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EDITED BY
Oliver Christ,
FHNW - University of Applied Sciences Northwestern Switzerland, Switzerland

REVIEWED BY
Daniele Giunchi,
University College London,
United Kingdom
Georgi V. Georgiev,
University of Oulu, Finland

*CORRESPONDENCE
Qiner Lyu,
1199224946@edu.k.u-tokyo.ac.jp

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Design-thinking skill enhancement in virtual reality: A literature study

Qiner Lyu[1]*, Kentaro Watanabe[2], Hiroyuki Umemura[2] and Akihiko Murai[2]

[1]Graduate School of Frontier Sciences, The University of Tokyo, Chiba, Japan, [2]Human Augmentation Research Center, National Institute of Advanced Industrial Science and Technology, Chiba, Japan

As a methodology, design thinking involves practicing "a way of thinking" that non-designers can use as a source of inspiration instead being limited to a group of professional designers. This methodology has gained research attention because of the growing demands for social innovation and sustainability. The general public is expected to gain design-thinking skills through training or by applying design-thinking tools. Virtual reality (VR) is considered a potential tool to help accelerate augmenting design-thinking skills because it allows users to have embodied and immersive experiences. This study reviews existing literature on how VR has been used to enhance design-thinking skills. The general features of the publications such as the year of publication, design-thinking stages, VR types, targeted participants, and publication fields are analyzed for determining the latest trends and scenarios under this research topic. Further, a thematic analysis that follows creative enhancement structures is conducted to understand the role of VR in enhancing design-thinking skills, and future research directions are discussed based on the results. The review concludes that VR has the potential to enhance creativity in many aspects. Moreover, it highlights the need of gaining deeper understanding about 1) art, humanities, and societal perspectives; 2) cognition processes in VR; 3) emphasizing and defining stages in the design-thinking process; 4) technological improvements combined with the Metaverse; and 5) hybrid of the virtual and real worlds.

KEYWORDS

design thinking, creative design, virtual design, virtual reality, virtual environment

1 Introduction

In recent years, the increasing popularity of design thinking has inspired the establishment of design-thinking tanks in well-known consulting firms, such as SAP, McKinsey, Accenture, PWC, Deloitte, and IBM; this demonstrates the future dominance of design-thinking skills (Godin and Pridmore, 2019). With design thinking, participants are expected to co-create with multiple stakeholders and foster organizational innovation using various innovative strategies in design projects. In principle, design thinking aims to immerse participants in scenarios that enable them to think and act in a manner similar to professional designers. Design thinking provides participants with appropriate design questions and strategies to analyze, synthesize, diverge, and generate insights (Brown and Katz, 2011; Panke, 2019). Thus, design thinking forms one of the best approaches to innovation and creativity (Johansson-Sköldberg et al., 2013).

Nations and corporations seek creative professionals to build competitiveness because gaining or improving design-thinking skills has progressively emerged as a necessity. Regardless of discipline, an increasing number of universities have developed training sessions to aid students in improving their design-thinking skills. However, as an experiential and interdisciplinary course, the training sessions on design-thinking skills are expensive and challenging (Seidel et al., 2020). Non-etheless, virtual reality (VR) is a proven aid for the experiential learning process because it promotes involvement and starts from a solid experience (Chang et al., 2020). More importantly, as VR reduces the cost of design iterations by a significant extent (Yoshida et al., 2000), it can be utilized to enhance the design-thinking process.

The development of tools for enhancing design thinking has emerged as a research hotspot for technological improvement. Previous studies investigated the human–computer interaction (HCI) experience of users (Fröhlich et al., 2018; Zimmerer et al., 2020), emotional activities in the virtual world (Rieuf et al., 2017), design-thinking education in VR such as experiential learning (Chang et al., 2020) and inventive thinking (Bujdosó et al., 2017), and the use of VR to facilitate industrial design-thinking processes (Berg and Vance, 2017; Bellalouna, 2019).

