Design and Artificial Intelligence 1 (2025) 100049

Contents lists available at ScienceDirect

Design and Artificial Intelligence

journal homepage: https://www.keaipublishing.com/en/journals/design-and-artificial-intelligence/

Full Length Article

IEDS in practice: A comparative study of an intelli-embodied design space combining AR and GAI for conceptual design ☆

Hongbo Zhang, Yifei Wu, Pei Chen *

College of Computer Science and Technology, Zhejiang University, Hangzhou, 310027, China

A R T I C L E I N F O

Keywords:
AI-assisted design
Generative AI
Augmented reality

A B S T R A C T

Conceptual design is an important stage in product development. In conceptual design, the design space that designers face and the design materials they utilize affect their perception and creation. The development of human–computer interaction (HCI) and artificial intelligence (AI) technologies expands the boundaries of design space and materials. On one hand, augmented reality (AR) technologies are being utilized to create a design space that merges physical and virtual representations, facilitating intuitive interaction and embodied cognition. On the other hand, generative artificial intelligence (GAI) is employed as a novel design material to enhance creativity and boost design productivity. Against this background, this study explored an Intelli-Embodied Design Space (IEDS) combining designers, AR, and GAI to support conceptual design, aiming to enhance designers' thinking by superposing embodied interaction and generative variability. In IEDS, designers can interact with physical prototypes intuitively, while GAI can refine them into virtual forms that can be embedded in the physical world through AR technology. In this paper, we developed three potential IEDS systems and conducted a comparative user study with 27 designers to evaluate them from a practical perspective. According to the qualitative and quantitative experimental results, we clarified the interactive guidelines and best practices of IEDS. We also critically discussed IEDS's influence on conceptual design and released its future vision to the HCI community.

1. Introduction

Conceptual design is one of the most critical stages in product development, typically responsible for 60–80 % of development costs [1,2]. It is crucial for design success because designers explore, evaluate, and select an overall product concept to pursue [3,4]. In conceptual design, the design space, including the design representation display and external environment, affects designers' cognition and perception [5]. The visual and spatial design representation shapes how designers perceive and interpret the design problems and solutions they face. Furthermore, design materials, containing design tools and prototypes, influence designers' creative modes and production efficiency [6]. The availability of these design materials can impact how effectively designers can create, test, and iterate on their ideas. In this sense, designers' thinking can be significantly enhanced if the expanded design space provides a more intuitive design representation and innovative design materials to optimize the traditional creative flow.

The expanded design space containing both physical and virtual objects is considered an interactive environment, which can enhance intuitive perception and promote embodied cognition [7]. As findings in cognitive science and psychology show that body movement can be part of thinking, the physical form of design information can augment the way designers think and create through body-based cognition— beyond the graphical display [8,9]. This is because physical design representation enables a richer and more intuitive way of exploring, manipulating, testing, and sharing ideas through bodies and physical space, which has the potential to enhance creativity during conceptual design [10]. Motivated by these theoretical foundations, the HCI community has paid attention to expanding the virtual interface and integrating computational media with the physical environment [11]. Among them, utilizing augmented reality (AR) technology is a mainstream method to tightly combine physical and virtual design representations, superposing the inherent strengths of both physical and virtual design spaces [7].

Artificial intelligence (AI) is now a fairly established technology, serving as a new design material for design practitioners [6,12]. Especially with recent advances in generative artificial intelligence (GAI), its integration within design tools and design space is burgeoning. As a novel design material, GAI has transformed the designer-centered paradigm of conceptual design. On the one hand, GAI has shown proficiency in generating high-quality design schemes indistinguishable from human-created artifacts [13]. It has changed the traditional creation

☆ Peer review under responsibility of Editorial Board of Design and Artificial Intelligence.
* Corresponding author.
E-mail address: peichen@zju.edu.cn (P. Chen).

https://doi.org/10.1016/j.daai.2025.100049
Received 16 September 2025; Received in revised form 14 November 2025; Accepted 20 November 2025
Available online 25 November 2025

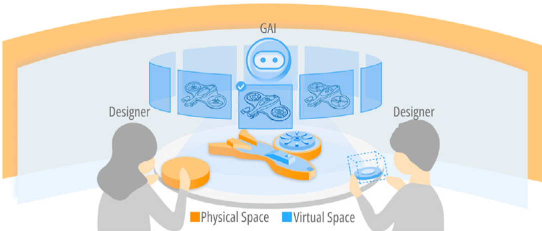


Fig. 1. The conceptual introduction of the Intelli-Embodied Design Space (IEDS). (GAI: generative artificial intelligence.)

mode and allowed designers to create design schemes using natural language instead of complex manipulation, improving the efficiency of idea exploration. On the other hand, GAI provides design inspiration or insights based on the capability of understanding common sense, as well as offers unpredictable design schemes based on generative variability [14]. In this sense, GAI can act as a design partner, leveraging knowledge and offering multi-perspective connections, while the human designer acts as a design manager, providing direction for conceptual design. The diverse and decentralized design roles might enrich and simplify the ideation process.

According to these benefits of integrating physical representation in design space and utilizing GAI as a new design material, we aim to explore a novel design space based on designers' embodied cognition and GAI's generative ability. By combining the rich expressivity of physical representation with the generative variability, designers may think and design within the novel design space in unprecedented ways—just as computers and graphic displays have changed the way designers create in the past [10]. In this sense, we proposed an Intelli-Embodied Design Space (IEDS) combining designer, AR, and GAI to support conceptual design. Fig. 1 shows the conceptual introduction of the proposed IEDS. In such a design space, designers can see physical prototypes and interact with the physical environment naturally and intuitively. GAI can first understand design intention through concrete physical design representation and textual requirements, then refine them into virtual forms that can be embedded in the physical world through AR technology. IEDS not only reduces designers' cognitive load and augments their thinking through an embodied design space but also enriches the ideation process and opens up an imaginary space through GAI generation.

In this paper, we proposed and explored an IEDS in practice. We developed three potential IEDS systems following expert insights and conducted a comparative user study to specify the interaction guidelines and best practices in IEDS. Finally, we clarified our vision for IEDS and formulated opportunities and challenges, guiding the HCI and design communities.

We provided the following contributions. First, aiming to realize the IEDS concept, we designed and developed three design systems that combine AR and GAI. Second, we conducted a user study and proposed new insights into the AR and GAI combination in conceptual design, especially the interactive guidelines and best practices in IEDS. Third, we specified our IEDS vision and formulated opportunities for both the HCI and design communities.

2. Related work

2.1. Design space containing physical design representation

In addition to verbal and textual expression, the conceptual design process heavily relies on the manipulation and modification of external representations, referred to as design representation [15]. These representations play a crucial role in facilitating idea generation by encoding complex information to free up designers' cognitive memory [16]. According to Kirsh's theory of distributed cognition, information representation modes can fundamentally change the domain and range of cognition, as processes naturally flow to wherever it is cheaper to perform them [5]. While these representations can take various forms, from sketches to CAD, physical design representation has distinct strengths in supporting design ideation through embodied cognition.

First, the physical environment promotes intuitive design exploration. Physical forms, such as clay models, make ideas visible and manipulable, significantly lowering the cognitive load for exploration. Compared to paper-based texts and images, physical models increase sensorial stimuli (touch, sight, and smell) during ideation sessions [17]. This surge in available tangible information is beneficial for spatial relationship reasoning, hidden feature perception, and unexpected insight discovery [18]. Second, physical representations support tangible design analysis. Instead of processing complex steps purely in their minds, designers can perceive and analyze concepts in a tangible form. Distributing more rules into external physical representations facilitates faster decision-making [19] and helps highlight significant discrepancies between actual solutions and conceptual predictions through direct functional testing [20,21]. Third, physical artifacts enhance collaboration by serving as a concrete anchor for discussion [22]. They allow seamless collaboration where multiple designers can manipulate the artifact simultaneously and see immediate results [23], effectively serving as shared objects of thought [5]. However, despite these cognitive benefits, physical representations often lack the flexibility for rapid iteration and variability compared to digital solutions.

