*IEDS: Exploring an **Intelli-Embodied Design Space** combining designer, AR, and GAI to support conceptual design*

A PREPRINT

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August 6, 2024

ABSTRACT

Conceptual design is an important stage in product development. In conceptual design, the design space 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. Under this background, this study proposed an Intelli-Embodied Design Space (IEDS) combining designer, AR, and GAI to support conceptual design, aiming to enhance designers' thinking by superposing the embodied interaction and generative variability. In IEDS, designers can interact with the 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 first built a corpus of 116 papers through a literature review to synthesize previous principles of integrating AR and GAI in design, respectively, from a theoretical perspective. Building upon common principles, we conducted expert interviews for a more focused scope of the combination of designer, AR, and GAI. Following expertise insights, we developed three potential IEDS systems and conducted an open-ended exploration study with 27 designers 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.

Keywords AI-assisted design · generative AI · augmented reality

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 design problems and solutions they face. Besides, the design materials, containing the 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 the innovative design materials 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 the 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 space [7].

Artificial intelligence is now a fairly established technology, serving as the new design material for design practitioners [6, 12]. Especially with the 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 mode and allowed designers to create design schemes through 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 commonsense, 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 to the 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 might 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. Figure 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.

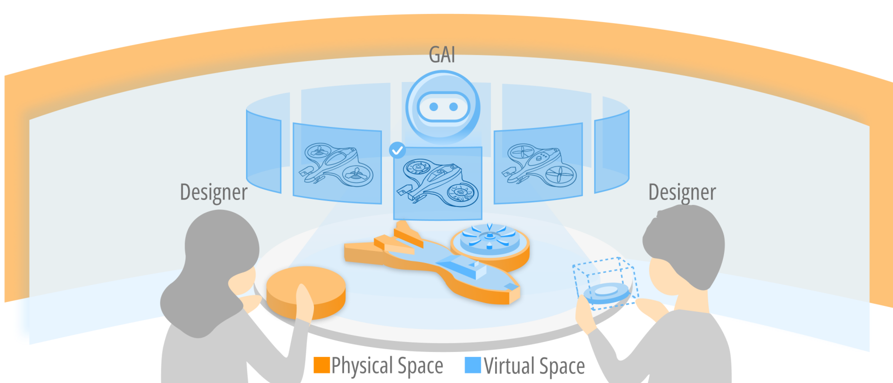


Figure 1: The conceptual introduction of the Intelli-Embodied Design Space (IEDS).

In this paper, we proposed and explored an IEDS by combining theory and practice. From a theoretical perspective, we first built a corpus of 116 papers through a literature review to synthesize previous principles of integrating AR and GAI in design, respectively. Building upon common principles, we conducted expert interviews for a more focused scope of the combination of designer, AR, and GAI in conceptual design. From a practical perspective, we developed three potential IEDS systems following expertise insights and conducted an open-ended exploration 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.

2 Scope, Methodology, and Contribution

2.1 Scope and Definition

The topic covered by this study is an IEDS combining designer, AR, and GAI to support conceptual design. In this section, we describe our concrete scope and definition.

2.1.1 Conceptual Design

Due to the dynamic and abstract nature of the design process, it is challenging to define the start and end of conceptual design clearly. The conceptual design in this paper is regarded as the process of identifying the design problem and exploring potential design solutions in product development, in which designers need to deepen the design problem, specify main functions, establish basic structures, and select appropriate principles to evaluate and implement [15]. Therefore, we focus on the exploration process, which proposes potentially feasible design concepts. In-depth evaluation and implementation of design schemes, such as simulation tests for structure, engineering analysis for material, and manufacturability assessment for assembly, are beyond the scope of our research.

2.1.2 AR Scope

The definition of AR can vary according to context [16]. Azuma et al. defined that AR has to satisfy three conditions: a combination of reality and virtuality, real-time interaction, and a 3D real world [17]. In this study, referring to Suzuki et al., we take AR as a broader scope and include any system that augments physical objects or surrounding environments in the real world regardless of the technology used [11]. We focus on enabling the physical environment and objects to be coupled with generated artifacts through AR in a design space.

2.1.3 GAI Scope

AI is also an extensive field with many research branches. In the design domain, it is common for designers to use discriminant AI tools to gain data-enabled design insights, such as design evaluation and decision-making [12]. This study focuses on the GAI, which refers to computational techniques that automatically create new and plausible media rather than utilizing data to support decisions, labels, and classifications [18]. Specifically, in our expected design space, we mainly focus on GAI's generation capability in design, which has the potential to augment designers' thinking and enrich the ideation process based on generative variability and uncertainty. In addition, aiming to integrate a hybrid design space, we pay more attention to the design generation of visual modal content instead of text reasoning.

2.2 Workflow and Methodology

Figure 2 shows this study's workflow, methods, and outcomes. Aiming to explore the IEDS, we completed three parts of work in this study. Initially, we reviewed a corpus of papers to extract the common principles of AR and GAI applications in design. Specifically, we collected related papers through systematic search and expertise review, constructing a corpus of 116 papers for literature analysis. We then extracted interaction methods, implementation principles, and application values of both AR and GAI in design, and invited four experts with extensive AR and GAI experience to participate in a semi-structured interview. We summarized experts' insights on the combination of designer, AR, and GAI in a design space. Building upon these basic proposals, we proposed three potential IEDS interaction

STEPS	METHODS	OUTCOMES
IEDS Concept Proposal	**Literature Review** Collecting papers related to "GAI+Design" and "AR + Design" through both systematic search and expertise review, selecting a corpus of 116 papers for further analysis.	**Common Principles** Extracting common interaction methods and principles, and application values of both AR and GAI in design.
	Expert Interview Conducting semi-structured interview with four experts possessing extensive experience with both AR and GAI.	**Experts' Insights** Summarizing experts' insights on the combination of AR and GAI in a hybrid design space.
IEDS Open-ended Exploration	**User Experiment** Developing three potential IEDS interaction systems combining AR and GAI, inviting 27 participants in user study, comparing their design experience by quantitative methods.	**Comparative Results** Understanding the strengths, limitations, and applicability in different combinations of AR and GAI in IEDS.
IEDS Guideline, Application & Vision	**Designer Interview** Conducting semi-structured interview with participants experiencing IEDS systems. Combining quantitative results to discuss findings comprehensively.	**Application and Vision** Releasing the practical guidelines, best practices, and future vision of IEDS.

Figure 2: Workflow, methodology, and outcome in this study.

modes and developed corresponding systems. 27 participants were invited to a comparative user study and randomly assigned to different groups. Eventually, based on experimental results, we understood and clarified the strengths and limitations of different combinations of AR and GAI in the design space. We further proposed the interactive guidelines and best practices in IEDS and its vision.

2.3 Contribution

We provided the following contributions. First, we proposed the novel concept of Intelli-Embodied Design Space (IEDS) combining designer, AR, and GAI to support conceptual design. IEDS allows designers to leverage embodied interaction with the physical environment while gaining creativity from generated artifacts. Second, aiming to realize the IEDS concept, we designed and developed three design systems that combine AR and GAI. Third, 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. Fourth, we specified our IEDS vision and formulated opportunities for both the HCI and design communities.

3 Theoretical Background

This study centers on combining designer, AR, and GAI in a design space to support conceptual design. As we drew inspiration from both embodied design representation and generative ability, we introduced the influence of design space containing physical representation and the influence of design materials with GAI on conceptual design. In this section, we focus on clarifying the theoretical background. Previous practical applications of integrating AR and GAI in design will be elaborated in the literature review in Section 4.2.

3.1 Design Space Containing Physical Design Representation

In addition to verbal and textual expression for design, the conceptual design process involves the manipulation and modification of external representations, also referred to as design representation [19]. It plays an important role in conceptual design because it allows designers to encode information to easily handle complex problems and serve as a long-term memory, as well as free their cognitive memory and facilitate idea generation [20]. These design representations can be in sketches, line drawings, CAD, physical models, and even gestures. They assist designers in representing their ideas and provide examples as stimuli for inspiration [21]. As Kirsh indicated that cognitive processes flow to wherever it is cheaper to perform them, the information representation modes are a way of changing the cognition domain and range [5].

The physical design representation has distinct strengths in supporting design ideation. First, the physical environment promotes design exploration. Physical forms of information, such as physical models and clay, make the idea visible and manipulatable, making idea exploration much easier. Moreover, during the ideation sessions, the physical model can increase the number of sensorial stimuli, such as touch, sight, and smell, compared to paper containing texts and images [22]. Therefore, there is a surge in the available design information for analogy, which is beneficial for spatial relationship reasoning, hidden features perception, and unexpected insights discovery [23]. Second, the physical environment supports design analysis. The physical environment allows designers to perceive and analyze design concepts in a tangible form instead of processing steps in their minds. It supports faster decision-making in the cognitive process because the more rules are distributed in the external representation, the easier it is to solve the problem [24]. In addition, physical models facilitate function test and problem visualization, underscoring flawed design assumptions and highlighting significant discrepancies between the actual solutions and their conceptual predictions [25, 26]. Third, the physical environment enhances design communication and collaboration. The tangible design object provides a concrete anchor for discussion occurs [27]. It allows more seamless collaboration among designers since all people can manipulate the artifact and see the action result immediately and simultaneously [28]. These physical artifacts can serve as shared objects of thought and an essential medium for collaboration [5].

3.2 Design Material Integrating GAI

As machine learning and GAI are fairly established technologies, designers serve them as novel design materials to think and create [6, 12]. Recently, the advancement of deep generative models has promoted significant progress in integrating GAI within conceptual design. The fundamental principle underlying generative models is their ability to learn distribution patterns from extensive datasets, thereby autonomously acquiring abstract knowledge. This capability ultimately enables GAI to generate novel visual and textual content. The recent surge of GAI has sparked increasing interest across a multitude of creative design fields, such as industrial design [29], layout design [30], diagram design [31], and UI design [32]. Previous studies have shown that GAI excels in supporting ideation [33], assisting prototype [29], stimulating inspiration [34], facilitating design reasoning [14], and advising iteration [35].

Based on the GAI's strong abilities, its participation is poised to fundamentally change traditional design materials. First, the interactive way of creation can be changed. The chat-like interfaces provided by GAI platforms like Bard [36] or ChatGPT [37] allow designers to create design schemes through their natural language, often in their mother tongue. This significantly reduces the design threshold, allowing design members without hand-drawing and modeling, such as engineers and customers, to participate effortlessly in the conceptual design process. Second, the modalities that designers perceive in design space can be richer. In traditional design platforms or tools, the perceptible design modalities are often constrained by the capabilities and formatting parameters inherent to the platform. For instance, designers cannot create 3D representations within 2D sketch software. However, with the generative ability of GAI, designers can utilize various generative models to effortlessly obtain multi-modal design information, including sketch [38], 2D high-fidelity scheme [39] and 3D prototype [40]. It enables a richer and more effective way of exploring, expressing, and manipulating ideas in design space. Third, the design roles in the design space become more diverse. GAI's variability allows it to contribute insights and suggestions that might not be immediately apparent to human designers [14]. In addition, it supports designers in efficiently gathering knowledge from fields outside their personal experience through data-enabled generation, enriching the ideation process [14].

4 Intelli-Embodied Design Space (IEDS)

4.1 The Scope of IEDS

Based on the above theoretical viewpoints, we aim to propose an innovative design space that integrates the advantages of both physical representation and GAI in conceptual design. Figure 3 presents the research scope of IEDS, combining designers, AR, and GAI.