We recognize VR as an effective tool for improving design-thinking skills because it aids in both the training and design processes. Nevertheless, the scope and character of design in virtual settings are understood adequately. A survey on the design-thinking processes in the virtual world can help improve our knowledge of these state-of-the-art design tools and allow us to create a more efficient design process in VR with evidence-based prescriptions. This study aims to determine the extent to which design-thinking skills have been studied in virtual environments and propose future research directions for implementing VR to improve the experience or education of design-thinking skills.

1.1 Definition

Before reviewing the applications of VR for enhancing design thinking, we must clarify the definition of VR and the scope of design-thinking skills. Although the precise definition of VR varies, it is defined as the digital form of a three-dimensional item and/or environment (Kavanagh et al., 2017). To include all relevant studies, we adopted this broad definition and surveyed both immersive VR—displayed on head-mounted displays (HMDs) or cave automatic virtual environment (CAVE) with high interactive implementation—and non-immersive VR—displayed on computer screens with keyboard and mouse interactions (Shahrbanian et al., 2012). This review covers diverse forms of VR, e.g., HMD, CAVE, desktop, and projection.

Design thinking has been predominantly cited in managerial domains. In the broad sense, design thinking originates from practicing "a way of thinking" that non-designers can use as a source of inspiration instead of being limited to a group of professional designers (Johansson-Sköldberg et al., 2013). The discourse of applying design thinking to organizational innovation is an ongoing cycle of generating ideas (abduction), predicting consequences (deduction), testing, and generalizing (induction), and it has become an approach for handling indeterminate organizational problems, which is a necessary skill for practicing managers familiar with cognitively grounded arguments. Therefore, it is a necessary component of management education (Johansson-Sköldberg et al., 2013). In this study, we emphasize translating the creative thinking and working methods of a designer into tools that anyone can learn to use to harbor and manifest creative ideas for organizations and societies, especially as a "finder" or "worker" (Razzouk and Shute, 2012). Consequently, this research focuses on 1) the general public rather than professional designers, 2) tooling up the design process or model the designers' thinking process, 3) creativity, and 4) classifying the design-thinking processes (Plattner et al., 2010).

1.2 Enhancing design-thinking skills

Design thinking can be defined as a process that encourages a person to iteratively experiment, create, prototype, and obtain feedback (Razzouk and Shute, 2012). It is rooted in a user-centered concept and promotes innovation that emphasizes human needs (Gruber et al., 2015). In addition, its several agreed-upon characteristics such as creativity and co-creation yield similar patterns even under various design-thinking processes. According to the Institute of Design at Stanford University, the design process includes the stages of empathizing, defining, ideating, prototyping, and testing (Plattner et al., 2010). IBM's suggested design process is a loop of observing, reflecting, and making (IBM, 2018). Furthermore, the renowned double-diamond model developed by the British Design Council depicts the design process as doing the right thing (first diamond) and doing things right (second diamond) (Design Council, 2019). The design-thinking process comprises a problem space and a solution space (Mueller-Roterberg, 2018), and this complex process requires a wide range of abilities and skills. As the improvement of design skills is considered an experiential and interdisciplinary process, the courses of design skills are expensive and difficult to teach (Seidel et al., 2020).

In recent years, an increasing number of global universities and graduate schools have been engaging in design thinking (Kurokawa, 2013). Scholars are exploring the impact of design thinking on various educational scopes, such as management education. Similarly, students are motivated to think extensively regarding challenges, develop a thorough grasp of users, and value others' contributions (Dunne and Martin, 2006). As observed in a project at Stanford University's design school, the education of design thinking ranges from issue comprehension to prototype building, and it includes the features of stakeholders' participation and brief presentations as a key deliverable. One of the most critical factors in design-thinking education is "learn from anything" (Kurokawa, 2013). The current practices for enhancing design skills through education recognize the critical role of experiential learning. Proposed in 1984, experiential learning presumes that knowledge can be acquired by reflective observation and active experimentation (Hanandeh, 2016), and recent evidence suggests that design motivation can be effectively simulated through experiential learning (Mulligan et al., 2018). As VR positively influences the experiential learning process, it can be used to enhance design performance (Chang et al., 2020).