2.2. Design material integrating GAI

As machine learning and GAI become established technologies, they are increasingly viewed not just as tools, but as novel design materials that designers can utilize to think and create [6,12]. The fundamental principle of these generative models—learning distribution patterns from extensive datasets to autonomously acquire abstract knowledge—has sparked immense interest across creative fields, including industrial design [24], layout design [25], diagram design [26], and user interface (UI) design [27]. Previous studies have demonstrated GAI's proficiency in supporting various design stages, from stimulating inspiration [28] and supporting ideation [29] to assisting prototyping [24], facilitating reasoning [14], and advising iteration [30].

Beyond these specific applications, the integration of GAI is fundamentally transforming the characteristics of traditional design materials and the design process itself in three key aspects. First, it lowers the interaction threshold of creation. Chat-like interfaces (e.g., Bard [31], ChatGPT [32]) allow users to create complex design schemes using natural language. This shift enables diverse members, such as engineers or customers without professional drawing skills, to participate effortlessly in conceptual design. Second, it enriches the perceptible modalities in the design space. Traditional tools are often constrained by their inherent formatting parameters (e.g., 2D sketching software cannot easily produce 3D representations). GAI overcomes this by effortlessly generating multi-modal design information, including sketches [33], 2D high-fidelity schemes [34], and even 3D prototypes [35] from simple inputs, enabling a richer way of exploring ideas. Third, it diversifies design roles. Unlike passive traditional materials, GAI can act as an active "partner," contributing insights not immediately apparent to human designers and efficiently gathering knowledge from fields outside their personal experience through data-enabled generation [14].

3. Intelli-embodied design space (IEDS)

3.1. The scope of IEDS

Based on the above theoretical viewpoints, we aim to explore an innovative design space that integrates the advantages of both physical representation and GAI in conceptual design.

Previous studies divide the AR approaches into three main approaches. First, the most widely used AR method is through head-

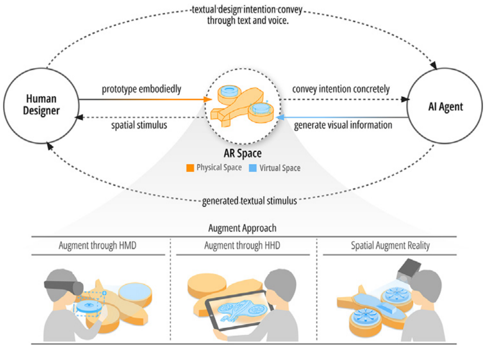


Fig. 2. The interaction in the proposed IEDS. (HMD: head-mounted display; HHD: hand-held device.)

mounted displays (HMDs), which can overlay virtual information directly onto the user's field of view, creating an immersive experience where virtual elements appear as part of the real world [36,37]. In addition, some studies utilize hand-held devices (HHDs) to augment reality. These tools relied on the shooting capabilities of mobile devices, such as tablets or mobile phones, to capture the physical environment and overlay virtual information onto the live camera feed [38,39]. The third method is spatial augmented reality (SAR). Raskar et al. [40] defined it as the projection of virtual content onto a physical object directly. This method employs fixed or portable projectors to attach the virtual information onto the physical objects or environments [41,42]. Different augment approaches have their advantages and limitations. It is necessary to choose the appropriate AR approach according to specific design tasks, design stages, and design teams in conceptual design rather than generalizing them.

We expect the IEDS to have the following characteristics and capabilities (the concepts are presented in Fig. 2):

- allowing designers to interact directly with physical representations, including the physical environment, objects, materials, and prototypes;
- enabling GAI to understand designers' intentions according to physical representations and provide generated artifacts;
- coupling the GAI-generated artifacts with the physical design representation tightly in a hybrid design space through AR techniques.

4. User study

We conducted an open-ended exploration user study, aiming to identify the applicable scenarios for different augmentation approaches and clarify their interaction principles in IEDS. To achieve this goal, we formulated two main research questions (RQs) focusing on the design process experience and the overall system evaluation, respectively:

- **RQ1**: How do different AR approaches in IEDS affect designers' experience during the conceptual design process?
  - **RQ1.1**: What are the effects of different IEDS on design load?
  - **RQ1.2**: What are the effects of different IEDS on creativity support?
- **RQ2**: How do designers evaluate the different IEDS systems after conceptual design tasks?
  - **RQ2.1**: What is the usability of different IEDS systems?
  - **RQ2.2**: What are designers' subjective preferences among different IEDS systems?

Aiming to answer these RQs, we developed three experimental systems and conducted a comparative experiment. We elaborate on our specific works in this section.

4.1. Experimental system

Based on the interaction design summarized in Section 3.1, we developed three experimental systems according to three different AR approaches (i.e., augment through HMD, augment through HHD, and SAR) to implement our IEDS concept. Hereafter, we simply refer to them as IEDS-HMD, IEDS-HHD, and IEDS-SAR.

4.1.1. System introduction

These three systems have the same generative ability and interaction mode, but the AR approaches utilized in IEDS are different, which leads to different AR interactions in IEDS. We compare three developed systems in Fig. 3 and introduce their technical architecture in Fig. 4. First, we achieved the IEDS-HMD system through the HoloLens. When the designer is building a physical prototype, the built-in camera of HoloLens will capture the designer's current vision and combine the textual requirements of voice input to understand the designer's intention. The virtual artifacts generated by GAI will be embedded in a hybrid space through the HMD. Due to the HMD's distinct characteristic that supports spatial editing, we integrated the 3D modeling functions in IEDS-HMD to support aerial modeling and manipulation. Second, we achieved the IEDS-HHD system through a tablet computer (iPad). Unlike IEDS-HMD, designers will digitally browse generated artifacts on the iPad screen. Based on the characteristics of HHD, we developed the sketching function for IEDS-HHD. Designers can draw on the captured image of the physical model through the touchscreen, which serves as input information to GAI. Third, we achieved the IEDS-SAR system through an independent camera and a projector. GAI comprehends design intention through captured images of physical prototypes and voice requirements, generating artifacts that meet designers' needs. The virtual artifacts will be attached to one of the surfaces of the physical prototype through a projector. Following the characteristics of SAR with strong presentation performance but weak operation, we developed the IEDS-SAR system that does not support virtual editing ability.

We aim to develop three potential IEDS systems to support comparative experiments and explore the influence of different AR approaches on conceptual design. To ensure the smooth development of the comparative experiment, we made some special considerations on the design and development of the three experimental systems. First, the virtual operation in three experimental systems was designed differently according to the corresponding characteristics of augment approaches. IEDS-HMD supports direct 3D modeling in the air, IEDS-HHD supports screen touch and sketch, while IEDS-SAR does not support any virtual editing. This was intended to make the experimental system closer to the natural AR environment and interact to collect effective user feedback. Second, as the same large-scale image generation model was utilized in the three experimental systems, all visually generated artifacts were images in this experiment. This is because it is still challenging to directly use 3D generative models to support the conceptual design process due to the limited quality and efficiency of current 3D generative models. Therefore, in this experiment, the generated images will be presented in the air through HoloLens in IEDS-HMD, displayed on the iPad screen in IEDS-HHD, and stuck on the surface of the physical prototype through a projector in IEDS-SAR.

4.1.2. System implementation

IEDS-HMD configuration design. The configuration of IEDS-HMD comprises three main hardware components: a HoloLens device, a router, and a computer for Unity's operation. During the conceptual design, designers wear the HoloLens, connecting to the host computer through a local area network. The wireless connection facilitates real-time data transmission between the HoloLens and Unity on the computer.