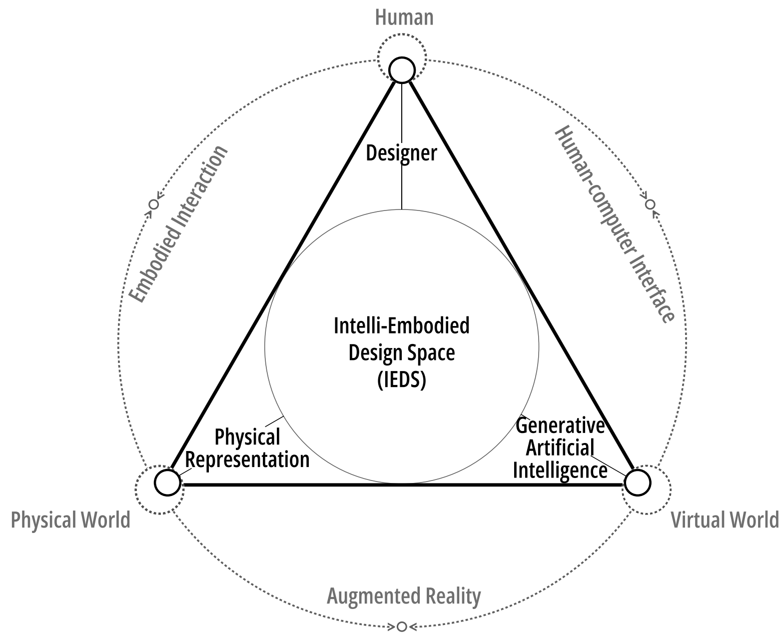


Figure 3: The research scope of the proposed IEDS.

We expect the IEDS to have the following characteristics and capabilities (present concepts in Figure 3):

- 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.

We hope the IEDS can reduce designers' cognitive load and augment their creativity through embodied interaction, as well as enrich the ideation process and open up an imaginary space through GAI generation. To propose and complete the IEDS concept, we first conducted a literature review to collect common interaction guidelines on how to utilize AR and GAI in supporting conceptual design. Second, based on these common principles, we organized expert interviews to summarize expertise insights on the combination of AR and GAI in a hybrid design space.

4.2 Part I: Survey of Literature Review

We initiated a comprehensive review of existing literature on AR+Design and GAI+Design respectively. For the dataset and inclusion criteria, we completed a systematic search and an expertise review. On the one hand, we conducted a systematic search in the ACM Digital Library, IEEE Xplore, Springer, Elsevier, and Taylor & Francis. For the AR+Design, our search terms included the combination of "*augment reality*" AND "*design*" in the title AND/OR author keywords since 2010. We also searched for synonyms of each keyword, such as "*AR*", "*mixed reality*", "*hybrid world*" for "*augmented reality*"

AND "*creative work*", "*creativity*" for "*design*". For the GAI+Design, our search terms included the combination of "*generative artificial intelligence*" AND "*design*" in the title AND/OR author keywords. As GAI was a relatively new research field, the publishing time started in 2020. The synonyms included "*GAI*", "*generative AI*", "*generative system*","*co-creation*" for "*generative artificial intelligence*" AND "*creative work*", "*creativity*" for "*design*". This gave us a total of 800 articles related to GAI+Design and 582 articles related to AR+Design. Then, four authors individually looked at each paper to select papers strongly related to our topic and excluded out-of-scope papers. For example, the AR papers related to AR techniques, such as optics and reconstruction algorithms, instead of the interaction perspectives, were withdrawn. After this process, we obtained 11 strongly related papers for GAI+Design and 16 for AR+Design.

On the other hand, we conducted an expertise review to complement the systematic search. Specifically, four authors reviewed several top-tier journals and conferences in both design and HCI fields, including *CHI*, *UIST*, *TOCHI*, *IJHCS*, *HCI*, *Design Studies*, and *The Design Journal*, to avoid ignoring papers whose titles do not contain the above keywords, but whose contents are strongly related to our topic. Consistent with the systematic search, in the expertise review, the scope of consideration for AR-related papers began in 2010, and GAI-related papers began in 2020. After four authors discussed and cleared up their differences, we supplemented 58 GAI+Design papers and 35 AR+Design papers. Eventually, by merging these papers and removing duplicates, we finally selected a corpus of 116 papers (Appendix 2), including 67 for GAI+Design and 49 for AR+Design, for our further analysis.

For the analysis and synthesis, four authors conducted open coding on a small subset of our sample to identify the dimensions and categories of the application of AR and GAI in the design space. All authors reflected upon the initial code classification to discuss the consistency and comprehensiveness of the categorization methods, and then categories were merged, expanded, and removed. Next, all authors performed the coding process and completed classification after discussion and disagreement elimination. We present our results in this section.

4.2.1 GAI+Design

In related articles, we focused on the AI Application Scenario (AS), AI Application Purpose (AP), Human-to-AI Communication Mode (HM), AI-to-Human Communication Mode (AM), Participation Style (PS), Task Distribution (TD), and AI Role (RO).

- For the AI Application Scenario (AS) & AI Application Purpose (AP):
  GAI has widely applied in diverse design fields, including *industry & product design* (AS1) [41, 42], *architectural & interior design* (AS2) [43, 44], *fashion & footwear design* (AS3) [45, 46], *UX & UI design* (AS4) [47, 48], *graphic & visual design* (AS5) [34, 49], *conceptualization* (AS6) [50, 51], *art creation* (AS7) [52, 53], and *research & education* in design (AS8) [54, 55]. Similar to what we mentioned in the theoretical background, most of the studies integrated the generation ability in order to *stimulate creativity* (AP1) [56, 57], *customization* (AP2) [58, 59], *automate tasks* (AP3) [34, 60], *improve efficiency & optimize processes* (AP4) [61, 62], and *facilitate collaboration & improve team synergy* (AP5) [63, 64].
- For the Human-to-AI Communication Modes (HM):
  We coded human users' input information and interaction modes to GAI here. Undoubtedly, the most common human-to-AI interaction is to directly input design requirements through *text* (HM1) [65, 66], part of which supports *voice input* (HM2) [32, 47]. *Sketch and graffiti* (HM3) [42, 67] are also one of the common input methods. Some systems supported to specify the design requirement in the *structured relationship* (HM4), such as the semantic map [68], bounding box [44], and graph-based network [51]. In addition, for some systems that support complex design requirements and fine editing, the functions of *direct editing and manipulation* (HM5) are developed, mainly including direct mouse drag and drop [58] and graphical panel control [69]. Other human-to-AI communication modes also exist but are rarely involved in our corpus, including *3D model* (HM6) [52, 70], *3D sketch* (HM7) [53], *image* (HM8) [34, 71], *body movement data* (HM9) [41, 72], and *UX & UI* diagrams (HM10) [47, 73].
- For the AI-to-Human Communication Modes (AM):
  The modalities for AI-initiated communication are mainly supported or limited by the ability to the generative models in generative systems. Based on our coding, the textual and visual

are the most common modalities in GAI's output. The textual information can be further divided into *text* (AM1) [54, 74] and *voice* (AM2) [72, 75], while the visual information can be divided into *icon* (AM3) [49], *image* (AM4) [61, 76], *animation* (AM5) [51, 77] and *UX & UI* diagrams (AM8) [32, 78]. With the development of the ability to generate models, the AI-to-human communication mode involved the multi-modal outputs, such as *stereo image* (AM6) [43, 53] and *3D model* (AM7) [41, 75]. In addition, in some studies, GAI generates relational configuration schemes, such as the color scheme [79] or circuit logic scheme [80], in which we code as the *configuration* (AM9).

- For the Participation Style (PS):

  As defined in Rezwana and Maher [38], the participation style refers to whether the collaborators can participate and contribute simultaneously or one collaborator has to wait until the partner finishes a turn. We classified the participation style into *parallel-tasking* (PS1) [72, 81] and *turn-tasking* (PS2) [59, 82]. In *parallel-tasking* participation, continuous parallel participation from the human designers and GAI occurs, while in *turn-tasking* interaction, they take turns to create and contribute. In our corpus, the *turn-tasking* style is more common because designers often need to correct the next iterative direction and adjust the human-to-AI communication according to GAI's response and feedback.

- For the Task Distribution (TD):

  We paid attention to the distribution of tasks among the human designers and GAI. We coded two types of task distribution. First, when it is the *same task* (TD1) [83, 84], human designers and GAI take part in the same task without work division. This mode was usually utilized in painting or sketching systems, human designers and GAI create in the same canvas space. However, more systems adopted the *divided task* (TD2) mode. Designers usually put forward design requirements and constraints. GAI completes and executes subtasks, including reasoning tasks (e.g., brainstorming and divergent reasoning [85]) and implementing tasks (e.g., generating image schemes based on requirements [61]).

- For the AI Role (RO):

  We investigated the GAI contribution form and its influence on the design process, classifying GAI into several roles. First, the GAI can be a *stimulator* (RO1) in ideation, in which GAI provides multi-perspective and interdisciplinary knowledge, assisting design reasoning and enriching ideation. When GAI is a stimulater, the generated artifacts were mostly text [55], as well as a few visual modes, such as conceptual image [44] and style image [76]. Second, GAI can be a *generator*, generating non-textual artifacts aligned with designers' intentions based on their requirements and restrictions. Specifically, according to the aim and contribution of generation, we divided the *generator* into *creator* (RO2) and *refiner* (RO3), distinguished by creating new artifacts [77, 86] and refining based on existing schemes [42, 67]. Third, GAI can be an *analyzer or evaluator* (RO4) [70, 87] to perform in-depth analysis and evaluation of design schemes, helping designers identify potential flaws and highlight ignored issues. It is worth mentioning that we find that the AI role in a generative system is not unique, and diverse roles are switching based on design tasks and designers' demands.

4.2.2 AR+Design

In related articles, we focused on the AR Application Scenario (AS), AR Application Purpose (AP). Augment Information (IN), Augment Approach (AA), and Interaction Modality (IM).

- For the AR Application Scenario (AS) & AR Application Purpose (AP):

  We reviewed and summarized the AR application scenarios. AR has been widely utilized in the field of *industry & product design* (AS1) [88, 89], *architectural & interior design* (AS2) [90, 91], *fashion design* (AS3) [92, 93], *conceptualization* (AS4) [94, 95], *game design* (AS5) [96, 97], *engineering assembly* (AS6) [98, 99], *guideline & education* in design (AS7) [100, 101], and *video & animation design* (AS8) [102, 103]. The AR application purpose mainly focused on *presenting rich information* (AP1) [104, 100], *supporting intuitive interaction and simulation* (AP2) [105, 106], *enhancing surrounding immersion* (AP3) [107, 104], *strengthening cooperation* (AP4) [108, 109], and *promoting rapid information access* (AP5) [100, 101].

- For the Augment Information (IN):

We summarized the types of information presented through AR interfaces in the design process. The categories we identified include *design prototype and scheme* (IN1), *design simulation and plan* (IN2), *design environment information* (IN3), and *design supplementary information* (IN4). Specifically, most design systems using AR techniques augmented the design scheme information, including digital design schemes [94, 95], structural design [106, 110], and detail display [111, 112]. These augmented schemes ranged from low-fidelity to high-fidelity, as well as from 2D to 3D form. These virtual prototypes and schemes were coupled with physical objects or environments to represent rich design. Besides, some studies presented the *design simulation and plan*, emphasizing the simulation and visualization of dynamic motion [88, 113] or interactive simulation based on physical design [114, 115]. The *design environment information* presented supporting components or surroundings related to the physical design, such as the reconstruction of the 3D environment and virtual background [91, 107]. The *design supplementary information* was mainly used to explain and clarify the additional information of the current design scheme, such as design notes [108] and comments [100, 104].

- For the Augment Approach (AA):

  We paid attention to how virtual information was enhanced in design space, that is, how physical and virtual information are coupled. First, the most widely used AR method is through head-mounted display devices (HMD), 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. We summarized that method as *augment through HMD* (AA1) [105, 116]. In addition, some studies utilized hand-held devices (HHD) 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 [93, 100]. We marked this method as *augment through HHD* (AA2). The third method was *spatial augmented reality* (AA3). Raskar et al. defined it as the projection of virtual content onto a physical object directly [117]. This method employed fixed or portable projectors to attach the virtual information onto the physical objects or environments [118, 119].