In addition to enhancing design skills through education, several design-thinking tools can help enhance the design process achieve successful innovation (Liedtka, 2011). For instance, fast prototyping is a rapid iterative series of activities that intend to translate the concepts developed in the "What If" stage into tangible models, and most studies have reported successful design outcomes using this tool (Gordon and Bieman, 1995). Moodboard is a tool that arranges images, text, or other materials to evoke concepts and ideas. It assists in honing semantic values and defining symbolic references, which inspires future phases (Ferrara and Russo, 2018). Journey mapping is a visualization approach for customer experience. A flowchart or other graphic formats can assist in understanding and refining services (Samson et al., 2017). Horizon scanning is a method used to predict future political, economic, social, and technological scenarios, which enables users to acquire "weak signals" of the social trend and simulate valuable innovations (Washida and Yahata, 2020). These are only certain examples of the existing design-thinking tools. Typically, design-thinking tools demonstrate evidence-proven methodologies, and users follow a certain pattern to think or prototype. Accordingly, these technologies can increase the effectiveness of design-thinking tools for users (Pham and Gault, 1998).

As discussed previously, design-thinking skills are mostly augmented through experiential learning education or the application of design tools. Thus, we seek more advanced approaches to deliver education and use these tools to enhance design-thinking skills.

1.3 Design skills and virtual reality

VR is not a recent technology; the earliest deployment of a VR system was reported in 1966 in the form of a flight simulator developed for educational purposes for the US Air Force (Page, 2000). Not surprisingly, VR has been used to enhance design-thinking skills with an increase in internet and computational speeds and an improvement in the quality of computer displays. Currently, VR can be simply accessed using only a cell phone, virtual headset, and software applications (van Ginkel et al., 2019).

Compared with traditional learning or design tools, VR is compatible with different types of devices. Both the desktop VR and HMD VR have visual representations of space, and users can explore the virtual environment and carry out activities therein. Moreover, HMD devices realize immersive visualization with built-in screens, enabling users to have a wide field of view. HMD devices can also track users' movements with sensors or cameras. Most VR headsets are coupled with handheld controllers to interact with virtual objects and environments. Researchers are exploring the application of hand-tracking technology or tangible objects as interaction media to provide natural and novel experience in design (Schkolne et al., 2001; Fan and Pong, 2020). To achieve better performance, some HMDs are required to physically connect to computers, such as HTC Vive (Roupé et al., 2020), while others can be used with a smart phone, such as Google Cardboard (Fan and Pong, 2020). A few studies used CAVE, which needs projectors to create the virtual space (Stark et al., 2010).

Previous studies have established the positive impact of VR on learning performance in terms of cognition, skills, and attitudes (van Ginkel et al., 2019). More specifically, cognitive and learning abilities can be considerably enhanced through VR because it can potentially increase brain neuroplasticity and facilitate the reconfiguration of brain networks (Foster, 2015; Dehn et al., 2018). Furthermore, scholars have confirmed the cognitive learning benefits of VR for exploring surrounding items and environments (Bhattacharjee et al., 2018), which enables students to effortlessly grasp abstract and complex ideas (Schaper et al., 2018). Design skills education can enormously benefit from the explorative space provided by VR, which can help enhance the students' cognitive abilities and enable skill acquisition through immersive experiences.

