driven design: Strategies and outcomes. *Design Studies*, *27*(5), 527–548. https://doi.org/10.1016/j.destud.2006.01.001

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), 383–391. https://doi.org/10.1016/j.autcon.2004.08.005

Leppink, J., Paas, F., Van Gog, T., van der Vleuten, C. P. M., & Van Merriënboer, J. J. G. (2014). Effects of pairs of problems and examples on task performance and different types of cognitive load. *Learning and Instruction*, *30*, 32–42. https://doi.org/10.1016/j.learninstruc.2013.12.001

Li, C. (2017). Why do online consumers experience information overload? An extension of communication theory. *Journal of Information Science*, *43*(6), 835–851. https://doi.org/10.1177/0165551516670096

Marion, T. J., & Fixson, S. K. (2021). The transformation of the innovation process: How digital tools are changing work, collaboration, and organizations in new product development. *Journal of Product Innovation Management*, *38*(1), 192–215. https://doi.org/10.1111/jpim.12547

Michalski, C., Cowan, M., Bohinsky, J., Dickerson, R., & Plochocki, J. H. (2023). Evaluation of cognitive load for a mixed reality anatomy application. *Translational Research in Anatomy*, *31*, 100247. https://doi.org/10.1016/j.tria.2023.100247

Mitchell, W. J., Inouye, A. S., & Blumenthal, M. S. (Eds.). (2003). *Beyond productivity: Information technology, innovation, and creativity*. National Academies Press.

Mortati, M., & Cautela, C. (2025). Data thickening: A new frontier in design cognition. *Design Studies*, *100*, 101327. https://doi.org/10.1016/j.destud.2025.101327

Mortati, M., Magistretti, S., Cautela, C., & Dell'era, C. (2023). Data in design: How big data and thick data inform design thinking projects. *Technovation*, *122*, 102688. https://doi.org/10.1016/j.technovation.2022.102688

Muratovski, G. (2021). *Research for designers: A guide to methods and practice* (2nd ed.). SAGE Publications.

Naismith, L. M., Cheung, J. J. H., Ringsted, C., & Cavalcanti, R. B. (2015). Limitations of subjective cognitive load measures in simulation-based procedural training. *Medical Education*, *49*(8), 805–814. https://doi.org/10.1111/medu.12732

Nelson, J., & Menold, J. (2020). Opening the black box: Developing metrics to assess the cognitive processes of prototyping. *Design Studies*, *70*, 100964. https://doi.org/10.1016/j.destud.2020.100964

Nguyen, T. A., & Zeng, Y. (2017). A theoretical model of design fixation. *International Journal of Design Creativity and Innovation*, *5*(3–4), 185–204. https://doi.org/10.1080/21650349.2016.1207566

Novica, D. R., Wianto, E., & Campos, S. A. (2023). Drawing and ideation process in design education: A systematic literature review. *Cogent Arts & Humanities*, *10*(1), 2219487. https://doi.org/10.1080/23311983.2023.2219487

O'Neil, H. F. (2014). *Learning strategies*. Academic Press.

Oxman, R. (2017). Thinking difference: Theories and models of parametric design thinking. *Design Studies*, *52*, 4–39. https://doi.org/10.1016/j.destud.2017.06.001

Patricio, R., Dias, J., Carella, G., & Gancho, S. (2024). Managing design innovation challenges in a digital environment. *International Journal of Design Creativity and Innovation*, *12*(3), 139–162. https://doi.org/10.1080/21650349.2024.2342325

Pearson, L. C. (2020). A machine for playing in: Exploring the videogame as a medium for architectural design. *Design Studies*, *66*, 114–143. https://doi.org/10.1016/j.destud.2019.11.005

Prabhu, R., Simpson, T. W., Miller, S. R., & Meisel, N. A. (2023). Break it down: Comparing the effects of lecture-and module-style design for additive manufacturing educational interventions on student designers' learning and creativity. *International Journal of Design Creativity and Innovation*, *11*(4), 229–252. https://doi.org/10.1080/21650349.2023.2241049

Ranscombe, C., & 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*, 3441–3450. https://doi.org/10.1017/pds.2021.605

Redifer, J. L., Bae, C. L., & DeBusk-Lane, M. (2019). Implicit theories, working memory, and cognitive load: Impacts on creative thinking. *SAGE Open*, *9*(1). https://doi.org/10.1177/2158244019835919

Renjith, R. (2017). The effect of information overload in digital media news content. *Communication and Media Studies*, *6*(1), 73–85.

Richey, M., Zender, F., Schrage, D. P., Jensen, G., McPherson, B., Fehr, J., Symmonds, M. M., & French, D. E. (2012). An innovative approach to an integrated design and manufacturing multi-site "cloud-based" capstone project. In H. Hans, H. Stephen & P. Arun (Eds.), *2012 ASEE International Forum Proceedings*, San Antonio, Texas, US (pp. 17.6.1–17.6.22). American Society for Engineering Education (ASEE). https://peer.asee.org/17250

Robertson, B. F., & Radcliffe, D. F. (2009). Impact of CAD tools on creative problem solving in engineering design. *Computer-Aided Design*, *41*(3), 136–146. https://doi.org/10.1016/j.cad.2008.06.007

Safin, S. (2016, September). The digital sketch as a central object of representation systems in creative design. In G. Lawson, T. Roper, & G. de Haan (Eds.), *Proceedings of the European Conference on Cognitive Ergonomics*, The University of Nottingham, UK (p. 37). The Association for Computing Machinery (ACM). https://doi.org/10.1145/2970930.2970968

Schembri, M., Farrugia, P., Wodehouse, A. J., Grierson, H., & Kovacevic, A. (2015). Influence of sketch types on distributed design team work. *Codesign*, *11*(2), 99–118. https://doi.org/10.1080/15710882.2015.1054841