- For the Interaction Modality (IM):

  We investigated the interaction modality in AR studies in the design field. First, designers can interact with AR space through *tangibility* (IM1), in which they change the shape or physically deform the physical object. In related systems with tangible interaction, there were mostly tangible design representations, such as tangible objects [96, 120] or physical prototypes [112, 90], which can be shaped or edited directly in the physical world. Second, in some AR systems augmented through HHD equipment, designers can interact with tablets or mobiles through *touch* interaction (IM2) [115, 121]. Third, the *spatial movement data* (IM3) was a common interaction modality for HMD-based interfaces, such as spatial gesture [120, 110]. Designers can model and edit design schemes through gesture movement and interact with virtual menus. Other interactive modes were also involved, such as *gaze* (IM4) [122, 99] and *voice* [99] (IM5). These auxiliary input methods enabled designers to fully use their bodies, making the interaction more direct and immersive. Some studies also utilized ancillary devices to interact in AR space, such as smart gloves [123] and smart pens [124].

4.3 Part II: Expert Interview

Based on the literature review and extracted codes (Figure 4), we further organized a semi-structured interview with four experts from the industry or academy. All experts possess extensive knowledge and experience with both GAI and AR tools. Our interview aimed to summarize expertise insights on the combination of AR and GAI in a hybrid design space, thereby proposing the initial concept of the IEDS.

4.3.1 Expert Background

Each of the four experts (E1-E4) has over 10 years of professional experience in AR interface research or development. They also have basic knowledge and rich experience using GAI in their design work.

- E1 is an AR interaction researcher at a famous mobile hardware research and development company currently working on intelligent HMD development.

- E2 is an AR interface design leader at an internet company. E2 is currently engaged in the combination of GAI ability and HoloLens application to support creative work.
- E3 is an assistant professor in the computer science college of a university. E3's research focuses on AR and its application in HCI.
- E4 is a co-founder of an AR technology company specializing in utilizing spatial augmented reality techniques to support product design.

4.3.2 Method and Outline

We initially introduced our theoretical background, research scope, and research vision to experts, as well as presented and explained our extracted codes from the literature review. Experts were asked to discuss each code and evaluate its potential value or positive influence for a hybrid design space combining AR and GAI based on their knowledge and experience. We asked experts to critically discuss from the necessity and importance perspective to help us screen each code effectively instead of agreeing with each item. The outline includes but is not limited to "*Do you think this item is valuable for our proposed hybrid design space? Where do you think its value lies and what role it plays in that design space? Do you think the lack of it will affect the design space?*" In addition, we invited experts to have a more open discussion, addressing their attitudes and comments on our IEDS vision, potential strengths, and expected challenges of IEDS construction. The outline includes but is not limited to "*Do you think such a hybrid design space is valuable or not? What is the difference between it and the current common design representation or design tools? Are you willing to design in such a hybrid space? What are the challenges and risks of designing and building such a hybrid design space? Do you have any comments or suggestions for the hybrid design space?*" Following the interview organization, all authors discussed recorded interview contents and summarized the following findings.

4.3.3 Results and Findings

Positive Attitudes to IEDS. All four experts expressed their strong interest and positive attitude towards our IEDS vision. E1 indicated that "*the space combining AR and GAI can give full play to their advantages and open an imaginary space while enhancing immersion*". E3 mentioned "*Physical representation and GAI are a clever combination, which allows designers to express their design intentions concretely with their familiar design materials*". E2 reported that "*I think IEDS might increase the available design information in the design space as never before, GAI can continuously generate multi-modal design information, and AR provides a cross-modal presentation medium for this diverse information*". We summarized the potential strengths of IEDS mentioned by experts, which include *enriching stimulation* (E1-4), *increasing available design information* (E2, 4), *expanding imagination* (E1, 3, 4), *deepening ideation* (E1, E4), *making creation more free* (E1-3), *improving prototype efficiency* (E2-4), *making design immersive and intuitive* (E2-4), *breaking away from data modal constraints* (E2, 3), *enhancing GAI usability and friendliness* (E3), *promoting cooperation and communication* (E1, 2, 4). These positive feedback findings corroborate experts' favorable views on IEDS concept, thereby providing a foundation for further research.

Insights and Suggestions for IEDS Design. Based on the literature review, we consulted experts for further suggestions on building IEDS. We extracted some codes that more than three experts considered valuable and necessary for IEDS design and highlighted them in Figure 4. We also show the specific coding results in Appendix 1. On the GAI integration in IEDS. The *text* (HM1), *3D model* (HM6), and *image* (HM8) were regarded as necessary Human-to-AI communication modes. E1-4 all considered the textual information the most basic way to convey design requirements and restrictions. E1-3 believed that the 3D model was an effective way to convey design intention. Both the virtual model and physical model contained rich information, helping GAI to understand detailed intentions. Similarly, the *text* (AM1), *image* (AM4), and *3D model* (AM7) were regarded as important AI-to-human communication modes. The *turn-tasking* (PS2) and *divided task* (TD2) were extracted to the preferred participation style and task distribution mode respectively by all experts. Experts indicated that it helped designers enhance their control over GAI, dominated the ideation process, and controlled its rhythm. For the AI participation role, experts demonstrated that all kinds of roles were meaningful in design, especially the *stimulator* (RO1), *creator* (RO2), and *refiner* (RO3). Experts indicated that it would be best to switch roles according to the design tasks and stages.

GAI+Design

AI Application Scenario (AS)
- AS1: industry & product design
- AS2: architectural & interior design
- AS3: fashion & footwear design
- AS4: UX & UI design
- AS5: graphic & visual design
- AS6: conceptualization
- AS7: art creation
- AS8: research & education

AI Application Purpose (AP)
- AP1: stimulate creativity
- AP2: customization
- AP3: automate tasks
- AP4: improve efficiency & optimize processes
- AP5: facilitate collaboration & improve team synergy

Human-to-AI Communication Mode (HM)
- ● HM1: text
- HM2: voice input
- HM3: sketch and graffiti
- HM4: structured relationship
- HM5: direct editing and manipulation
- ● HM6: 3D model
- HM7: 3D sketch
- ● HM8: image
- HM9: body movement data
- HM10: UX & UI

AI-to-Human Communication Mode (AM)
- ● AM1: text
- AM2: voice
- AM3: icon
- ● AM4: image
- AM5: animation
- AM6: stereo image
- ● AM7: 3D model
- AM8: UX & UI
- AM9: configuration

Participation Style (PS)
- PS1: parallel-tasking
- ● PS2: turn-tasking

Task Distribution (TD)
- TD1: same task
- ● TD2: divided task

AI Role (RO)
- ● RO1: stimulator
- ● RO2: creator
- ● RO3: refiner
- RO4: analyzer or evaluator

AR+Design

AR Application Scenario (AS)
- AS1: industry & product design
- AS2: architectural & interior design
- AS3: fashion design
- AS4: conceptualization
- AS5: game design
- AS6: engineering assembly
- AS7: guideline & education
- AS8: video & animation creation

AR Application Purpose (AP)
- AP1: present rich information
- AP2: support intuitive interaction and simulation
- AP3: enhance surrounding immersion
- AP4: strengthen cooperation
- AP5: promote rapid information access

Augment Information (IN)
- ● IN1: design prototype and scheme
- IN2: design simulation and plan
- IN3: design environment information
- IN4: design supplementary information

Augment Approach (AA)
- AA1: augment through HMD
- AA2: augment through HHD
- AA3: spatial augmented reality

Interaction Modality (IM)
- ● IM1: tangibility
- IM2: touch
- ● IM3: spatial movement data
- IM4: gaze
- ● IM5: voice
- IM6: ancillary device

Figure 4: Classification and codes extracted through literature review. ● indicates that most experts think this item is necessary for IEDS.

On the AR application in IEDS, we focused on the augment information, augment approach, and interaction modality in IEDS. First, experts agreed on the augment information, in which they considered the *design prototype and scheme* (IN1) as the most basic and necessary information in conceptual design. In addition, although experts mentioned that the more interactive modes in an AR environment, the more natural and immersive the interaction, experts commonly thought that *tangibility* (IM1), *spatial movement data* (IM3), and *voice* (IM5) were the most indispensable interactive modes in IEDS.

Uncertainty and Challenges in IEDS Implementation. For the AR application in IEDS, there was a great difference among experts on the augmented approach. Specifically, E1 considered *augmenting through HMD* (AA1) was the most suitable approach because it was the mainstream AR mode at present and achieved immersion to the greatest extent. However, E3 indicated that the HMD equipment weight might reduce the friendliness in the practical design process. And E3 pointed out that *augment through HHD* (AA2) was the closest augment approach to the practical design work, which most naturally supported the conceptual design process. E4 argued that *spatial augmented reality* (AA3) was the most real interaction mode because designers could get what they see, while E2 acknowledged the value and benefits of three augment approaches. Although there were differences in AR approaches, it could be agreed that experts believed that different augment approaches had their advantages and limitations. It was necessary to choose the appropriate augment approach according to specific design tasks, design stages, and design teams in conceptual design rather than generalizing them.

For the GAI integration in IEDS, experts' concerns mainly focued on the generation ability to generative models. For example, E1 pointed out that "*I think 3D models must be the most useful generative output mode in IEDS, which contains the richest design information. But at present, the quality and efficiency of 3D model generation still make it difficult to support complex design. In this sense, alternatives such as multi-view or stereo image generation may need to be considered*". E2 clarified that "*Although the generative quality is very important, I think the interaction in IEDS is the primary consideration. With the GAI development, the multi-modal generative ability will be significantly improved. Still, it is necessary to define in advance how designers in IEDS interact with GAI and AR environments*".

4.4 A Brief Summary

After a literature review and expert interview, we further clarified the IEDS concept and defined the interaction mechanism in IEDS. Figure 5 shows the proposed interaction in IEDS. Specifically, designers can input textual design intention through text and voice (②), as well as convey concrete requirements through physical models embodiedly (①). The GAI will participate in the cooperation in the form of turn-tasking. Based on the understanding of designers' intentions (③), GAI can generate virtual prototypes and schemes according to specific design requirements and restrictions (④). The generated virtual artifacts can be embedded in the physical world through AR techniques. The AR space containing physical and virtual prototypes provides rich spatial stimulation to designers (⑥). After the literature review and expert interview, the unclear interaction mechanism mainly lies in how to design the augment approaches in IEDS (⑦), their strengths, limitations, and their influence on conceptual design.

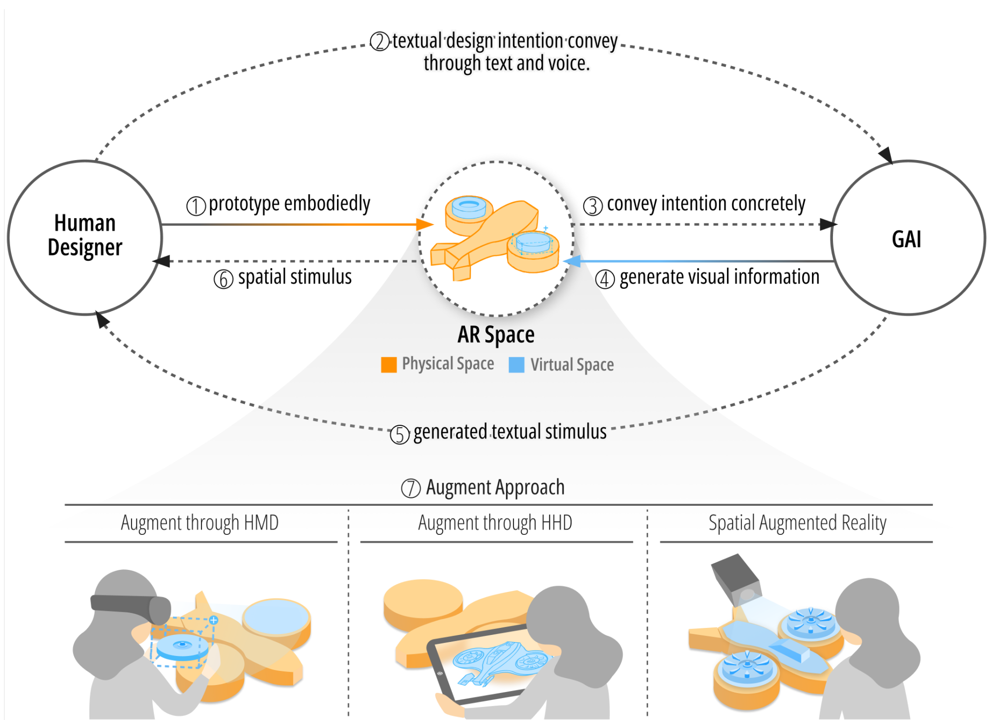


Figure 5: Interaction in IEDS, which is defined after literature review and expert interview.