Extensive research has demonstrated the benefits of using VR to train design skills. First, VR can promote exploration and interaction, which promotes deep observation and empathy. Prior research has suggested that an explorable space is crucial in co-design (Evans and Söderlund, 2021). VR can provide a space in which students gain first-hand experience of their ideas (Jensen, 2017; Lin et al., 2020) and closely study their design in the aspects of materials and artistic aesthetics (Huang et al., 2018), which helps stimulate cognitive actions and divergent design thinking (Lee et al., 2019). Second, VR augments experiential learning and immersing designers in virtual worlds with prototypes increase their participation in terms of both body and emotions (Rieuf et al., 2015). Therefore, VR focuses on the interactions and experiences related to design processes (Bartosh and Anzalone, 2019). Students learning creative design using VR start their learning journey from a concrete experience, which promotes reflective observation and conceptualization; this process naturally follows an experiential learning method (Chang et al., 2020). Finally, the VR is playful and provides positive emotional feedback. Lau and Lee suggested that students from Hong Kong, who are generally conservative, performed more creatively in virtual systems because they perceived the system to be joyful (Lau and Lee, 2015). More importantly, immersive design experiences have been proven to be pleasant, enjoyable, and addictive (Rieuf et al., 2015). Consequently, students tend to spend more time designing in VR (Bujdosó et al., 2017).

Furthermore, VR can potentially augment the design processes by promoting the effectiveness of design-thinking tools. For instance, a semantic network is used to generate creative ideas, and users can walk through the virtual concept space in VR. Existing studies indicated that subjects generate more ideas after a walkthrough (Georgiev et al., 2017). Moreover, the immersive mood board improves the overall quality of the concept because the immersive experience can establish interactions between designers, design tools, and users (Rieuf et al., 2015).

Several cross-sectional studies have illustrated the potential of using VR to enhance design-thinking skills through education or the design process itself. Despite these positive results, the extent to which design-thinking skills have been enhanced in virtual environments remains unclear. Literature reviews conducted to date, such as those exploring VR integration into brainstorming activities, have revealed the affordances of VR toward the creative process (Gong et al., 2022). Thus, this study explores the aspect of creativity by structurally incorporating the design-thinking process to obtain a comprehensive overview of using VR to enhance creativity throughout the design-thinking journey. Furthermore, we investigated the approaches, effects, and rationale behind them.

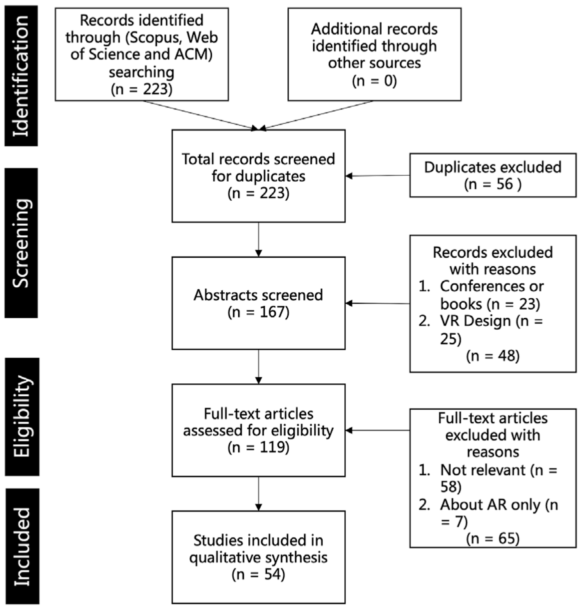

FIGURE 1
4-step PRISMA flowchart of this literature review based on included, eligibility, screening, and identification.

1.4 Aims

The utilization of VR for enhancing design-thinking skills has demonstrated immense potential, and it acts as a logical extension of co-creative design-thinking research. The characteristics of VR, such as translating abstract concepts into tangible events and establishing interactions (Alexiou et al., 2004), promote design-thinking skills by augmenting experiential learning and design processes. Motivated by the increasing popularity of applying VR to enhance design thinking and the lack of unified and systematic comprehension in this emerging field, this study attempts to gain a more comprehensive understanding of the extent to which design-thinking skills have been enhanced in virtual environments and to provide future research directions to strengthen VR as a skill-enhancement tool for design thinking.

To fulfill this objective, we intend to uncover 1) the latest research status, especially the research perspectives frequently covered and the aspects that require in-depth study, and 2) the role of VR in enhancing design-thinking skills.

The remainder of the paper is structured as follows. The methodology is described in Section 2, and an overview of the existing publications are presented in Section 3. In Section 4, a thematic analysis is conducted to derive insightful findings and results, based on which the future research directions are discussed in Section 5. Finally, the conclusions of this review are summarized in Section 6.