IEDS-HMD software implementation. For the software design, the implementation of IEDS-HMD encompasses two main parts. The first involves supporting designers in creating and editing 3D virtual models in the air through gesture-based interactions. We utilized Unity (version

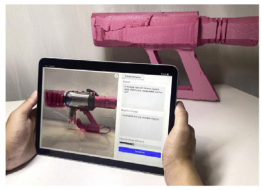
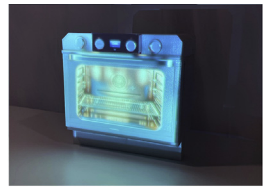
	IEDS-HMD	IEDS-HHD	IEDS-SAR
AR Approach	augment through HMD	augment through HHD	augment through SAR
System			
Equipment	an HMD (HoloLens)	an HHD (iPad)	a camera a projector
Information Capture Channel	the built-in camera of HoloLens	the built-in camera of iPad	an independent camera
Information Embedding Mode	digital artifacts generated by GAI are embedded in a hybrid space through an HMD equipment	digital artifacts generated by GAI are displayed on the screen of an HHD equipment	digital artifacts generated by GAI are attached on the surface of the physical prototype through a projector equipment
Physical Operation	physical prototype editing	physical prototype editing	physical prototype editing
Virtual Operation	virtual modeling in air	sketching on screen	n/a
Interaction Mechanism	1. physically prototype 2. digitally model in air based on physical prototype 3. capture HMD vision to image 4. image to image generation 5. embed generated scheme to hybrid space	1. physically prototype 2. capture 3D model to image 3. sketch on the captured image 4. image to image generation 5. display generated scheme on the screen	1. physically prototype 2. capture 3D model to image 3. image to image generation 4. attach generated scheme on the surface of physical prototype through projector

Fig. 3. Introduction and comparison of three developed IEDS systems. (SAR: spatial augmented reality.)

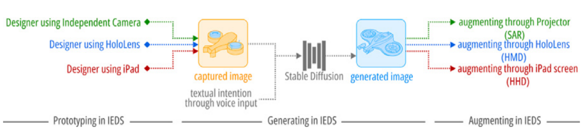


Fig. 4. Technical architecture diagram of three IEDS systems.

2020.3.26) [43] and MRTK (version 2.8) [44] to develop the software. To support the real-time modeling, we integrated two Rhino packages into Unity: Rhino3dm [45] and compute-Rhino3d [46], which enable the invocation of modeling functions directly from Unity and operate based on the local Rhino servers. Our integration allows for real-time conversion of mid-air sketches created via HoloLens into 3D models by the Rhino server, with the processed data swiftly relayed back to the HoloLens for visual rendering. Through this way, we developed and implemented the basic mid-air modeling functions: Revolve, Sweep, Extrude, and the basic editing functions: Move, Copy, Rotate. Besides, for the virtual model presentation in the hybrid space, the Spatial Awareness function of the HoloLens system was activated to scan the physical environment and offered the mesh upon system initiation. It allows the system to discern spatial relationships between virtual model presentation and physical prototypes, displaying appropriate occlusion effects. Second, we achieved the scheme generation and refinement in the software. During the design process, designers can input the textual requirements via voice and capture their current vision (including the physical environment and created virtual model) through the HoloLens. The textual and visual information gathered via Unity will be sent to the back-end server of the system to generate images through diffusion models, which are then relayed back to Unity and presented in the designers' vision through the HoloLens.

IEDS-HHD configuration design. The configuration of IEDS-HHD only comprises one hardware component: a tablet computer (iPad). During the conceptual design, designers hold the iPad or put it on the table to capture their physical design representation. The iPad connects to the back-end server through a local area network, supporting real-time information transmission.

IEDS-HHD software implementation. For the software design, the implementation of IEDS-HHD encompasses two main parts. The first involves supporting designers in capturing physical representations and sketching based on captured images on the screen. Accordingly, we developed a web application for accessibility on mobile devices. The built-in rear camera of iPad facilitates direct capture of physical environments or objects. The UI of the IEDS-HHM system was developed based on Stable Diffusion Web UI [47] and a Gradio library-based browser interface, which has a canvas to support image presentation and sketch. Another development work is to implement the design scheme generation and presentation. During the design process, designers can convey captured images on the screen (including the captured physical object and virtual sketch on canvas) and voice-input textual requirements to the GAI model in the back-end server. The back-end server of the system invokes diffusion models to generate images, which are then relayed back and presented on the canvas.

IEDS-SAR configuration design. The configuration of IEDS-SAR comprises three hardware components: an independent portable camera (GoPro Hero 10), a projector (EPSON CB-X49), and a computer for the operation of information transmission. Designers can hold or wear the portable camera on heads or chests to capture physical representations. The projector is used to project the virtual design scheme to the surface of physical models. The connection of multi-devices and information transmission is achieved through a local area network.

IEDS-SAR software implementation. As we follow the characteristics of SAR with strong presentation performance but weak operation, we did not develop the virtual editing functions like the other two systems. We only achieved the generative function in the IEDS-SAR system. Specifically, the captured image of physical objects through the individual portable camera will be sent to the host computer. The host computer can collect designers' voice-input textual requirements, transmitting them with the captured image to the GAI model in the back-end server. The back-end server of the system invokes diffusion models to generate images, which are then relayed back to the host computer and stuck on the surface of physical objects via a projector.

GAI model and implementation. All three systems employ the same pre-trained image-to-image diffusion model, Stable Diffusion XL 1.0 [48], to achieve image generation in the back-end server. To avoid the influence of complex parameters on the conceptual design process and experimental result, we reserved the most important control parameters to support designers in modifying, including *prompt, negative prompt*, and *denoising strength*. Designers can interact with the three IEDS systems to adjust parameters through voice input. We utilized the default recommended values for other necessary parameters, which did not support user perception and modification. The back-end server is hosted on a local server equipped with a GTX 3090 GPU.

4.2. Methodology

4.2.1. Participant

We recruited 27 designers with a background in industrial design. We mainly recruited professional designers with more than three years of design experience. All participants have the basic knowledge and practical experience of GAI tools, such as ChatGPT, Midjourney, and Stable Diffusion, which was determined via a registration questionnaire. Three experimental groups, each composed of nine participants, were formed randomly and assigned to use IEDS-HMD, IEDS-HHD, and IEDS-SAR systems to complete the design tasks. In each experimental group, designers were divided into triads to perform design tasks together. We opted for teams of three to simulate realistic small-scale design collaboration, ensuring diverse perspectives and necessary negotiation while maintaining active hands-on participation from all members to avoid social loafing. During grouping, the gender, age, and design experience were balanced to minimize individual differences across teams. All participants signed a consent form approved by our institution. There were no other ethical or privacy impacts in this experiment.

4.2.2. Design task

In order to explore the design diversity with the IEDS support, we set two design task types: the appearance-oriented design task and the structure-oriented design task. They are products with relatively commonly fixed structures but different appearances and styles, and those with dynamic and changeable structures, respectively. In this study, we chose an *electric oven* as an appearance-oriented task while a *modularized cleaner* as a structure-oriented task. These two tasks were carefully selected. On the one hand, they are electrical industrial products, which have enough innovation space in their function at the conceptual design stage. On the other hand, they are universally known and commonly used, which can facilitate using prior knowledge and experience to generate and develop design ideas [49]. To enable designers to have a similar ability to explore and complete design as they usually do in actual design activities, we provided a design problem card to specify the design task (presented in Appendix A), including the potential design background, target user, and main requirements [50]. During the design stage, only a design problem card (presented in Appendix A) was provided to designers as design information, and they were required to extensively explore design concepts based on the problem. Each design task lasted 30 min. At the end of each task, designers were asked to introduce design outcomes and provide explanations, which were translated into text for the record.

4.2.3. Analysis metrics

Three questionnaires were utilized in this study to evaluate designers' perceptions of design task load, creativity support, and system usability during conceptual design. Specifically, the NASA Task Load Index (TLX) [51] was adopted to assess the workload of the conceptual design process. It is an overall workload score based on weighted average ratings on *mental demand*, *physical demand*, *temporal demand*, *effort*, *performance*, and *frustration level*. Besides, the creativity support index (CSI) [52] was utilized to evaluate the support of the design environment for creativity. It measures six dimensions of creativity support: *collaboration*, *enjoyment*, *exploration*, *expressiveness*, *immersion*, and *results worth effort*. The system usability scale (SUS) [53] was applied to evaluate the usability of IEDS. The total *SUS score*, *usability score*, and *learnability score* were analyzed. In addition to completing questionnaires, all designers were invited to one-on-one semi-structured interviews after design tasks. The interview content focused on six key issues, including the *design experience*, *comparison with traditional tools*, *GAI cooperation*, *AR influence*, *creativity*, and *attitude to IEDS*.