5 Open-Ended Exploration Study

We conducted an open-ended exploration study, aiming to make clear the influence of different augment approaches in IEDS through a comparative experiment and further clarify interaction principles in IEDS. This open-ended exploration study has two main research questions (RQs).

- **RQ1**: What are the applicable scenarios of three AR approaches in IEDS during conceptual design?
  - **RQ1.1**: What are the effects of different IEDS on design load?
  - **RQ1.2**: What are the effects of different IEDS on design creativity support?
- **RQ2**: What are designers' attitudes towards IEDS during conceptual design?
  - **RQ2.1**: What is the usability of IEDS in conceptual design?
  - **RQ2.2**: What are the designer's subjective preferences for IEDS during conceptual design?

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

5.1 Experimental System

Based on the interaction design summarized in Section 4.4, we developed three experimental systems according to three different AR approaches (i.e., augment through HMD, augment through HHD, and spatial augmented reality) to implement our IEDS concept. Hereafter simply called IEDS-HMD, IEDS-HHD, and IEDS-SAR respectively.

5.1.1 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 Figure 6 and introduce their technical architecture in Figure 7. 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 the 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 through an independent camera and a projector. GAI will comprehend 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. We follow the characteristics of SAR with strong presentation performance but weak operation, developing the IEDS-SAR 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 have 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. The IEDS-HMD supports direct 3D modeling in the air, IEDS-HHD supports screen touch and sketch, while the IEDS-SAR does not support any virtual editing. It is 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, the visually generated artifacts were all 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

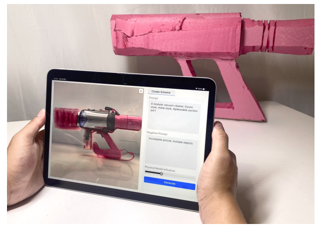
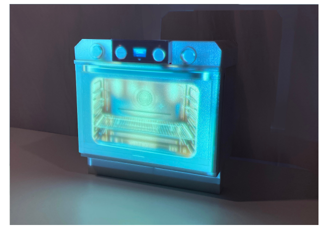
	IEDS-HMD	IEDS-HHD	IEDS-SAR
AR Approach	augment through HMD	augment through HHD	augment through SAR
System			
Equipment	a HMD (HoloLens)	a HHD (iPad)	a camera a projector
Information Capture Channel	the built-in camera of HoloLens	the built-in camera of iPad	an independent camera
Information Embedding Mode	digital artifacts generated by GAI are embedded in a hybrid space through a HMD equipment	digital artifacts generated by GAI are displayed on the screen of a 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

Figure 6: Introduction and comparison of three developed IEDS systems.

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.

5.1.2 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 works. The first involves supporting designers in creating and editing 3D virtual models in the air through gesture-based interactions. We utilized Unity (version 2020.3.26) [125] and MRTK (version 2.8) [126] to develop the software. To support the real-time modeling, we integrated two Rhino packages into Unity: *Rhino3dm* [127] and *compute-Rhino3d* [128], 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 function: *Revolve*, *Sweep*, *Extrude*,

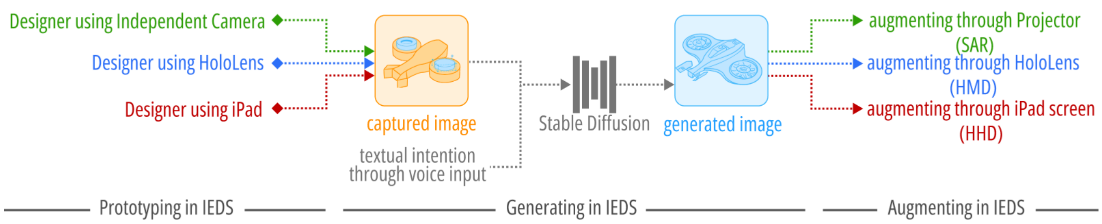


Figure 7: Technical architecture diagram of three IEDS systems.

and the basic editing function: *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 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 designers' vision through 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 works. 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 user interface of the IEDS-HHM system was developed based on Stable Diffusion Web UI [129] 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 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 [130] 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 the *prompt*, *negative prompt*, and *denoising strength*. Designers can interact with 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.

5.2 Methodology

5.2.1 Participant

We recruited 27 designers (16 males and 11 females, with an average age of 25.04) 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 the 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, every three designers performed a design task together. During grouping, the gender, age, and design experience have been balanced to eliminate individual differences. All participants signed a consent form approved by our institution. There were no other ethical or privacy impacts in this experiment.

5.2.2 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 electric 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 [131]. 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 (present in Appendix 3), including the potential design background, target user, and main requirements [132]. During the design stage, only a design problem card (present in Appendix 3) 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 minutes. At the end of each task, designers were asked to introduce design outcomes and provide explanations, which were translated into text for record.

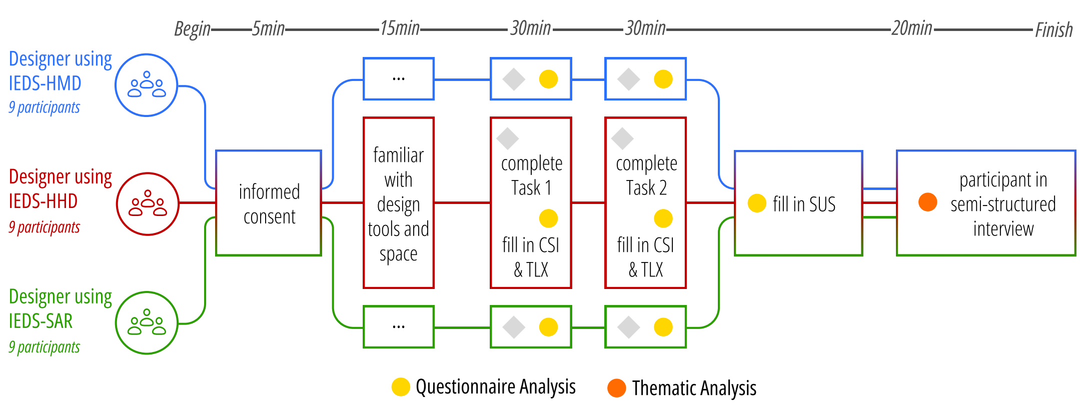


Figure 8: Procedure of the open-ended exploration study.

5.2.3 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) [133] was adopted to assess the workload of the conceptual design process. It is an overall workload score based on a weighted average ratings on *mental demand*, *physical demand*, *temporal demand*, *effort, performance*, and *frustration level*. Besides, the Creativity Support Index (CSI) [134] 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) [135] 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*. The structure and outline of the semi-structured interview are presented in Table 1.

5.2.4 Procedure

Designers from all groups followed the experimental procedure shown in Figure 8. Specifically, after the study introduction, participants have completed the informed consent confirmation, and then are instructed to familiarize themselves with the IEDS environment and Think-aloud method. In the design task stage, designers are 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 are balanced among participants. After each design task, designers are required to complete CSI and TLX questionnaires. Eventually, there was a phase to answer the SUS questionnaire and engage in a semi-structured interview. The entire experiment took approximately 100 minutes.

5.2.5 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 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 [136] to analyze and report SUS results. For the interview data, we used thematic analysis to analyze raw interview data [137]. Two researchers independently assigned and coded all statements.

Table 1: The structure and outline of the semi-structured interview.

Key Issue (K)	Outline and Question (Q)
K0: Ice Breaker	Q1: "*Could you introduce your design?*" Q2: "*Which design are you most satisfied with?*"
K1: Design Experience	Q1: "*What was your overall experience when you used IEDS to complete conceptual design?*" Q2: "*What do you think is the biggest challenge in using IEDS during design?*"
K2: Comparison with Traditional Design Tool	Q1: "*What do you think is different from the design tools you commonly used before?*" Q2: "*What do you think are the advantages and disadvantages compared with traditional design tools?*"
K3: GAI Cooperation	Q1: "*How was your cooperation experience with GAI during the design process?*" Q2: "*When and where do you think GAI is helpful for your design process?*"
K4: AR Influence	Q1: "*What kind of design content did you augment through AR in your design?*" Q2: "*What effect do you think AR's participation has on your conceptual design?.*"
K5: Creativity	Q1: "*Do you think IEDS can affect your creativity?*" Q2: "*How does your interaction with AR or GAI affect and iterate your design concept?*"
K6: Attitude to IEDS	Q1: "*Would you like to use IEDS for your conceptual design work?*" Q2: "*Which design task and stage do you prefer to use IEDS?*"

Next, the two researchers shared their codes, discussing inconsistent codes to resolve disagreements and merging similar codes until they reached a consensus.

6 Result and Finding

6.1 The Design Outcome Showcase

We randomly select and present some showcases from the design outcomes completed by participants during the experiment in Figure 9. We also highlight the prototype in the physical, virtual, and hybrid domains in 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.

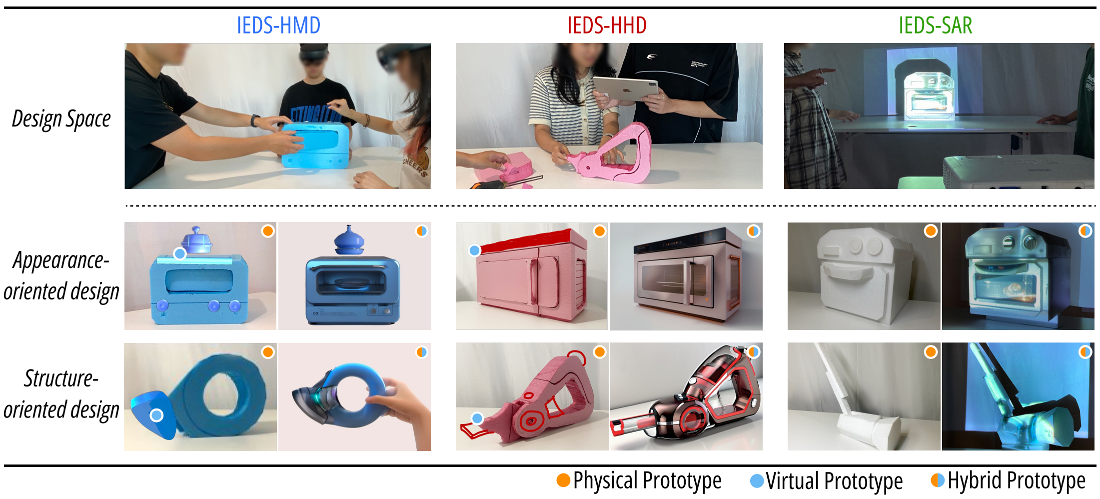


Figure 9: The design outcome showcases during the experiment.