2 Methodology

This study primarily conducted a systematic literature review of relevant research and discussed theoretical knowledge to derive critical findings and provide future research directions on the current topic.

2.1 Step 1: Systematic literature review

After clarifying key concepts, we aimed to systematically review the mechanisms through which VR technology enhances design-thinking skills. Therefore, we employed the preferred reporting items for the systematic reviews and meta-analyses (PRISMA) framework (Moher et al., 2009). A four-phase process—identification, screening, eligibility, and inclusion—is prescribed in this framework (Figure 1).

Accordingly, we identified the related keywords "virtual reality" and "design thinking." However, as an emerging field, scholars have used various expressions to describe design thinking. To ensure the inclusion of relevant studies, the keywords "creative design" and "design skills" were also used. The database and search syntax are presented in Table 1. The search was conducted on 30 April 2022, in the Scopus, Web of Science, and ACM Library databases, and the terms were matched in title, abstract, and keywords.

The results obtained from Scopus, Web of Science, and ACM are 161, 55, and 7, respectively. For relevance, we eliminated duplicates and scanned the abstracts of the remaining 167 records. This exclusion is valid because the records refer to conference information instead of specific studies or articles. Moreover, certain articles discussed VR design, i.e., the research focused on designing a suitable VR system; however, our current objective involves the application of VR for augmenting design skills. In this stage, 48 records were excluded from consideration.

A full-text screening was conducted on the remaining 119 articles to review their applicability. A major challenge was that the creative design activity discussed in this study can be classified as design-thinking skills. According to the scope of design-thinking skills defined in our earlier discussion, studies that translated the creative design process into tools or methodologies to promote creativity among the general public were considered for further survey. However, 58 records were recognized as irrelevant, either because they did not satisfy the defined scope of design-thinking skills or they did not report using VR to enhance design thinking. Furthermore, seven additional studies were excluded because they primarily discussed augmented reality technology, although they instanced mixed reality or immersive technology in their abstracts. Ultimately, 54 records were considered relevant for further review.

2.2 Step 2: Thematic analysis

Step 2 involved a qualitative thematic analysis that is generally applied to qualitative data to identify, analyze, and report thematic patterns (Braun and Clarke, 2006). Because the current aim is to clarify the mechanism and extent of enhancement in design-thinking skills achieved using VR, the current structure of the thematic analysis incorporated five outlines through which VR can be used to enhance creativity and problem solving (Thornhill-Miller and Dupont, 2016).

TABLE 1 Database and search syntax with the number of results (as on 30 April 2022).

Database	Search syntax	Results
Scopus	TITLE-ABS-KEY ("design thinking" OR "design skills" OR "creative design") AND TITLE-ABS-KEY ("virtual reality" OR "VR")	161
Web of Science	TS = ("design skills" OR "design thinking" OR "creative design") AND TS = ("virtual reality" OR "VR")	55
ACM Library	[Abstract: "design thinking"] OR [Abstract: "design skills"] OR [Abstract: "creative design"]] AND [[Abstract: "virtual reality"] OR [Abstract: "vr"]	7

The creative enhancement structure includes: 1) self and self-perception, 2) interactions and collaborations, 3) environmental conditions, 4) process, and 5) integration of technologies. The creative enhancement structure originates from the four distinct approaches suggested by Lubart (2005) that use HCIs to promote creativity. Lubart (2005) concluded that HCI can assist "the management of creative work, communication between individuals collaborating on creative projects, use of creativity enhancement techniques, and creative act through integrated human–computer cooperation during idea production." Moreover, upon implementing VR technology, creativity can be enhanced through the fifth approach, labeled "VR and converging technologies of enhancement" (Thornhill-Miller and Dupont, 2016). These thoughts provided the theoretical basis of the creative enhancement structure, and it is well-suited to the thematic analysis of this study.