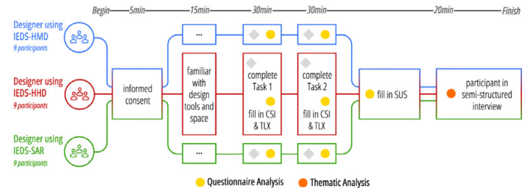


Fig. 5. Procedure of the open-ended exploration study. (CSI: creativity support index; TLX: task load index; SUS: system usability scale.)

4.2.4. Procedure

Designers from all groups followed the experimental procedure shown in Fig. 5. Specifically, after the study introduction, participants completed the informed consent confirmation and were then instructed to familiarize themselves with the IEDS environment and the think-aloud method. In the design task stage, designers were required to complete two design tasks (i.e., appearance-oriented design & structure-oriented design). To avoid the influence of the experimental order on the results, the design tasks were balanced among participants. Immediately after completing each collaborative design task, participants were separated to complete the CSI and NASA TLX questionnaires individually. This protocol was enforced to capture personal cognitive load and subjective experiences while minimizing immediate peer influence or group consensus bias. Finally, participants individually completed the SUS questionnaire and engaged in one-on-one semi-structured interviews. The entire experiment took approximately 100 min.

4.2.5. Data analysis

For the CSI and TLX questionnaire results, we conducted statistical analysis. The Shapiro–Wilk test and Levene's test were run at a significance level of 0.05 for the normality test and variance homogeneity before the statistical analysis. The mixed analysis of variance (ANOVA) was employed to measure the interaction effect and main effect in AR approaches and design tasks if the normality and homogeneity of variances assumptions were satisfied. In contrast, the Aligned Rank Transform ANOVA was used if the data did not meet the normality or homogeneity of variances assumptions. Post-hoc multiple analyses were also performed to identify significant differences among groups. The level of statistical significance for all of these analyses was set at 0.05. For the SUS results, we refer to the application guide of the Likert scale [54] to analyze and report SUS results. For the interview data, we used thematic analysis to analyze raw interview data [55]. Two researchers independently assigned and coded all statements. Next, the two researchers shared their codes, discussing inconsistent codes to resolve disagreements and merging similar codes until they reached a consensus.

5. Result and finding

5.1. The design outcome showcase

We randomly selected and presented some showcases of design outcomes created by participants during the experiment in Fig. 6. We also highlighted the prototype in the physical, virtual, and hybrid domains in

Table 1
Results of NASA TLX. Significant effects are highlighted in bold. P value rounds to three decimal places, F score and η^2 round to two decimal places. ↓ indicates that the lower value is better.

Measure	Effect	F score	P	value η^2	Post-hoc
NASA TLX↓	AR approach	60.29	**<0.001**	0.88	SAR: appearance < structure
	Design task	48.45	**<0.001**	0.86	Structure: HHD < HMD < SAR
	AR × task	43.98	**<0.001**	0.85	Appearance: HHD < SAR < HMD
Mental demand↓	AR approach	54.43	**<0.001**	0.87	SAR: appearance < structure
	Design task	5.37	**0.049**	0.40	Structure: HHD < HMD < SAR
	AR × task	15.37	**<0.001**	0.66	Appearance: HHD, SAR < HMD
Physical demand↓	AR approach	53.41	**<0.001**	0.87	
	Design task	0.30	0.598	0.04	HHD < SAR < HMD
	AR × task	0.24	0.749	0.03	
Temporal demand↓	AR approach	7.19	**0.006**	0.47	
	Design task	0.01	0.928	0.00	HMD, HHD < SAR
	AR × task	1.62	0.235	0.17	
Effort↓	AR approach	2.79	0.092	0.26	
	Design task	0.12	0.743	0.01	–
	AR × task	0.31	0.616	0.04	
Performance↓	AR approach	43.91	**<0.001**	0.85	
	Design task	49.50	**<0.001**	0.86	SAR: appearance < structure
	AR × task	55.77	**<0.001**	0.88	Structure: HHD < HMD < SAR
Frustration level↓	AR approach	62.61	**<0.001**	0.89	SAR: appearance < structure
	Design task	21.55	**0.002**	0.73	Structure: HHD < HMD < SAR
	AR × task	40.85	**<0.001**	0.84	Appearance: HHD < HMD

TLX: task load index; AR: augmented reality; SAR: spatial augmented reality; HHD: hand-held device; HMD: head-mounted display.

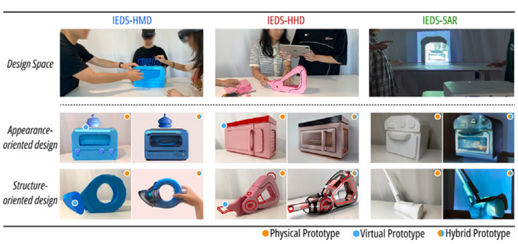


Fig. 6. The design outcome showcases during the experiment.

IEDS in showcases. To distinguish three experimental groups and avoid the influence of color selection and usage in the early conceptual design stage, each group was provided with the physical material in one color, and the corresponding virtual editing color was set to be consistent.

5.2. *The design load (for RQ1.1)*

The NASA TLX questionnaire was used to evaluate the workload during the conceptual design process, which has six perspectives: mental demand, physical demand, temporal demand, effort, performance, and frustration level. As all the data satisfied the normality and variances homogeneity test, the mixed ANOVA was used for the statistical analysis. The results are presented in Table 1 and Fig. 7. For the NASA TLX score, an interaction effect was found ($P < 0.001, \eta^2 = 0.85$). The post-hoc test indicated that the TLX score in appearance-oriented tasks was lower than in structure-oriented tasks for IEDS-SAR. Besides, in all design tasks, the TLX score in HHD was significantly lower than in HMD and SAR. The TLX score in HMD was lower than in SAR in structure-oriented design, while the result was the opposite in appearance-oriented design.

For the six weighted average ratings in TLX, there was an interaction effect in mental demand ($P < 0.001, \eta^2 = 0.66$), performance ($P < 0.001, \eta^2 = 0.88$), and frustration level ($P < 0.001, \eta^2 = 0.84$). Specifically, in these three perspectives, scores for appearance-oriented design were lower than structure-oriented design in IEDS-SAR. The scores of mental demand and frustration level in HHD were significantly lower than HMD in all design tasks. The SAR had the highest workload in mental demand, performance, and frustration level during structured-oriented tasks.

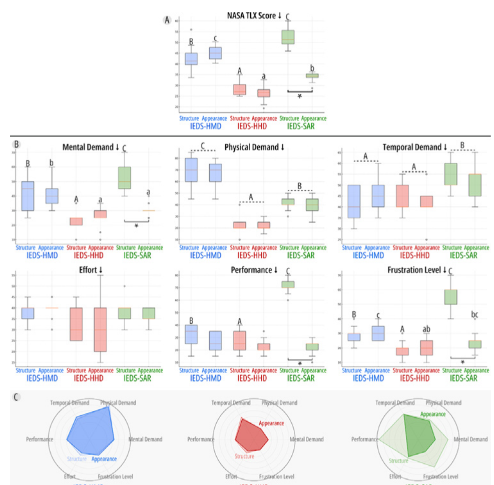


Fig. 7. NASA TLX results: (A) weighted average ratings and (B) subscale scores, and (C) radar charts of NASA TLX results. The "↓" symbol indicates that lower scores are preferable. For each subscale, conditions not sharing a common letter are significantly different ($p < 0.05$) between AR approaches. The asterisk (*) indicates a significant difference ($p < 0.05$) between design tasks.

In addition, there was a main effect of the AR approach on physical demand ($P < 0.001, \eta^2 = 0.87$) and on temporal demand ($P = 0.006, \eta^2 = 0.47$). Specifically, in physical demand, its workload score in HHD was significantly lower than others, and its score in HMD was higher than others. In temporal demand, the timeload in SAR was significantly higher than others.