6.2 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 2 and Figure 10. For the *NASA TLX Score*, there was an interaction effect that could be found ($F(2,7) = 43.98, P < 0.001, \eta^2 = 0.85$). The post-hoc test indicated that the TLX score in appearance-oriented tasks was lower than structure-oriented in IEDS-SAR. Besides, in all design tasks, the TLX score in HHD was significantly lower than HMD and SAR. The TLX score in HMD was lower than 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 the interaction effect in *mental demand* ($F(2,7) = 15.37, P < 0.001, \eta^2 = 0.66$), *performance* ($F(2,7) = 55.77, P < 0.001, \eta^2 = 0.88$), and *frustration level* ($F(2,7) = 40.85, P < 0.001, \eta^2 = 0.84$). Specifically, in these three perspectives, their scores of 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.

In addition, there was the main effect of the AR approach in *physical demand* ($F(2,7) = 53.41, P < 0.001, \eta^2 = 0.87$) and *temporal demand* ($F(2,7) = 7.19, P = 0.006, \eta^2 = 0.47$). 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.

Table 2: Results of NASA TLX. Significant effects are highlighted in bold. $P\ value$ rounds to 3DP, $F\ score$, and η^2 round to 2DP. ↓ indicates 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

Table 3: Results of CSI. Significant effects are highlighted in bold. $P\ value$ rounds to 3DP, $F\ score$, and η^2 rounds to 2DP. ↑ indicates 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

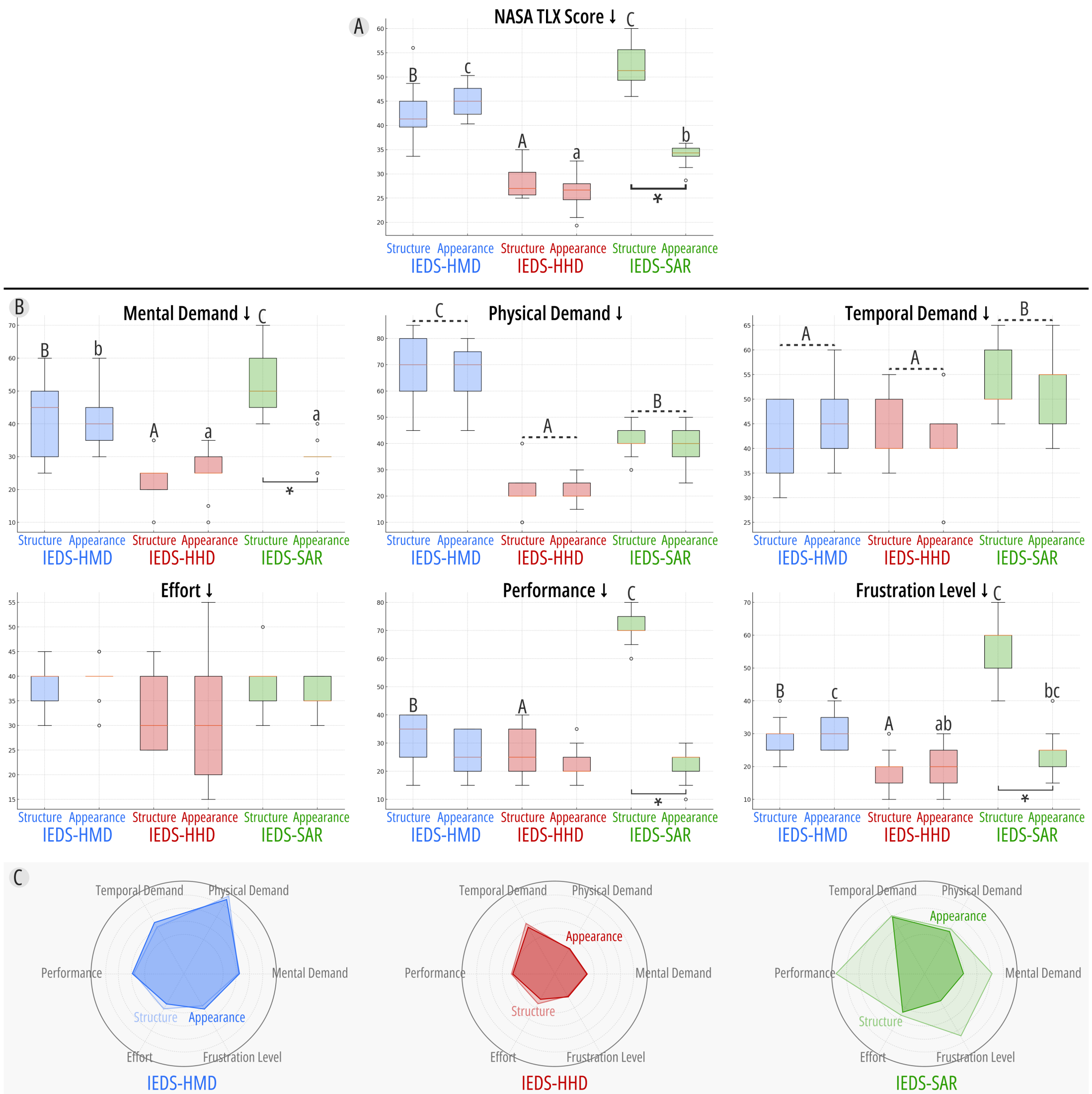


Figure 10: Results of NASA TLX (A) and its weighted average ratings (B). ↓ indicates the lower value is better. Capital and lowercase letters indicate significant differences in AR approaches. * indicates significant differences in design tasks. The Radar Chart of NASA TLX results (C).

6.3 The Creativity Support (for RQ1.2)

The CSI questionnaire was used to evaluate the workload 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 distribution. Other scores satisfied the normal distribution. Therefore, the Mixed ANOVA was used for the statistical analysis, which is present in Table 3 and Figure 11. For the *CSI score*, there was an interaction effect between the AR approach and design task ($F(2, 7) = 87.73, P < 0.001, \eta^2 = 0.92$). The post-hoc test indicated that the CSI in appearance-oriented design was higher than structured-oriented design in IEDS-SAR, while the result is the opposite in IEDS-HHD. During the structure-oriented design, the CSI in HMD and HHD was higher than it in SAR.

For the six weighted average ratings in CSI, there was the interaction effect in *collaboration*, *exploration*, *expressiveness*, and *results worth effort*. Specifically, for the *collaboration* ($F(2, 7) = 36.00, P <$

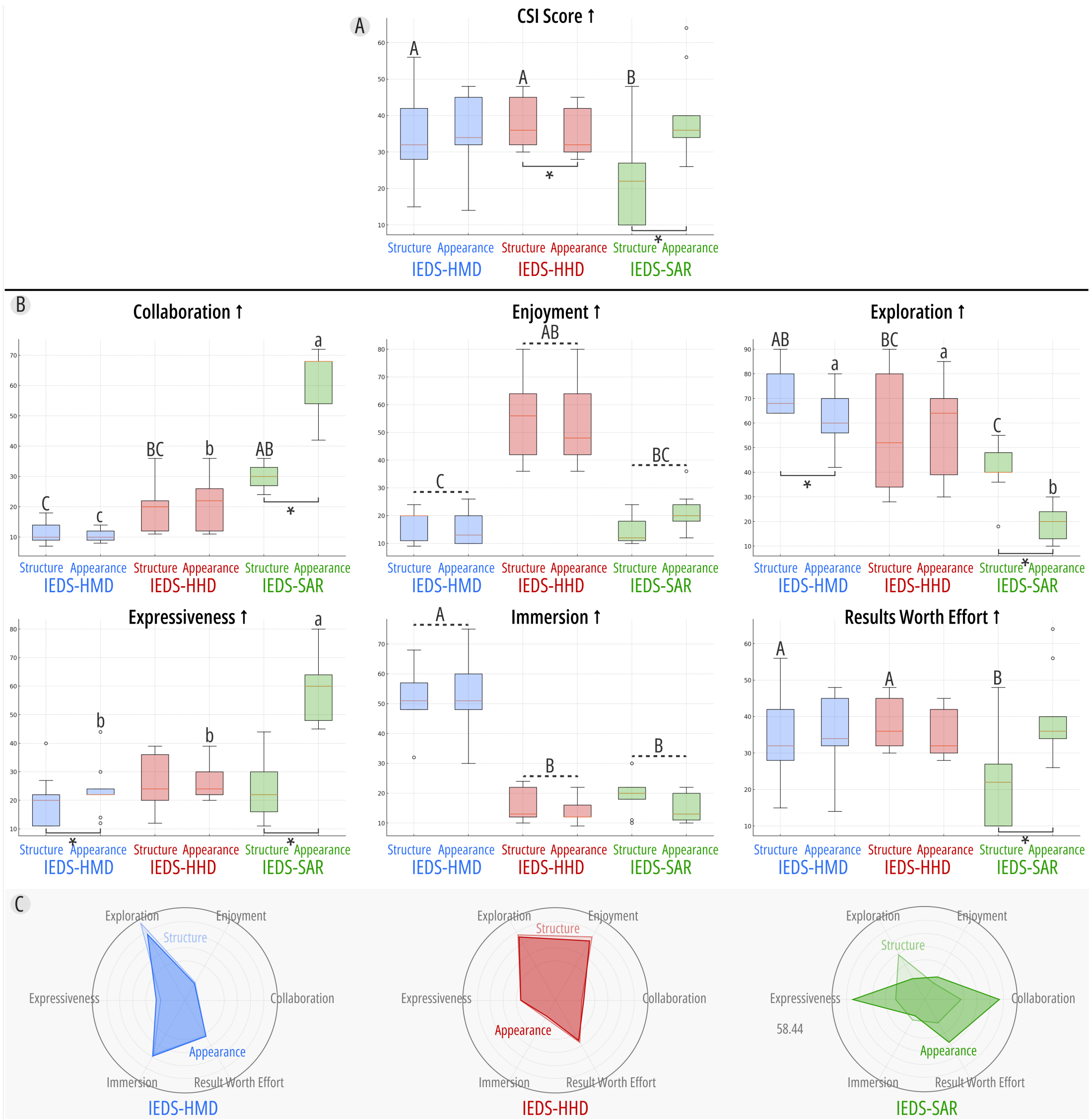


Figure 11: Results of CSI (A) and its weighted average ratings (B). ↑ indicates the higher value is better. Capital and lowercase letters indicate significant differences in AR approaches. * indicates significant differences in design tasks. The Radar Chart of CSI results (C).

$0.001, \eta^2 = 0.82$), 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 the *exploration* ($F(2,7) = 8.05, P = 0.004, \eta^2 = 0.50$), 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 the *expressiveness* ($F(2,7) = 24.80, P < 0.001, \eta^2 = 0.76$), the SAR had the best expressiveness than others during the appearance-oriented tasks. For the *results worth effort* ($F(2,7) = 13.89, P = 0.001, \eta^2 = 0.64$), the appearance-oriented had a higher score in IEDS-SAR. However, during the structure-oriented tasks, the SAR had the lowest score than others.

There was the main effect of the AR approach in *enjoyment* and *immersion*. For the *enjoyment*, the HHD had a higher score than HMD ($F(2,7) = 48.20, P < 0.001, \eta^2 = 0.86$). However, for the *immersion*, the HMD had a higher immersion than others ($F(2,7) = 78.35, P < 0.001, \eta^2 = 0.91$).