We review all aspects of this structure and discuss the manner in which VR enhances design-thinking skills based on these aspects, i.e., the benefits of implementing a VR system. Furthermore, we discuss the drawbacks and current limitations of VR technology based on these five perspectives. Because certain publications may cover multiple aspects and the discussion is not limited to a single aspect, we allocated a given article according to its most emphasized aspect of discussion.

2.3 Step 3: Identify future directions

Based on the findings obtained from Steps 1 and 2, we suggest future research directions. The future agenda aims to cover the aspects that are under-researched thus far and those promising immense potential.

3 Overview of reviewed publications

Supplementary Table S1 presents an overview of our reviewed publications. To capture the trends and characteristics of VR and design-thinking skills, the overviews of the year of publication, design-thinking classification, VR type, targeted participants, and research field are discussed.

3.1 Year of publication

During the search in all databases, we did not set any limitation on the year of publication. This setting allowed us to derive an initial insight from analyzing the emergence of using VR for enhancing design skills based on the year of the reviewed publications (Figure 2).

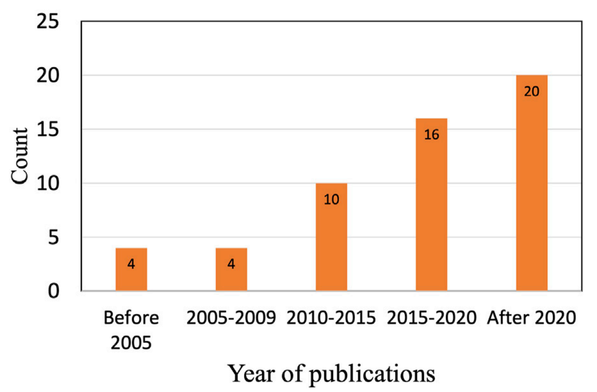

FIGURE 2
Count of publications by year since before 2005 to after 2020.

In our review, the earliest study was published in 2000, and it focused on automobile styling design in a 3D virtual world (Yoshida et al., 2000). Interestingly, the number of publications between 2010 and 2015 more than doubled compared with that in the previous 5 years. In recent years, the number of publications has increased rapidly, and publications after 2020 constitute the largest portion of our reviewed publications, which illustrates the continued growth of research interest in this topic.

The fundamental reason for this increasing trend is the development of related technologies. Almost 6 decades ago, the idea of immersive VR was initially proposed by Sutherland (1965). Thereafter, inspired by various generations of hardware such as CRT displays and electromagnetic tracking, VR re-emerged as a research hotspot in the 1980s and 1990s (Slater and Sanchez-Vives, 2016). The continuous development of VR displays and interactions created more advanced devices such as Oculus, HTC Vive, and Google Cardboard. Currently, we are approaching the availability of inexpensive displays for mass consumption, and every new generation of VR hardware has stimulated interest in innovative applications of VR. More importantly, an increasing number of opportunities are available in this informatics era. VR technology is closely related to the use of 5G and the latest developments in storage/memory, fog/edge computing, computer vision, and artificial intelligence (Bastug et al., 2017). The relevant technologies are developing rapidly at this stage.

In contrast, new requirements in the design field underscore the significance of design-thinking skills and raise the demand for further enhancement of creative design. For instance, we are

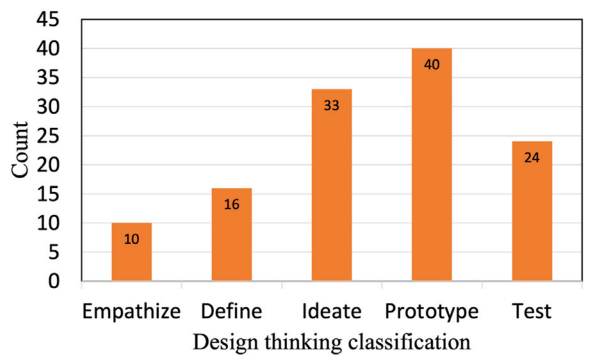

FIGURE 3
Classification of publications based on 5 design-thinking stages.

shifting from the user-centered design that emphasizes user satisfaction with participatory design approaches (Sanders, 2002) to the concept of meta-design that creates sociotechnical environments involving end users (Fischer et al., 2004). The increasing interest in educating or assisting humans to be more creative in developing solutions of current social issues has accelerated the rising number of publications on this topic.