5.3. *The creativity support (for RQ1.2)*

The CSI questionnaire was used to evaluate creativity support during the conceptual design process, which has six perspectives, including collaboration, enjoyment, exploration, expressiveness, immersion, and results worth effort. The Shapiro–Wilk tests and quantile–quantile plots indicated that the exploration score ($P = 0.044$) in HMD during structure-oriented tasks and the immersion score ($P = 0.048$) in HHD during structure-oriented tasks approximately satisfied the normal dis-

Table 2
Creativity support index (CSI) results. Significant effects are highlighted in bold. P value rounds to three decimal places, F score and η^2 rounds to two decimal places. ↑indicates that the higher value is better.

Measure	Effect	F score	P value	η^2	Post-hoc
CSI score↑	AR approach	8.88	**0.003**	0.53	SAR: appearance > structure
	Design task	42.82	**<0.001**	0.84	HHD: structure > appearance
	AR × task	87.73	**<0.001**	0.92	Structure: HMD, HHD > SAR
Collaboration↑	AR approach	131.29	**<0.001**	0.94	SAR: appearance > structure
	Design task	27.19	**<0.001**	0.77	Structure: SAR > HMD
	AR × task	36.00	**<0.001**	0.82	Appearance: SAR > HHD > HMD
Enjoyment↑	AR approach	48.20	**<0.001**	0.86	
	Design task	0.14	0.723	0.02	HHD > HMD
	AR × task	3.55	0.075	0.31	
Exploration↑	AR approach	14.48	**<0.001**	0.64	SAR/HMD: structure > appearance
	Design task	29.65	**<0.001**	0.79	Structure: HMD > SAR
	AR × task	8.05	**0.004**	0.50	Appearance: HMD, HHD > SAR
Expressiveness↑	AR approach	24.60	**<0.001**	0.76	
	Design task	27.52	**<0.001**	0.78	Appearance: SAR > HMD, HHD
	AR × task	24.80	**<0.001**	0.76	
Immersion↑	AR approach	78.35	**<0.001**	0.91	
	Design task	1.65	0.234	0.17	HMD > SAR, HHD
	AR × task	0.96	0.397	0.11	
Results worth effort↑	AR approach	1.14	0.345	0.13	
	Design task	6.82	**0.031**	0.46	SAR: appearance > structure
	AR × task	13.89	**0.001**	0.64	Structure: HMD, HHD > SAR

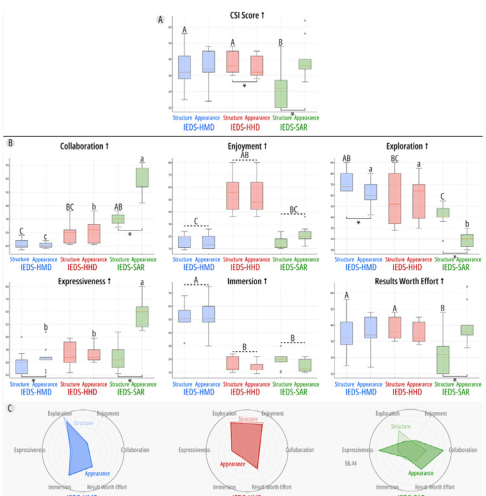


Fig. 8. CSI results: (A) weighted average ratings and (B) subscale scores, and (C) radar charts of CSI results. The "↓" symbol indicates that lower scores are preferable. For each subscale, conditions not sharing a common letter are significantly different ($p < 0.05$) between AR approaches. The asterisk (*) indicates a significant difference ($p < 0.05$) between design tasks.

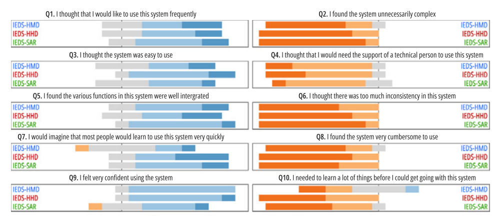


Fig. 9. Results of SUS questionnaires, rating on the 5-point Likert scale.

tribution. Other scores satisfied the normal distribution. Therefore, the mixed ANOVA was used for the statistical analysis, which is present in Table 2 and Fig. 8. For the CSI score, there was an interaction effect between the AR approach and design task ($P < 0.001, \eta^2 = 0.92$). The post-hoc test indicated that the CSI scores for appearance-oriented design were higher than structured-oriented design in IEDS-SAR, while the result showed the opposite in IEDS-HHD. During the structure-oriented design, the CSI in HMD and HHD was higher than that in SAR.

For the six weighted average ratings in CSI, there was an interaction effect in collaboration, exploration, expressiveness, and results worth effort. Specifically, for collaboration ($P < 0.001, \eta^2 = 0.82$), the appearance-oriented task had a higher score in SAR. The SAR had the highest collaboration scores in all design tasks, while HMD had the lowest scores. For exploration ($P = 0.004, \eta^2 = 0.50$), the structure-oriented task had a higher score in SAR and HMD. The HMD had higher exploration scores than SAR in all design tasks. For expressiveness ($P < 0.001, \eta^2 = 0.76$), the SAR had the best expressiveness among the three systems during the appearance-oriented tasks. For results worth effort ($P = 0.001, \eta^2 = 0.64$), the appearance-oriented had a higher score in IEDS-SAR. However, during the structure-oriented tasks, the SAR had the lowest score among the three systems.

There was a main effect of the AR approach on enjoyment and immersion. For enjoyment, the HHD had a higher score than HMD ($P < 0.001, \eta^2 = 0.86$). However, for immersion, the HMD had a higher immersion than others ($P < 0.001, \eta^2 = 0.91$).

5.4. The system usability (for RQ2.1)

We utilized the SUS questionnaires to evaluate the usability of the three IEDS systems (Fig. 9). The results indicated that the IEDS-HHD system had a higher mean SUS score ($M = 83.33, SD = 2.36$) than IEDS-SAR ($M = 80.00, SD = 4.25$) and IEDS-HMD ($M = 76.11, SD = 3.93$) during the conceptual design process. In addition, for SUS learnability, the score of IEDS-HHD ($M = 94.44, SD = 8.56$) was also higher than IEDS-SAR ($M = 79.17, SD = 4.42$) and IEDS-HMD ($M = 70.83, SD = 15.59$).

5.5. The subjective preference (for RQ2.2)

To evaluate designers' subjective preferences among three IEDS systems, we invited all participants to semi-structured interviews, asking them to reflect on their user experience in the conceptual design. Then, we classified two themes about the advantages (A) and disadvantages (D) of the IEDS systems from the interviews and extracted the three most frequent codes for each (Table 3).

Table 3
Extracted codes and corresponding quotes from interview data. A represents the advantages of the IEDS systems, while D represents the disadvantages.

Code	Part of the quotes
HMD-A1: immersion and intuition	"I can model directly on the physical prototype, making me immersed."
HMD-A2: multi-view exploration	"I can explore and verify the structure from different views."
HMD-A3: beyond physical limitations	"During design process, I can transcend physical limitations, such as gravity, in the virtual world."
HMD-D1: physical discomfort	"Working for a long time makes me feel my neck ache and dizzy."
HMD-D2: collaborating challenge	"Partners will have different horizons and are prone to misoperation."
HMD-D3: parallax	"HMD's camera is different in height from my eyes, and seems to have parallax with what I see."
HHD-A1: convenience and efficiency	"It is convenient to use the system through a tablet, and no additional equipment is needed."
HHD-A2: conforming to habit	"The usage and operation are in line with my usual cognition and habits during design."
HHD-A3: on-site design test	"The tablet supports on-site design, also supports me in verifying the structure of my vacuum cleaner in many scenes, without location limitation."
HHD-D1: indirect editing	"I can only modify and edit 3D on the screen, and I need to imagine the perspective relationship, which is not direct and intuitive enough."
HHD-D2: occupied hand	"My hand needs to hold the tablet all the time, which makes it difficult for me to handle physical prototyping at the same time."
HHD-D3: no immersion	"Mixing physical prototypes and virtual prototypes on a screen makes me feel no immersion or even augmented reality."
SAR-A1: real and presence	"What you see is what you get, which makes me feel real."
SAR-A2: promote communication	"We can see the same hybrid prototype, which provides a shared base for our communication with each other."
SAR-A3: high expressiveness	"Expressiveness surprises me, just like a real oven."
SAR-D1: small use range	"It seems that this can only be used for designs with square dimensions with flat surfaces."
SAR-D2: single view	"I cannot comprehensively design multiple faces of the model simultaneously."
SAR-D3: more labor and time	"Only the higher-quality physical model can have a better augmenting effect, which costs me more manual labor and production time."