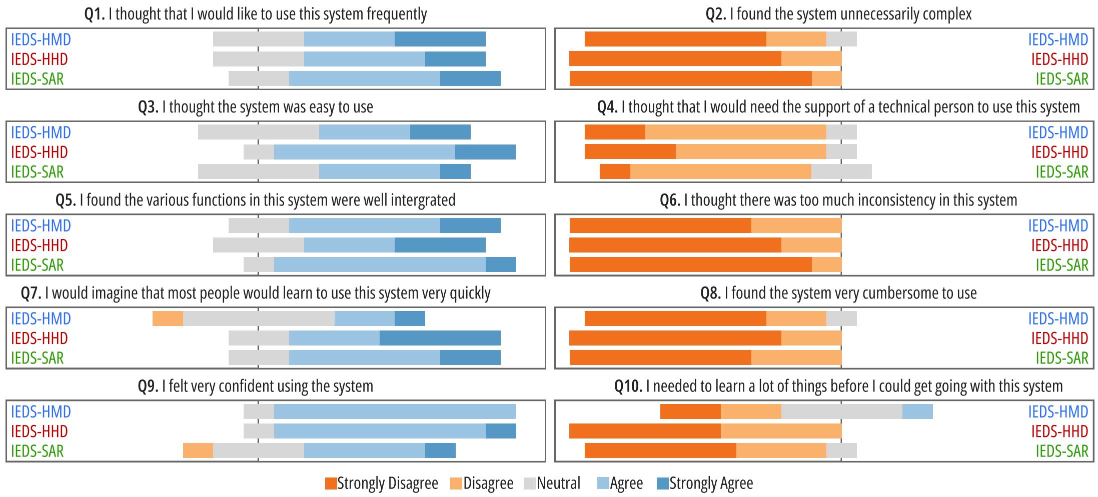


Figure 12: Results of SUS questionnaires, rating on the 5-point Likert scale.

6.4 The System Usability (for RQ2.1)

We utilized the SUS questionnaires to evaluate the system usability in three IEDS systems (Figure 12). The results indicated that the IEDS-HHD system had the highest *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 the *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 ($M = 70.83, SD = 15.59$).

6.5 The Subjective Preference (for RQ2.2)

To evaluate designers' subjective preferences among three IEDS systems, we invited all participants to semi-structured interviews, asking for reflections 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 corresponding three codes with the highest frequency (Table 4).

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.

7 Discussion

7.1 Design Guideline in IEDS

In this section, we aim to comprehensively discuss our qualitative and quantitative results to answer two RQs, as well as clarify the respective application scope and best practice of IEDS.

7.1.1 Respective Application Scope of Three IEDS Systems

Based on the qualitative and quantitative results, we summarized the typical capabilities and limitations of the three IEDS systems (Figure 13).

Expressly, for the IEDS-HMD system, the CSI results indicated the HMD was beneficial in promoting design exploration and enhancing immersion. Similarly, designers reported that the HMD promoted structural exploration and verification through mid-air modeling, as well as created an intuitive hybrid space combining physical models and virtual prototypes by the HMD equipment. There were also

Table 4: Extracted codes and corresponding quotes from interview data. A represents the advantages of IEDS system, while D represents the disadvantages.

Codes	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.*"

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 the IEDS-HMD was adverse to cooperation and communication. Similarly, designers reported that there might be a gap in the vision of hybrid space seen by different partners, and it was frequent to operate unconsciously and wrongly when collaborating and communicating. In addition, the SUS results indicated that the learnability of IEDS-HMD was relatively low, which might be related to designers' subjective reports that there were 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 the IEDS-HHD had the lowest workload in all design tasks, and had distinct strengths in mental demand, physical demand, and temporal 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-HMD had a high sense of 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 hand, 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, the 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

	IEDS-HMD	IEDS-HHD	IEDS-SAR
Advantages	promote design exploration	promote design exploration	suitable for appearance-orinted tasks
	enhance immersion	wide application scope	high expressiveness
	support structure design and verification	low workload	promote communication and cooperation
	beyond physical limitations	high sense of enjoyment	real and presence
	intuitive perception from multi-views	conform to habit	
		high usability	
Limitations	adverse to cooperation	low immersion	adverse to structure design
	heavy physical load	occupied hand	more labor and time
	low learnability	indirect virtual editing	single view
	parallax		narrow application scope

Quantitative result support Qualitative result support

Figure 13: Extracted advantages and limitations of three IEDS system from our qualitative and quantitative results.

and communication, promoting design collaboration [11]. 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.

7.1.2 Application Guideline and Best Practice of IEDS

Based on the results of our research, we aim to put forward the application guidelines and best practices of IEDS to help designers choose the appropriate system in conceptual design, as well as provide theoretical guidance for the HCI community. Specifically, we summarized the IEDS best practice in Figure14. We suggested to choose the appropriate IEDS system according to three pre-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?*". In the best practice of IEDS, we suggested 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 the design tasks with multiple suitable IEDS systems, we also clarified the inherent strength of each system to enable designers to choose more suitable IEDS systems according to their requirements and improve the IEDS utility. Specifically, the IEDS-HMD was suggested to be given priority for better immersion and structural tests. The IEDS-HHD was recommended when faced with an efficiency-oriented design task without high requirements for immersion and intuition. The IEDS-SAR was given priority to use for better expressiveness and communication.

In addition to best practices, we also extracted the most unique strength of three IEDS systems to meet special requirements in conceptual design. First, the IEDS-HMD was able to assist the prototype beyond the limitations of the physical world, which was consistent with previous studies that HMD enabled 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 Figure9) 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, the 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, the 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.

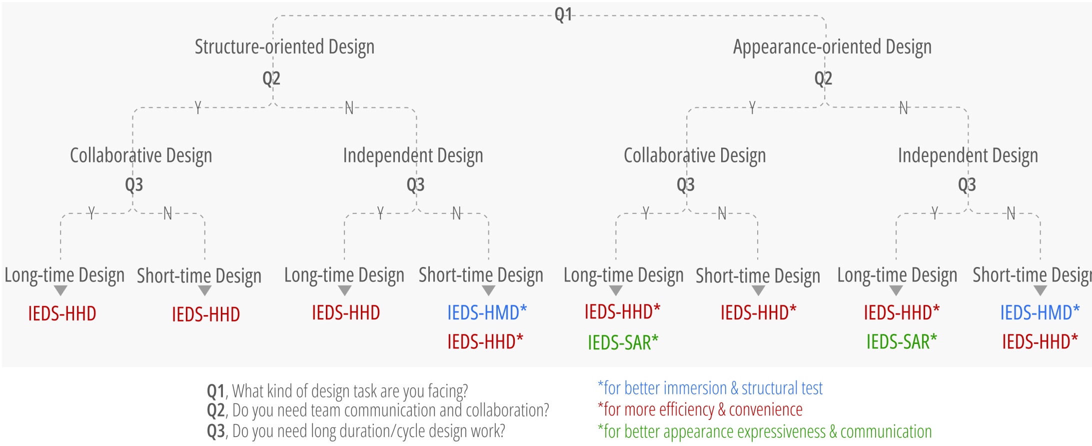


Figure 14: The best practice for choosing the IEDS systems.

7.2 The Influence of IEDS on Conceptual Design

In this section, we discussed participants' attitudes towards the integration of designer, AR, and GAI in IEDS. Specifically, we paid attention to the commonly mentioned integration contributions of AR and GAI, as well as critically discussed common limitations in IEDS.

7.2.1 IEDS Contribution for Conceptual Design

IEDS enhances design creativity. Designers indicated that the GAI participation enabled them to obtain diverse design schemes by simply adjusting input prompts and parameters, providing infinite creativity stimulation and opening up an imaginative space [138]. Specifically, designers have repeatedly reported that they obtained inspiration for GAI generation, which can provide new elements or transform physical prototypes into new elements. Besides, designers also mentioned that AR participation provided more immersion and intuition, which was also conducive to improving creativity. This was consistent with previous studies that indicated the high immersion and intuitive environment can enrich the design experience [139] and improve design expression [140].

IEDS promotes structural and detailed exploration. The physical design representation in IEDS can promote structural exploration and test [23]. The hybrid space presented by AR further contributed to structural consideration in conceptual design. In the IEDS-HMD and IEDS-HHD groups, designers prototype with both physical and virtual representation in a mixed way, using physical materials to represent the main design part while prototyping details through virtual editing. For example, designers used physical models to represent the vacuum cleaner body. They used mid-air models (in IEDS-HMD) or screen sketches (in IEDS-HHD) to explore diverse modular suction nozzles. Similarly, in appearance-oriented design, designers used physical material to define the scale and shape of the oven while prototyping virtually to explore button positions and appearance details. This mixed design representation enables designers to pay more attention to the structure and details in conceptual design, supporting them in intuitively testing the dynamic interaction and structural feasibility.

IEDS enhances expressiveness and fidelity. Previous studies demonstrated that one inherent limitation of the physical prototype was that the fidelity often decreased as the manufacturing time shrunk [141]. Designers always faced a trade-off between quality and time when selecting prototype methods [142]. During the conceptual design process supported by IEDS, the generative ability can instantly generate and refine design schemes based on low-fidelity physical prototypes, while AR technology can improve expressiveness by coupling virtual and physical design information. The IEDS provided an innovative prototype method that balances the manufacturing time and fidelity through the AR and GAI combination.

IEDS optimizes design rhythm and improves iteration efficiency. As the GAI participation took over the tedious and laborious expression and refinement tasks [143], many designers reported that designing in IEDS enabled them to better focus on concept exploration and iteration, which was regarded as the most important thing in conceptual design [44], instead of concept expression. Specifically, in IEDS-HMD and IEDS-HHD, designers mentioned that they could quickly implement and verify an idea with the rough physical or virtual prototype, optimizing the conceptual design rhythm. Even in the IEDS-SAR group with the highest requirements for manual labor, designers still thought that IEDS greatly released their time and energy to express the scheme compared with traditional modeling and rendering, allowing designers to focus on creating and iterating. GAI participation can optimize design rhythm and free designers to focus on higher-level creative and strategic thinking.

7.2.2 IEDS Limitation for Conceptual Design

In addition to the strengths of IEDS, we also paid attention to the mentioned limitations in IEDS for critical discussion. We focused on the common problems caused by the integration of AR and GAI in IEDS in this section, rather than the usability defects in a specific system.

IEDS does not support fine generation control of details and iterations. Designers mentioned that GAI capability in IEDS did not support detail editing and local generation. For example, one designer complained that "*GAI has provided me with a good oven design, and I just want to optimize the knob on it, but the regenerated scheme changes my satisfaction*". As randomness and variability of the generative ability make the generation process like a black box [138], fine editing and control might enhance the effectiveness of human-AI communication and thus enhance the GAI usability in IEDS.

IEDS lacks an understanding of abstract design elements in physical representation. Designers pointed out that "*GAI can only meet my design intention on the whole but cannot understand and generate all details correctly*". Similarly, they also indicated that "*When my physical prototype is unusual, GAI cannot understand my abstract elements and cannot even distinguish the front and the back of it*". As an image-based model was integrated with current IEDS, it was better at providing visual creative stimulation but lacked common knowledge to reason abstract elements in low-fidelity prototypes. This not only required more refined physical representation and higher manual labor but also hindered unconventional design innovation.

Design concepts and schemes will be influenced by the color of physical material or virtual editing in IEDS. From the design outcomes (Figure9), it can be seen that the color and style of the design scheme were seriously affected by the color of physical materials and virtual editing. It might be caused by the adding noise process in the generation mechanism of the Stable Diffusion model. On the one hand, this will limit the diversity of colors and styles in conceptual design. On the other hand, as designers have to select editing color initially, they unconsciously pay attention to low-level design decisions early in conceptual design, which might cause early design fixation [144].

7.3 Optimization Space and Future Vision of IEDS

After comprehensive consideration and reflection on IEDS, we put forward the optimization space and future vision of IEDS (Figure 15). 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 highly available design collaborator in conceptual design. For example, the multi-modal vision language models, such as GPT-4V [145], Gemini 1.5 [146], and Claude 3 [147] 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 jointly 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. The cross-device joint interaction can give full play to the strengths of different AR approaches and make up for each other's limitations.