We continue to be in pursuit of developing an interconnected VR system with the ultimate aim of achieving a completely interconnected VR world (Bastug et al., 2017). The discussion on various applications of VR will continue to expand, and creative designs will prove beneficial.

3.2 Design-thinking classification

Most prior studies applied VR technology in multiple design-thinking stages. Ideation and prototyping are the key design-thinking stages that have been most explored, whereas empathizing and defining are the least explored stages (Figure 3).

Forty articles discussed VR as a prototyping tool in the design-thinking process. Prototyping has become an entry point of research in applying VR to enhance design thinking because prototyping in VR involves a spatial and interactive mechanism. Certain studies discussed the test stage after prototyping and treated prototyping and user testing as an iterative and completing process (O'Dwyer et al., 2007; Shih and Kuo, 2017).

Certain other studies highlighted the use of VR as an ideation tool in the early stage of design, and 33 articles covered the ideation stage of design thinking. Several studies reported that ideation in the early stage of design requires rapid prototyping with low fidelity. In this regard, the prototyping tools in VR are intuitive and easy to learn (Yoshida et al., 2000), which requires less time and money (Roupé et al., 2020), which demonstrates the usefulness of VR in the ideation stage. In addition, ideation can be conducted through a semantic network, and the research findings suggest an immersive semantic network that users can walk through to generate more ideas (Georgiev et al., 2017).

Among the design steps, empathizing and defining were relatively less discussed, and most review publications covered these aspects to discuss the entire design-thinking process; however, they did not attend to these two stages. In terms of design, the first notion involves the process of transforming ideas into real objects. In the case of using VR to enhance the design process, the most direct connection is "computer-aided design" (CAD), which considers VR as a prototyping tool. Therefore, the empathizing and defining stages of design have been understated, despite being essential aspects of design thinking. In principle, VR holds immense potential for enhancing empathy because it enables perspective-taking and embodiment (Ahn et al., 2016). In future, more research attention should be invested on empathizing and defining.

3.3 VR type

This review covered various types of VR according to the defined scope of VR. In total, 27 studies used immersive VR, i.e., the use of HMD or CAVE as the hardware. A majority of these studies used HMD (23), whereas a few used CAVE 3), and only one study explored both HMD and CAVE (Figure 4). Moreover, non-immersive VR hardware was used in certain reviewed articles, wherein the researchers used a virtual desktop environment such as Second Life to conduct experiments. Notably, ten publications did not clarify the exact equipment they used or were not classified because these studies were theoretical discussions rather than empirical studies.

In addition, the various forms of hardware used in these studies were analyzed based on year. Since 2015, the number of non-immersive VR systems decreased following a moderate increase prior to that period, although the overall amount of research increased considerably. This finding indicates a significant rise in interest in immersive VR systems promoted by more affordable and easy-to-access HMD equipment. Thus, immersive VR systems will become mainstream with the continuous development of immersive headsets and devices.

3.4 Targeted participants

The publications targeted diverse groups of individuals with varied purposes for enhancing design-thinking skills. The target participants of all publications were analyzed to determine the group of users receiving the most attention.

As depicted in Figure 5, most studies (33%) did not focus on a specific group and aimed to enhance the creativity and design skills among general groups of individuals. The VR-assisted design methodology or technology proposed in these studies can be used by any individual intending to augment their own creative or design skills. A total of 16 articles (30%) aimed to enhance design skills from an educational aspect; they aimed to aid students in gaining design skills *via* more efficient learning modes. The students in such studies were involved in various fields, such as architecture (Sopher et al., 2019; Jenek et al., 2021), business (Olmos, 2006), and engineering (Chang, 2022). Thus, this is another form of targeting a generalized group of individuals.