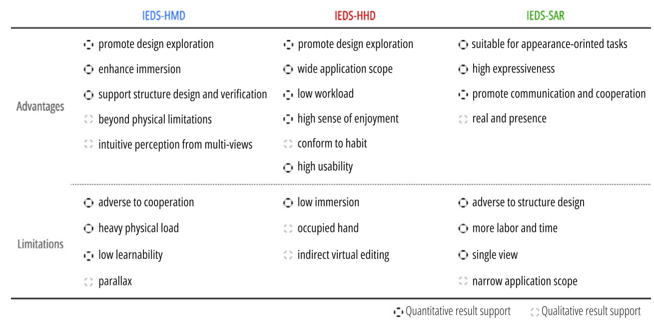


Fig. 10. Extracted advantages and limitations of the three IEDS systems from our qualitative and quantitative results.

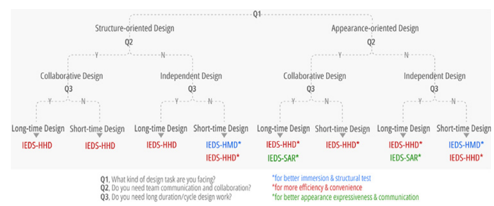


Fig. 11. Best practices for choosing the IEDS system.

In addition to these codes, we also paid attention to the design experience in IEDS, including the GAI cooperation, AR influence, and creativity enhancement during conceptual design, which is discussed comprehensively in the next section with quantitative results.

6. Discussion

6.1. Respective application scope of three IEDS systems

Based on the qualitative and quantitative results, we summarized the typical advantages and limitations of the three IEDS systems (Fig. 10). Our study utilized design triads to simulate realistic collaborative friction and idea exchange. Under this setup, we observed distinct collaboration dynamics across different IEDS systems, which significantly influenced their respective application scopes.

Specifically, for the IEDS-HMD system, the CSI results indicated that HMD was beneficial in promoting design exploration and enhancing immersion. Similarly, designers reported that HMD promoted structural exploration and verification through mid-air modeling, as well as created an intuitive hybrid space combining physical models and virtual prototypes via the HMD equipment. There were also some inherent limitations in IEDS-HMD. The TLX results showed that IEDS-HMD had a higher workload, especially the physical load, which was consistent with designers' subjective reports. More than half of designers mentioned that wearing HMD can cause neck pain and dizziness, especially when working for a long time. The CSI results indicated that IEDS-HMD hindered cooperation and communication. This can be attributed to the *asymmetric collaboration dynamic* inherently created by typical HMDs: Only the wearer has the full hybrid view, while partners are excluded from the immediate visual context. Similarly, designers reported that there might be a gap in the vision of hybrid space seen by different partners, and participants frequently operated unconsciously or incorrectly when collaborating and communicating. In addition, the SUS results indicated that the learnability of IEDS-HMD was relatively low, which might be related to the reported learning difficulties and operating thresholds in mid-air modeling.

For the IEDS-HHD system, the CSI results indicated that it promoted design exploration during conceptual design. The TLX results showed that IEDS-HHD had the lowest workload in all design tasks and had distinct strengths in mental demand, physical demand, and temporal

Fig. 12. Optimization space and future vision of IEDS.

demand. Designers reported that "it is convenient and efficient to use a tablet computer as the medium of hybrid space, and it conforms to my daily design work style and habits, so that I have the opportunity to complete the design with my familiar design tools and materials." It might be the reason why IEDS-HHD received high ratings for enjoyment in CSI results and high usability in SUS results. In addition, the most outstanding strength of IEDS-HHD was its wide application scope, which was suitable for almost all design tasks and did not show obvious shortcomings in workload, creativity support, and usability. The mentioned limitations included relatively low immersion, occupied hands, and indirect virtual editing. It might relate to the interactive media of IEDS-HHD, the screen of the tablet computer, which brought convenience but reduced the interaction immersion and editing intuition.

The IEDS-SAR system had a narrow application scope. During the appearance design, IEDS-SAR brought the highest expressiveness, as well as a sense of reality and presence. Designers reported that "the SAR's fidelity is beyond my imagination, and it is like a real product." This kind of high-fidelity ("what you see is what you get") prototype provided a concrete foundation for team cooperation. Unlike the fragmented views in HMD, SAR creates a *shared visual space* where all team members have equal, simultaneous access to the design artifact. This aligns with previous findings that tangible objects serve as essential "shared objects of thought" [5] and provide concrete anchors for discussion [22], thereby effectively promoting design collaboration in our triads. However, the limitations of IEDS-SAR were also very obvious, mainly focusing on the narrow application scope. Specifically, the SAR can hardly be applied to structure-oriented design tasks, even complex appearance-oriented tasks. There was only one single main view during the appearance-oriented design. Besides, due to the SAR characteristics, this AR approach required higher quality and fidelity of the physical prototype, which increased the manual labor burden and manufacturing time.

6.2. Application guideline and best practice of IEDS

Based on the results of our research, we aim to propose application guidelines and best practices for IEDS to help designers choose the appropriate system in conceptual design, as well as provide theoretical guidance for the HCI community. Specifically, we summarized IEDS best practices in Fig. 11. We suggest choosing the appropriate IEDS system according to three preliminary questions: "What kind of design tasks are you facing?", "Do you need team communication and collaboration?", and "Do you need long duration/cycle design work?". Based on these best practices, we suggest that designers avoid using IEDS-SAR to complete structure-oriented design tasks and short-term efficient tasks in conceptual design, and also avoid using IEDS-HMD for team cooperation and long-duration tasks. In addition, for design tasks with multiple suitable IEDS systems, we also clarified the inherent strengths of each system to enable designers to choose more suitable IEDS systems according to their requirements and improve IEDS utility. Specifically, IEDS-HMD should be given priority for better immersion and structural tests. IEDS-HHD is recommended when faced with an efficiency-oriented design task without high requirements for immersion and intuition. IEDS-SAR is given priority for better expressiveness and communication.

In addition to best practices, we also extracted the most unique strengths of the three IEDS systems to meet special requirements in conceptual design. First, IEDS-HMD can assist prototyping beyond the limitations of the physical world, which is consistent with previous studies indicating that HMD devices enable designers to express visual feedback without constraints of physical reality [11]. For example, one participant designed "an oven with a magnetic suspension timer on it" (shown in Fig. 6) and reported that "I can create freely in the hybrid space and realize my design concepts without restrictions on gravity and weight balance." Second, due to the simplicity and portability of HHD equipment, IEDS-HHD can support on-site design, demonstrating in the conference room or even testing in real scenes beyond the laboratory or design studio. Third, IEDS-SAR can provide tactile information based on high-fidelity prototypes. For example, designers can intuitively see the buttons on the prototype and touch them to get multi-sensory stimulation. Therefore, when designers need to take advantage of the above unique strengths, they can ignore its potential defects to complete the special design tasks.

6.3. Optimization space and future vision of IEDS

After comprehensive consideration and reflection on IEDS, we propose optimization spaces and a future vision for IEDS (Fig. 12). First, GAI can take on more roles than scheme generation in IEDS and truly become a design collaborator. In the literature review and expert interviews, the diversity and ability of design roles that GAI can undertake far exceed the image-based model utilized in our experiment. Therefore, in the future vision of IEDS, GAI can become the intelligent brain of IEDS, making IEDS a more capable design collaborator in conceptual design. For example, multi-modal vision language models, such as GPT-4V [56], Gemini 1.5 [57], and Claude 3 [58] can be integrated with IEDS, which can support abstract element understanding, design reasoning, design evaluation, and consultation through textual interaction.

Second, different AR approaches are not necessarily independent and can be utilized conjointly in IEDS. The experimental results indicated that the three IEDS systems showed unique advantages and disadvantages. As different AR approaches and interaction modes are not mutually exclusive, a wider application range and higher usability can be achieved through better AR medium fusion. For example, in the future vision of IEDS, designers can wear HMD equipment to create prototypes beyond physical limitations through mid-air modeling. At the same time, they can make fine modifications through HHD and finally augment the generated high-fidelity scheme to the physical model directly through SAR. Cross-device joint interaction can give full play to the strengths of different AR approaches and compensate for each other's limitations.