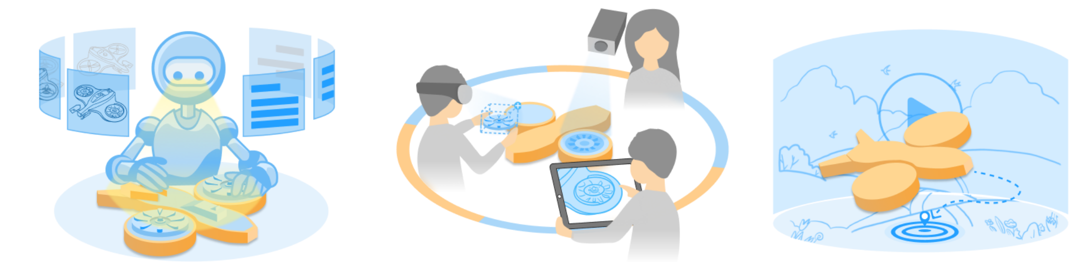


Figure 15: The optimization space and future vision of IEDS.

Third, augmented design information can be enriched and expanded, establishing a multi-modal hybrid design space in IEDS. Due to the limitation of speed and quality in the 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 the augmented information can be diverse in addition to the prototype. In the future vision, IEDS might realize the mixing 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.

7.4 Limitation

We discuss the limitations in this study that can be addressed in future studies. First, due to the limitation of quality and time of the 3D generative model, we only utilized an image generative model to complete the user study, which may reduce the immersion of the design process, especially for the virtual design information. This is the first study to propose and verify the initial concept of IEDS from the 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.

8 Conclusion

In this study, we proposed an Intelli-Embodied Design Space (IEDS) combining designer, AR, and GAI to support conceptual design. We first built a corpus of 116 papers through a literature review, synthesizing methods of constructing design space with AR and GAI, respectively. Besides, we proposed an initial combination of designer, AR, and GAI in a design space after conducting expert interviews based on existing literature and expert insights. We developed three potential IEDS systems and conducted an open-ended exploration study with 27 designers. According to the qualitative and quantitative experimental results, we clarified the interactive guidelines and best practices of IEDS. For example, the IEDS-HHD had a wide application scope in conceptual design, the IEDS-SAR provided high expressiveness and promoted design communication in appearance-oriented design, while the IEDS-HMD supported the 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.

Appendix1

Table 5: Expert (E1-4) feedback on codes extracted through literature review. A check indicates that the expert assesses that the given item would be useful for IEDS.

		GAI+Design				
Category	Code	Description	E1	E2	E3	E4
Human-to-AI Communication Modes (HM)	HM1	text	•	•	•	•
	HM2	voice input	•		•	
	HM3	sketch and graffiti		•		
	HM4	structured relationship				
	HM5	direct editing and manipulation				
	HM6	3D model	•	•	•	
	HM7	3D sketch				
	HM8	image	•		•	•
	HM9	body movement data	•	•		
	HM10	UX & UI				
AI-to-Human Communication Modes (AM)	AM1	text	•	•	•	•
	AM2	voice				
	AM3	icon			•	
	AM4	image	•	•	•	•
	AM5	animation	•			
	AM6	stereo image		•		
	AM7	3D model	•		•	•
	AM8	UX & UI				
	AM9	configuration				
Participation Style(PS)	PS1	parallel-tasking				
	PS2	turn-tasking	•	•	•	•
Task Distribution (TD)	TD1	same task				
	TD2	divided task	•	•	•	•
AI Role (RO)	RO1	stimulator	•	•	•	•
	RO2	creator	•		•	•
	RO3	refiner	•	•	•	•
	RO4	analyzer or evaluator			•	
		AR+Design				
Category	Code	Description	E1	E2	E3	E4
Augment Information(IN)	IN1	design prototype and scheme	•	•	•	•
	IN2	design simulation and plan	•			•
	IN3	design environment information		•		•
	IN4	design supplementary information				
Augment Approach (AA)	AA1	augment through HMD	•	•		
	AA2	augment through HHD		•	•	
	AA3	spatial augmented reality		•		•
Interaction Modality (IM)	IM1	tangibility	•	•	•	•
	IM2	touch				
	IM3	spatial movement data	•	•		•
	IM4	gaze		•		•
	IM5	voice	•	•	•	•
	IM6	ancillary device				

Appendix2

Table 6: Collected corpus related to GAI+Design. 1-58 were collected from expertise review while 59-67 were collected from systematic search.

	Study	Publication Format	Year	Application Scenario (AS)	Application Purpose (AP)	Human-to-AI Communication Mode (HM)	AI-to-Human Communication Mode (AM)	Participation Style (PS)	Task Distribution (TD)	AI Role (RO)
					GAI+Design					
1	Duan et al. [73]	CHI	2024	AS4	AP4	HM3, HM4, HM10	AM1	PS2	TD2	RO1, RO4
2	OmniActions[47]	CHI	2024	AS4	AP3, AP4	HM2, HM5, HM8	AM1	PS2	TD1	RO1, RO3
3	SimUser[48]	CHI	2024	AS4	AP4	HM1, HM10	AM1, AM4	PS2	TD2	RO1, RO4
4	Lee et al. [148]	CHI	2024	AS8	/	HM2	AM1, AM4	PS2	TD2	RO1, RO2
5	TypeDance[49]	CHI	2024	AS5, AS7	AP1, AP3, AP4	HM1, HM8	AM3	PS2	TD1	RO1, RO2, RO4
6	LumiMood[52]	CHI	2024	AS4, AS5, AS7	AP3, AP4	HM6	AM4	PS2	TD1	RO1, RO3
7	C2Ideas[43]	CHI	2024	AS2	AP3, AP4	HM1, HM5	AM6	PS2	TD1	RO1, RO2
8	IntentTuner[50]	CHI	2024	AS6	AP1, AP4	HM1, HM5	AM1, AM4	PS2	TD1	RO1, RO3, RO4
9	GenQuery[61]	CHI	2024	AS1, AS2, AS5	AP3, AP4	HM1	AM4	PS2	TD2	RO1, RO3
10	Neural Canvas[53]	CHI	2024	AS5, AS6, AS7	AP3, AP4	HM1, HM7	AM6	PS2	TD1	RO1, RO3
11	CreativeConnect[3	CHI	2024	AS5	AP3, AP4	HM1, HM8	AM1, AM4	PS2	TD2	RO1, RO2, RO4
12	Jigsaw[75]	CHI	2024	/	AP3, AP4	HM1, HM2, HM6, HM8	AM1, AM2, AM4, AM7	PS2	TD2	RO1, RO2, RO3, RO4
13	From Paper to Card[54]	CHI	2024	AS8	AP3, AP4	HM1, HM8	AM1, AM4	PS2	TD1	RO1, RO3
14	PlantoGraphy[44]	CHI	2024	AS2	AP3, AP4	HM1, HM4, HM5	AM4	PS2	TD1	RO1, RO2
15	ContextCam[65]	CHI	2024	/	AP3	HM1	AM1, AM4	PS2	TD1	RO1, RO2
16	StyleMe[45]	CHI	2023	AS3	AP3, AP4	HM3, HM8	AM4	PS2	TD1	RO1, RO2, RO3
17	RePrompt[66]	CHI	2023	/	AP4	HM1	AM1, AM4	PS2	TD1	RO1, RO2, RO3

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	Study	Publication Format	Year	Application Scenario (AS)	Application Purpose (AP)	Human-to-AI Communication Mode (HM)	AI-to-Human Communication Mode (AM)	Participation Style (PS)	Task Distribution (TD)	AI Role (RO)
	GAI+Design									
18	Beyond Skin Deep[41]	CHI	2023	AS1, AS3	AP3, AP4	HM1, HM2, HM9	AM7	PS2	TD1	RO1, RO2, RO3
19	Magical Brush[86]	CHI	2023	AS7	AP3, AP4	HM5	AM4	PS2	TD1	RO2
20	De-Stijl[62]	CHI	2023	AS5, AS7	AP3, AP4	HM1, HM3	AM9	PS2	TD2	RO1, RO2
21	Perceptual Pat[149]	CHI	2023	AS5	AP1, AP4	HM5, HM8	AM1, AM4	PS2	TD2	RO1, RO4
22	fAIlureNotes[150]	CHI	2023	AS4	AP1, AP4	HM8	AM1	PS2	TD2	RO1, RO4
23	Collaborative Diffusion[151]	CHI EA	2023	/	AP5	HM1, HM8	AM4	PS2	TD1	RO1, RO2, RO3
24	Jing et al. [78]	CHI	2023	AS4	AP4	HM1, HM8	AM8	PS2	TD1	RO1, RO2
25	Stylette[32]	CHI	2022	AS4	AP2, AP4	HM1, HM2, HM8	AM8	PS2	TD1	RO1, RO3
26	TaleBrush[56]	CHI	2022	AS7	AP1, AP2, AP3, AP4	HM1, HM3	AM1, AM4	PS2	TD1	RO1, RO2
27	FlatMagic[67]	CHI	2022	AS5, AS7	AP3, AP4	HM3	AM4	PS2	TD2	RO3
28	BunCho[152]	CHI EA	2021	AS7	AP1, AP2, AP3, AP4	HM1, HM5	AM1	PS2	TD1	RO1, RO2, RO3
29	FashionQ[46]	CHI	2021	AS3	AP1, AP2, AP4	HM5, HM8	AM1, AM4	PS2	TD1	RO1, RO4
30	StoryDrawer[81]	CHI EA	2021	AS8	AP1, AP2	HM2, HM3	AM4	PS1	TD1	RO1, RO2, RO3
31	Vinci[58]	CHI	2021	AS5	AP1, AP2, AP3, AP4	HM1, HM5, HM8	AM4	PS2	TD1	RO1, RO2, RO3
32	VINS[71]	CHI	2021	AS4	AP1, AP3, AP4	HM8	AM4	PS2	TD1	RO1, RO4
33	It Is Your Turn[42]	CHI	2020	AS1, AS3	AP1, AP4	HM3	AM4	PS2	TD1	RO3
34	EmoG[82]	CHI	2020	AS8	AP1, AP3, AP4	HM3, HM5	AM4	PS2	TD1	RO1, RO3
35	VISAR[74]	UIST	2023	AS8	AP1, AP3, AP4	HM1, HM5	AM1	PS2	TD1	RO1, RO2, RO3

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	Study	Publication Format	Year	Application Scenario (AS)	Application Purpose (AP)	Human-to-AI Communication Mode (HM)	AI-to-Human Communication Mode (AM)	Participation Style (PS)	Task Distribution (TD)	AI Role (RO)
	GAI+Design									
36	PromptPaint[69]	UIST	2023	AS5, AS7	AP2, AP3, AP4	HM1, HM5	AM4	PS2	TD1	RO1, RO2, RO3
37	Style2Fab[70]	UIST	2023	AS1, AS3, AS6	AP2, AP3, AP4	HM5, HM6	AM9	PS2	TD1	RO4
38	GenAssist[153]	UIST	2023	AS3, AS5, AS7	AP1, AP4	HM1, HM8	AM1	PS2	TD1	RO1, RO4
39	XCreation[68]	UIST	2023	AS7	AP2, AP3, AP4	HM1, HM3, HM4	AM4	PS2	TD1	RO1, RO2, RO3
40	Warner et al. [60]	UIST	2023	AS5, AS7	AP2, AP3, AP4	HM5, HM8	AM4	PS2	TD1	RO1, RO3, RO4
41	PColorizor[76]	UIST	2023	AS7	AP1, AP3, AP4	HM1, HM5, HM8	AM4	PS2	TD2	RO1, RO3, RO4
42	WorldSmith[83]	UIST	2023	AS5, AS7	AP2, AP3, AP4	HM1, HM5	AM4	PS2	TD1	RO1, RO2, RO3
43	Promptify[84]	UIST	2023	AS5, AS6, AS7	AP1, AP2, AP4	HM1, HM5	AM1, AM4, AM9	PS2	TD1	RO1, RO2, RO3, RO4
44	Wakey-Wakey[77]	UIST	2023	AS5, AS7	AP2, AP3, AP4	HM1, HM8	AM4, AM5	PS2	TD1	RO2
45	Spellburst[51]	UIST	2023	AS5, AS6, AS7	AP1, AP2, AP4	HM3, HM4, HM5	AM4, AM5	PS2	TD1	RO1, RO2
46	Opal[154]	UIST	2022	AS5, AS7	AP1, AP2, AP3, AP4	HM1, HM5	AM1, AM4	PS2	TD1	RO1, RO2, RO4
47	We-toon[64]	UIST	2022	AS7	AP2, AP3, AP4, AP5	HM5	AM4	PS2	TD1	RO1, RO2, RO3
48	Screen2Words[85]	UIST	2021	AS4	AP1, AP4	HM8	AM1	PS2	TD2	RO1, RO4
49	Fosco et al. [155]	UIST	2020	AS5, AS7	AP1, AP2	HM8	AM4	PS2	TD2	RO1, RO4
50	Design Adjectives[156]	UIST	2020	AS5, AS7	AP1, AP2, AP3, AP4	HM5, HM8	AM1, AM4	PS2	TD1	RO1, RO2, RO4
51	CoAIcoder[63]	TOCHI	2023	AS8	AP4, AP5	HM1, HM5	AM1	PS2	TD1	RO1, RO4
52	Color2Vec[87]	TOCHI	2023	AS6	AP1, AP2, AP4	HM1	AM9	PS2	TD1	RO4