Schmitt, J. B., Breuer, J., & Wulf, T. (2021). From cognitive overload to digital detox: Psychological implications of telework during the COVID-19 pandemic. *Computers in Human Behavior*, *124*, 124. https://doi.org/10.1016/j.chb.2021.106899

Shanmugasundaram, M., & Tamilarasu, A. (2023). The impact of digital technology, social media, and artificial intelligence on cognitive functions: A review. *Frontiers in Cognition*, *2*, 1203077. https://doi.org/10.3389/fcogn.2023.1203077

Shih, Y. T., Sher, W. D., & Taylor, M. (2017). Using suitable design media appropriately: Understanding how designers interact with sketching and CAD modelling in design processes. *Design Studies*, *53*, 47–77. https://doi.org/10.1016/j.destud.2017.06.005

Skulmowski, A., & Xu, K. M. (2022). Understanding cognitive load in digital and online learning: A new perspective on extraneous cognitive load. *Educational Psychology Review*, *34*(1), 171–196. https://doi.org/10.1007/s10648-021-09624-7

Stones, C., & Cassidy, T. (2007). Comparing synthesis strategies of novice graphic designers using digital and traditional design tools. *Design Studies*, *28*(1), 59–72. https://doi.org/10.1016/j.destud.2006.09.001

Stones, C., & Cassidy, T. (2010). Seeing and discovering: How do student designers reinterpret sketches and digital marks during graphic design ideation? *Design Studies*, *31*(5), 439–460. https://doi.org/10.1016/j.destud.2010.05.003

Sudha, B., & Premkumar, K. (2025). Influence of cognitive, affective-conative resources toward creativity in the realm of architecture 'a latent variable model for indicators of creativity'. *International Journal of Design Creativity and Innovation*, *13*(3), 194–220. https://doi.org/10.1080/21650349.2025.2471970

Sun, G., & Yao, S. (2012). Investigating the relation between cognitive load and creativity in the conceptual design process. *Proceedings of the Human Factors and Ergonomics Society Annual Meeting*, *56*(1), 308–312. https://doi.org/10.1177/1071181312561072

Sun, G., Yao, S., & Carretero, J. A. (2014). Comparing cognitive efficiency of experienced and inexperienced designers in conceptual design processes. *Journal of Cognitive Engineering and Decision Making*, *8*(4), 330–351. https://doi.org/10.1177/1555343414540172

Sweller, J. (2011). Cognitive load theory. In J. P. Mestre & B. H. Ross (Eds.), *Psychology of learning and motivation* (Vol. 55, pp. 37–76). Academic Press.

Sweller, J. (2022). The role of evolutionary psychology in our understanding of human cognition: Consequences for cognitive load theory and instructional procedures. *Educational Psychology Review*, *34*(4), 2229–2241. https://doi.org/10.1007/s10648-021-09647-0

Sweller, J., van Merriënboer, J. J. G., & Paas, F. (2019). Cognitive architecture and instructional design: 20 years later. *Educational Psychology Review*, *31*(2), 261–292. https://doi.org/10.1007/s10648-019-09465-5

Tang, H. H., Lee, Y. Y., & 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), 1–29. https://doi.org/10.1016/j.destud.2010.06.004

Tatipala, S., Larsson, T., Johansson, C., & Wall, J. (2021). The influence of industry 4.0 on product design and development: Conceptual foundations and literature review. In A. Chakrabarti, R. Poovaiah, P. Bokil, & V. Kant (Eds.), *Design for Tomorrow-Volume, 2: Proceedings of ICoRD, 2021* (pp. 757–768). Springer.

Tufail, M., Zaib, S., Uzma, S., Karim, R. M., & Kim, K. (2024). Exploring designers' cognitive abilities in the concept product design phase through traditional and digitally-mediated design environments. In M. Štorga, S. Škec, T. Martinec, D. Marjanović, N. Pavković, & M. M. Škec (Eds.), *Proceedings of the Design Society* (Vol. 4, pp. 1135–1146). Cambridge University Press.
Vasantha, G. V. A., Chakrabarti, A., Rout, B. K., & Corney, J. (2014). Influences of design tools on the original and redesign processes. *International Journal of Design Creativity and Innovation*, *2* (1), 20–50. https://doi.org/10.1080/21650349.2013.839076
Vinker, Y., Voynov, A., Cohen-Or, D., & Shamir, A. (2023). Concept decomposition for visual exploration and inspiration. *ACM Transactions on Graphics*, *42*(6), Article 241.1–13. https://doi.org/10.1145/3618315
Wang, J., Ranscombe, C., & Eisenbart, B. (2023). Prototyping in smart product design: Investigating prototyping tools to support communication in the early stage smart product development. *International Journal of Design Creativity and Innovation*, *11*(3), 159–184. https://doi.org/10.1080/21650349.2023.2222115
Wang, X., Zhu, Y., Sun, H., & Jia, F. (2018). Production decisions of new and remanufactured products: Implications for low carbon emission economy. *Journal of Cleaner Production*, *171*, 1225–1243. https://doi.org/10.1016/j.jclepro.2017.10.053
Wickens, C. D., & Carswell, C. M. (2021). Information processing. In G. Salvendy & W. Karwowski (Eds.), *Handbook of human factors and ergonomics* (5th ed. pp. 114–158). Wiley.
Zimmerer, C., & Matthiesen, S. (2021). Study on the impact of cognitive load on performance in engineering design. In B. Ion (Ed.), *Proceedings of the Design Society: ICED21* (Vol. 1, 1st ed., pp. 2761–2770). Cambridge University Press.