Third, augmented design information can be enriched and expanded, establishing a multi-modal hybrid design space in IEDS. Due to the limitations of speed and quality in current multi-modal generative models, we have completed this study by utilizing the Stable Diffusion model, which is highly available for conceptual design. With the development of GAI and the improvement of multi-modal generative ability, the design information in IEDS can be enriched and expanded. Specifically, on the one hand, the design representation in IEDS can be diverse. For example, virtual prototypes in 3D modality can be generated and tightly coupled with physical prototypes through AR technology. On the other hand, our literature review demonstrated that augmented information can be diverse in addition to the prototype. In the future vision, IEDS might realize the fusion of multi-modal design information, such as augmenting images and even videos to the background of the physical prototype or presenting the prototype's interaction path and movement trajectory.

6.4. Limitation

We discuss the limitations in this study that can be addressed in future studies. First, due to the limitations of quality and time of the 3D generative model, we utilized only an image generative model to complete the user study, which may have reduced the immersion of the design process, especially for virtual design information. This is the first study to propose and verify the initial concept of IEDS from an HCI perspective. With the development of GAI, more multi-modal generative models can be integrated into IEDS to continuously enhance immersion and usability. Second, as IEDS represents a novel integration of AR and GAI, it presents a challenge to identify comparable baselines or existing design tools for comparative analysis. In future work, more comparative analysis against existing design tools or traditional design space, as a benchmark, can be conducted to fully explore the underlying factors that contribute to conceptual design in IEDS. Third, this is a laboratory study, in which the design duration and participant sample are limited. A more realistic user study can be conducted in a practical design workflow, involving large-scale designers and complex design requirements. We intend to release IEDS to the wild for a broader evaluation.

7. Conclusion

In this study, we explored an IEDS combining designers, AR, and GAI to support conceptual design. We developed three potential IEDS systems and conducted a comparative user study with 27 designers. According to the qualitative and quantitative experimental results, we clarified the interactive guidelines and best practices of IEDS. For example, IEDS-HHD had a wide application scope in conceptual design, IEDS-SAR provided high expressiveness and promoted design communication in appearance-oriented design, while IEDS-HMD supported structure design and verification. We also critically discussed IEDS's influence on conceptual design and released its future vision to the HCI community.

Our work put forward the preliminary concept for the novel design space combining AR and GAI, providing theoretical guidance and practical support for the HCI community in further constructing the hybrid design space.

Funding

This work was supported by the National Key Research and Development Program of China (2022YFB3303301).

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

CRediT authorship contribution statement

Hongbo Zhang: Writing – review & editing, Writing – original draft, Methodology, Conceptualization. **Yifei Wu:** Writing – review & editing, Software, Methodology. **Pei Chen:** Writing – review & editing, Supervision, Resources.

Appendix A

The problem cards provided in the open-ended exploration study (Fig. 13).

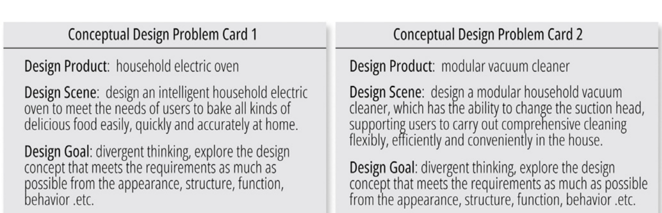


Fig. 13. Problem cards in the open-ended exploration study.

Reference

[1] L. Fiorineschi, F.S. Frillici, F. Rotini, Enhancing functional decomposition and morphology with TRIZ: Literature review, Comput. Ind. 94 (2018) 1–15, doi:10.1016/j.compind.2017.09.004.

[2] Z. Huang, X. Guo, Y. Liu, et al., A smart conflict resolution model using multi-layer knowledge graph for conceptual design, Adv. Eng. Inform. 55 (2023) 101887, doi:10.1016/j.aei.2023.101887.

[3] G. Pahl, W. Beitz, Engineering Design: A Systematic Approach, 2nd Ed., Springer, London, 1996.

[4] P. Haynes, S. Yang, Supersystem digital twin-driven framework for new product conceptual design, Adv. Eng. Inform. 58 (2023) 102149, doi:10.1016/j.aei.2023.102149.

[5] D. Kirsh, Thinking with external representations, AI SOCIETY 25 (4) (2010) 441–454, doi:10.1007/s00146-010-0272-8.

[6] G. Dove, K. Halskov, J. Forlizzi, et al., UX design innovation: challenges for working with machine learning as a design material, in: Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems, ACM, 2017, pp. 278–288, doi:10.1145/3025453.3025739.

[7] D. Smit, B. Hengeveld, M. Murer, et al., Hybrid design tools for participatory, embodied sensemaking: an applied framework, in: Proceedings of the Sixteenth International Conference on Tangible, Embedded, and Embodied Interaction, ACM, 2022, Article No. 26, doi:10.1145/3490149.3501332.

[8] M. Wilson, Six views of embodied cognition, Psychon. Bull. Rev. 9 (4) (2002) 625–636, doi:10.3758/BF03196322.

[9] D. Kirsh, Embodied cognition and the magical future of interaction design, ACM Trans. Comput.-Hum. Interact. 20 (1) (2013) 3, doi:10.1145/2442106.2442109.

[10] R. Suzuki, Dynamic shape construction and transformation with collective elements, Ph.D Thesis, University of Colorado at Boulder, Boulder, CO, USA, 2020.

[11] R. Suzuki, A. Karim, T. Xia, et al., Augmented reality and robotics: a survey and taxonomy for AR-enhanced human-robot interaction and robotic interfaces, in: Proceedings of the CHI Conference on Human Factors in Computing Systems, ACM, 2022, Article No. 553, doi:10.1145/3491102.3517719.

[12] Q. Yang, N. Banovic, J. Zimmerman, Mapping machine learning advances from HCI research to reveal starting places for design innovation, in: Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems, ACM, 2018, Paper No. 130, doi:10.1145/3173574.3173704.

[13] S. Wang, S. Petridis, T. Kwon, et al., PopBlends: strategies for conceptual blending with large language models, in: Proceedings of the 2023 CHI Conference on Human Factors in Computing Systems, ACM, 2023, Article No. 435, doi:10.1145/3544548.3580948.

[14] F. Stella, C. Della Santina, J. Hughes, How can LLMs transform the robotic design process? Nat. Mach. Intell. 5 (6) (2023) 561–564, doi:10.1038/s42256-023-00669-7.

[15] R. Oxman, Design by re-representation: a model of visual reasoning in design, Des. Stud. 18 (4) (1997) 329–347, doi:10.1016/S0142-694X(97)00005-7.

[16] D.O. Buskermolen, J. Terken, Co-constructing stories: a participatory design technique to elicit in-depth user feedback and suggestions about design concepts, in: Proceedings of the 12th Participatory Design Conference: Exploratory Papers, Workshop Descriptions, Industry Cases - Volume 2, ACM, 2012, pp. 33–36, doi:10.1145/2348144.2348156.

[17] G. Goldschmidt, M. Smolkov, Variances in the impact of visual stimuli on design problem solving performance, Des. Stud. 27 (5) (2006) 549–569, doi:10.1016/j.destud.2006.01.002.

[18] M.G. Gomes, A. Ogliari, R.B. Fernandes, et al., Evaluation of physical models as creative stimuli in conceptual design of products, Des. Stud. 81 (2022) 101119, doi:10.1016/j.destud.2022.101119.

[19] S. Iyengar, The Art of Choosing, Hachette, New York, NY, 2010.

[20] M.B. Jensen, C.W. Elverum, M. Steinert, Eliciting unknown unknowns with prototypes: Introducing prototrials and prototrial-driven cultures, Des. Stud. 49 (2017) 1–31, doi:10.1016/j.destud.2016.12.002.

[21] J. Nelson, J. Menold, Opening the black box: Developing metrics to assess the cognitive processes of prototyping, Des. Stud. 70 (2020) 100964, doi:10.1016/j.destud.2020.100964.