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	Study	Publication Format	Year	Application Scenario (AS)	Application Purpose (AP)	Human-to-AI Communication Mode (HM)	AI-to-Human Communication Mode (AM)	Participation Style (PS)	Task Distribution (TD)	AI Role (RO)
GAI+Design										
53	Eisbach et al. [157]	TOCHI	2023	AS4, AS5	AP1, AP4	HM8	AM1	PS2	TD1	RO4
54	DeepThInk[59]	IJHCS	2024	AS5, AS7	AP2, AP3, AP4	HM3, HM5	AM4	PS2	TD1	RO1, RO2, RO3
55	Karim et al. [79]	IJHCS	2023	AS5	AP3, AP4	HM5, HM8	AM9	PS2	TD1	RO3, RO4
56	CReBot[55]	IJHCS	2022	AS8	AP1, AP4	HM1	AM1	PS2	TD1	RO1, RO3, RO4
57	FritzBot[80]	IJHCS	2021	AS1, AS6	AP3, AP4	HM1, HM5	AM9	PS2	TD1	RO1, RO2, RO3
58	Michailidou et al. [57]	IJHCS	2021	AS4, AS5	AP1	HM8	AM4	PS2	TD1	RO4
59	Suessmuth et al. [158]	Conference	2023	AS3, AS6	AP1, AP2, AP3, AP4	HM1, HM5, HM8	AM4	PS2	TD1	RO1, RO2, RO3
60	OwnDiffusion[159]	Conference	2023	AS1, AS6	AP1, AP2, AP3, AP4	HM3, HM5, HM8	AM4	PS2	TD2	RO1, RO2, RO3, RO4
61	Zhang et al. [160]	Conference	2023	AS2, AS6	AP1, AP3, AP4	HM1, HM3, HM5	AM4	PS2	TD1	RO1, RO2, RO3
62	Evaluating ChatGPT[161]	Conference	2023	AS8	AP1, AP3, AP4	HM1	AM1	PS2	TD1	RO1, RO2, RO3, RO4
63	Designing with AI[162]	Conference	2023	AS6	AP1, AP3, AP4	HM1, HM5	AM1, AM4	PS2	TD1	RO1, RO2
64	AutoPoster[163]	Conference	2023	AS5	AP2, AP3, AP4	HM1, HM5, HM8	AM4	PS2	TD2	RO1, RO2, RO3
65	Sand Playground[72]	Conference	2022	AS7	AP2, AP3, AP4	HM9	AM2	PS1	TD1	RO3
66	Wu et al. [164]	Journal	2024	AS1	AP1, AP2, AP3, AP4	HM1, HM5, HM8	AM1, AM4	PS2	TD2	RO1, RO2, RO3, RO4
67	Kwieciński and Słyk [165]	Journal	2023	AS2	AP2, AP3, AP4	HM1, HM5	AM1, AM4	PS2	TD2	RO3, RO4

Table 7: Collected corpus related to AR+Design. 1-33 were collected from expertise review while 34-49 were collected from systematic search.

	Study	Publication Format	Year	Application Scenario (AS)	Application Purpose (AP)	Augment Information (IN)	Augment Approach (AA)	Interaction Modality (IM)
AR+Design								
1	pARam[105]	CHI	2024	AS1	AP2	IN1, IN2	AA1	IM3
2	DungeonMaker[96]	CHI	2024	AS5	AP2	IN2	AA2, AA3	IM1, IM2
3	ProObjAR[94]	CHI	2023	AS4	AP2	IN1, IN2	AA1	IM3
4	Teachable Reality[114]	CHI	2023	AS4	AP2	IN2	AA2	IM3
5	4Doodle[93]	CHI	2023	AS3, AS4	AP2	IN1, IN2, IN4	AA2	IM3
6	Meta-AR-App[100]	CHI	2020	AS7	AP1, AP2, AP4, AP5	IN4	AA2	IM2
7	C-Space[90]	CHI	2020	AS2	AP1, AP2, AP4	IN1	AA3	IM1
8	Mix&Match[116]	CHI	2020	AS1	AP2	IN1	AA2	IM3
9	Mobi3DSketch[95]	CHI	2019	AS4	AP2	IN1	AA2	IM2
10	SymbiosisSketch[124]	CHI	2018	AS4	AP2	IN1, IN2	AA1, AA2	IM1, IM6
11	Mobi3DSketch[95]	CHI	2018	AS1, AS2	AP1, AP2	IN1, IN2	AA2	IM2
12	RoMA[166]	CHI	2018	AS1	AP2	IN1	AA1	IM3
13	Pmomo[118]	CHI	2016	AS1, AS3	AP2	IN1	AA3	IM1
14	MixFab[167]	CHI	2014	AS1	AP2	IN1	AA3	IM3
15	TeleAdvisor[168]	CHI	2012	AS8	AP2, AP4	IN4	AA3	IM3
16	RealityCanvas[102]	UIST	2023	AS8	AP2	IN1, IN2	AA2	IM3
17	Reframe[169]	UIST	2023	AS8	AP2	IN1, IN3	AA1, AA2	IM2
18	HoloBots[108]	UIST	2023	AS2, AS7	AP4	IN4	AA1	IM3
19	Sketched Reality[115]	UIST	2022	AS4, AS8	AP2	IN2	AA2	IM2
20	MechARspace[120]	UIST	2022	AS1	AP1, AP2	IN1, IN2	AA1	IM1, IM3

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AR+Design								
	Study	Publication Format	Year	Application Scenario (AS)	Application Purpose (AP)	Augment Information (IN)	Augment Approach (AA)	Interaction Modality (IM)
21	Rapido[103]	UIST	2021	AS8	AP2	IN1, IN2	AA2	IM2
22	GesturAR[170]	UIST	2021	AS8	AP2	IN2	AA1	IM3
23	WIKA[171]	UIST	2020	AS6	AP2	IN2	AA3	IM1, IM3
24	SceneCtrl[91]	UIST	2017	AS2	AP2, AP3	IN3	AA1	IM3
25	Oda et al. [98]	UIST	2015	AS6	AP2	IN4	AA1	IM3
26	Muresan et al. [101]	TOCHI	2024	AS7	AP2, AP5	IN2, IN4	AA1	IM3
27	Strada et al. [97]	IJHCS	2023	AS5	AP1, AP2, AP3, AP4	IN2, IN4	AA2	IM2
28	Morosi et al. [121]	IJHCS	2021	AS1	AP2	IN1	AA2, AA3	IM1, IM2
29	MorphBenches[119]	IJHCS	2019	AS4	AP2	IN2	AA3	IM1
30	Brade et al. [107]	IJHCS	2017	AS2	AP3	IN3	AA3	IM3
31	Kang et al. [88]	The Design Studies	2023	AS1	AP1, AP2, AP3	IN1	AA1	IM3
32	Şen and Şener [89]	The Design Journal	2022	AS1	AP1, AP2, AP4	IN1	AA1	IM3
33	Kim and Hong [104]	The Design Studies	2020	AS7	AP1, AP3, AP5	IN4	AA2	IM2
34	PointShopAR[113]	CHI	2023	AS2	AP2	IN1, IN2	AA2	IM2
35	ARCritique[172]	Conference	2022	AS1	AP2	IN1, IN4	AA2	IM2
36	ARtect[173]	Conference	2020	AS2	AP2	IN1	AA2	IM2
37	Zhao and Ma [92]	Conference	2018	AS3	AP2, AP4	IN1	AA2	IM2
38	AR Furniture[174]	Conference	2017	AS2	AP2	IN1	AA2	IM2
39	Adas et al. [175]	Conference	2013	AS6, AS7	AP5	IN4	AA1	IM2
40	Nakajima et al. [176]	Conference	2011	AS5	AP2	IN4	AA3	IM3

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	Study	Publication Format	Year	Application Scenario (AS)	Application Purpose (AP)	Augment Information (IN)	Augment Approach (AA)	Interaction Modality (IM)
				AR+Design				
41	Von Itzstein et al. [112]	Conference	2011	AS1	AP2	IN1	AA3	IM1
42	Shen et al. [122]	The Design Studies	2010	AS1	AP1, AP4	IN1	AA1	IM1, IM3, IM4
43	Chen et al. [177]	Journal	2024	AS7	AP1, AP5	IN4	AA2	IM2
44	Chu and Liu [123]	Journal	2023	AS6	AP4	IN4	AA1	IM1, IM6
45	Radu et al. [110]	Journal	2023	AS6	AP2, AP5	IN1, IN2	AA1	IM1, IM3
46	Rajaratnam et al. [178]	Journal	2022	AS2	AP2, AP4	IN1	AA1, AA2, AA3	IM2, IM3
47	Ariansyah et al. [99]	Journal	2022	AS6, AS7	AP2, AP5	IN4	AA1	IM1, IM3, IM4, IM5
48	Masclet et al. [109]	Journal	2021	AS1	AP4	IN1	AA2, AA3	IM1, IM2
49	Park et al. [111]	Journal	2015	AS1	AP2, AP3	IN1	AA3	IM1

Appendix3

The problem cards provided in the open-ended exploration study.

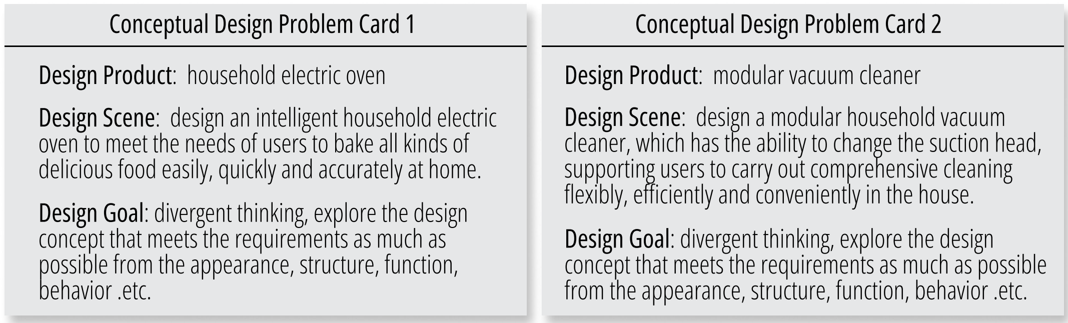

Figure 16: Problem Cards in the open-ended exploration study.

Funding

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

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