[22] S.R. Klemmer, B. Hartmann, L. Takayama, How bodies matter: five themes for interaction design, in: Proceedings of the 6th Conference on Designing Interactive Systems, ACM, 2006, pp. 140–149, doi:10.1145/1142405.1142429.

[23] P. Dourish, Where the Action Is: The Foundations of Embodied Interaction, MIT Press, Cambridge, MA, 2001, doi:10.7551/mitpress/7221.001.0001.

[24] F. Gmeiner, H. Yang, L. Yao, et al., Exploring challenges and opportunities to support designers in learning to co-create with AI-based manufacturing design tools, in: Proceedings of the 2023 CHI Conference on Human Factors in Computing Systems, ACM, 2023, Article No. 226, doi:10.1145/3544548.3580999.

[25] K. Borg, V. Sahadevan, V. Singh, et al., Leveraging generative design for industrial layout planning: SWOT analysis insights from a practical case of papermill layout design, Adv. Eng. Inform. 60 (2024) 102375, doi:10.1016/j.aei.2024.102375.

[26] L. Pan, C. Yu, Z. He, et al., A human-computer collaborative editing tool for conceptual diagrams, in: Proceedings of the 2023 CHI Conference on Human Factors in Computing Systems, ACM, 2023, Article No. 360, doi:10.1145/3544548.3580676.

[27] T.S. Kim, D. Choi, Y. Choi, et al., Stylette: styling the web with natural language, in: Proceedings of the CHI Conference on Human Factors in Computing Systems, ACM, 2022, Article No. 5, doi:10.1145/3491102.3501931.

[28] D. Choi, S. Hong, J. Park, et al., CreativeConnect: supporting reference recombination for graphic design ideation with generative AI, in: Proceedings of the CHI Conference on Human Factors in Computing Systems, ACM, 2024, Article No. 1055, doi:10.1145/3613904.3642794.

[29] J. Tholander, M. Jonsson, Design ideation with AI - sketching, thinking and talking with generative machine learning models, in: Proceedings of the 2023 ACM Designing Interactive Systems Conference, ACM, 2023, pp. 1930–1940, doi:10.1145/3563657.3596014.

[30] J. Li, H. Cao, L. Lin, et al., User experience design professionals' perceptions of generative artificial intelligence, in: Proceedings of the CHI Conference on Human Factors in Computing Systems, ACM, 2024, Article No. 381, doi:10.1145/3613904.3642114.

[31] J. Manyika, S. Hsiao, An overview of Bard: an early experiment with generative AI, https://ai.google/static/documents/google-about-bard.pdf, 2023.

[32] OpenAI, ChatGPT, https://chat.openai.com/, 2023.

[33] J. Rezwana, M.L. Maher, Understanding user perceptions, collaborative experience and user engagement in different human-AI interaction designs for co-creative systems, in: Proceedings of the 14th Conference on Creativity and Cognition, ACM, 2022, pp. 38–48, doi:10.1145/3527927.3532789.

[34] R. Huang, H. Lin, C. Chen, et al., PlantoGraphy: incorporating iterative design process into generative artificial intelligence for landscape rendering, in: Proceedings of the 2024 CHI Conference on Human Factors in Computing Systems, ACM, 2024, Article No. 168, doi:10.1145/3613904.3642824.

[35] V. Liu, J. Vermeulen, G. Fitzmaurice, et al., 3DALL-E: integrating text-to-image AI in 3D design workflows, in: Proceedings of the 2023 ACM Designing Interactive Systems Conference, ACM, 2023, pp. 1955–1977, doi:10.1145/3563657.3596098.

[36] E. Stemasov, S. Demharter, M. Rädler, et al., pARam: leveraging parametric design in extended reality to support the personalization of artifacts for personal fabrication, in: Proceedings of the 2024 CHI Conference on Human Factors in Computing Systems, ACM, 2024, Article No. 337, doi:10.1145/3613904.3642083.

[37] E. Stemasov, T. Wagner, J. Gugenheimer, et al., Mix&Match: towards omitting modelling through *in situ* remixing of model repository artifacts in mixed reality, in: Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems, ACM, 2020, pp. 1–12, doi:10.1145/3313831.3376839.

[38] Y. Tao, S. Wang, J. Ji, et al., 4Doodle: 4D printing artifacts without 3D printers, in: Proceedings of the 2023 CHI Conference on Human Factors in Computing Systems, ACM, 2023, Article No. 731, doi:10.1145/3544548.3581321.

[39] A. Villanueva, Z. Zhu, Z. Liu, et al., Meta-AR-app: an authoring platform for collaborative augmented reality in STEM classrooms, in: Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems, ACM, 2020, pp. 1–14, doi:10.1145/3313831.3376146.

[40] R. Raskar, G. Welch, H. Fuchs, Spatially augmented reality, in: Proceedings of the international workshop on Augmented reality: placing artificial objects in real scenes, A K Peters, Ltd., Natick, MA, 1999, pp. 63–72.

[41] Y. Zhou, S. Xiao, N. Tang, et al., Pmomo: projection mapping on movable 3D object, in: Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems, ACM, 2016, pp. 781–790, doi:10.1145/2858036.2858329.

[42] C.F. Cano, A. Roudaut, MorphBenches: Using mixed reality experimentation platforms to study dynamic affordances in shape-changing devices, Int. J. Hum. Comput. Stud. 132 (2019) 1–11, doi:10.1016/j.ijhcs.2019.07.006.

[43] Unity, Unity 2020.3.36, https://unity.com/releases/editor/whats-new/2020.3.36, 2022.

[44] Microsoft Learn, MRTK2-Unity Developer Documentation - MRTK 2, https://learn.microsoft.com/en-us/windows/mixed-reality/mrtk-unity/mrtk2/?view=mrtkunity-2022-05, 2022.

[45] R. McNeel, Nuget gallery | rhino3dm 7.15.0, https://www.nuget.org/packages/Rhino3dm/, 2021.

[46] R. McNeel, Rhino - compute guides, https://developer.rhino3d.com/guides/compute/, 2020.

[47] AUTOMATIC1111, Stable diffusion web UI, https://github.com/AUTOMATIC1111/stable-diffusion-webui, 2022.

[48] Stability AI, Stable diffusion XL 1.0, https://huggingface.co/stabilityai/stable-diffusion-xl-base-1.0, 2023.

[49] E. Kim, K. Kim, Cognitive styles in design problem solving: Insights from network-based cognitive maps, Des. Stud. 40 (2015) 1–38, doi:10.1016/j.destud.2015.05.002.

[50] J. Liao, P. Hansen, C. Chai, A framework of artificial intelligence augmented design support, Hum.–Comput. Interact. 35 (5–6) (2020) 511–544, doi:10.1080/07370024.2020.1733576.

[51] S.G. Hart, NASA-task load index (NASA-TLX); 20 years later, Proc. Hum. Factors Ergon. Soc. Annu. Meet. 50 (9) (2006) 904–908, doi:10.1177/154193120605000909.

[52] E. Cherry, C. Latulipe, Quantifying the creativity support of digital tools through the creativity support index, ACM Trans. Comput.-Hum. Interact. 21 (4) (2014) 21, doi:10.1145/2617588.

[53] J. Brooke, et al., SUS: a 'quick and dirty' usability scale, in: P.W. Jordan, B. Thomas, I. Lyall, et al. (Eds.), Usability Evaluation In Industry, 1st Ed., CRC Press, London, 1996, pp. 207–212, doi:10.1201/9781498710411-35.

[54] D. Barry, Do not use averages with Likert scale data, https://bookdown.org/Rmadillo/likert/, 2017.

[55] J. Swain, A hybrid approach to thematic analysis in qualitative research: using a practical example, Sage Research Methods Cases Part 2, SAGE Publications, Ltd., 2018, doi:10.4135/9781526435477.

[56] OpenAI, Gpt-4v(ision) system card, https://chat.openai.com/, 2023.

[57] Google, Gemini 1.5, https://deepmind.google/technologies/gemini, 2023.

[58] Anthropic, Claude 3, https://claude.ai, 2023.