The remainder of classifications included targeted participants, wherein Architecture, Engineering & Construction (AEC) design

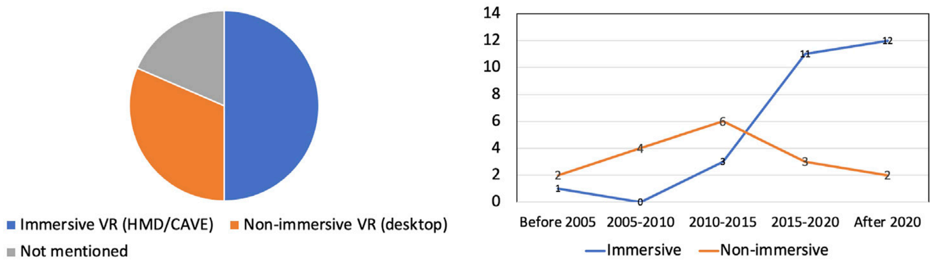

FIGURE 4
Frequency distribution of immersive and non-immersive VR devices used in research (left) and change in quantity by year (right).

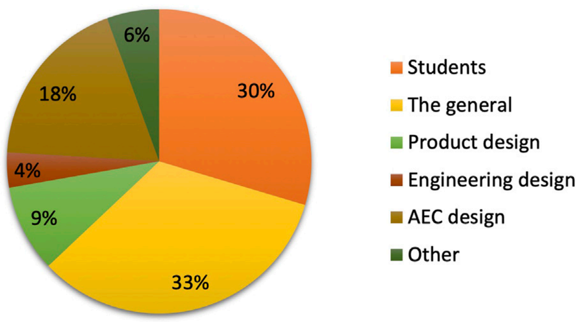

FIGURE 5
Targeted design participants in the publications.

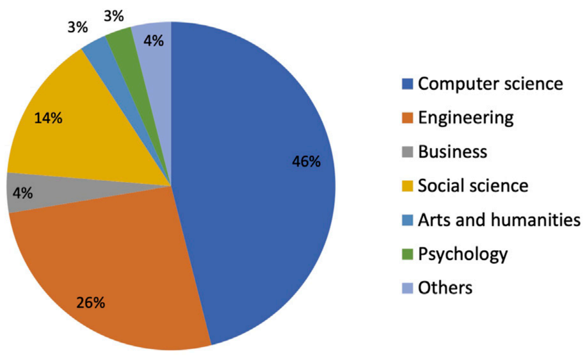

FIGURE 6
Research fields of the publications.

forms the most discussed group. In addition, five studies discussed the use of VR to enhance design thinking in product design, and two studies focused on engineering design. Furthermore, three studies investigated fashion, automobile styling, and emergency departments.

According to this survey, the publications at the current stage tend to be generalized applications of design-thinking skills, with relatively more attention invested in users in the AEC and product design fields. A large portion of studies targeted students and demonstrated the increasing interest in design-skill education. Following the initial attempt to apply VR-assisted design-skill enhancement in AEC fields, future research can specialize and focus on other fields to augment design skills in all applicable industries.

3.5 Research field

We analyzed the research fields of the reviewed publications to determine their motivation. We counted the total frequency of each research area because one article can be associated with several fields. For all publications, the research areas sourced from the Scopus database are statistically represented in Figure 6.

As depicted in Figure 6, most publications are associated with computer science, i.e., approximately half of all reviewed articles are published in journals related to computer science. Most studies recognized VR technology as a part of computer science technology and discussed it as a computer system or CAD tool. Engineering forms the second-largest share among the reviewed publications. As numerous studies attempted to use VR for enhancing engineering design, these studies were published in the engineering design field. Consequently, nearly 70% of the publications pertained to the computer science or engineering fields.

The remaining articles were related to social science (14%), business (4%), arts and humanities (3%), psychology (3%), and other fields (4%), among which social science accounted for 50%. Although certain articles were published in technology fields, they covered social or psychology-related content. Thus, further research is required on aspects other than technology, e.g., business, arts, humanities, and society.

4 Thematic analysis

In this section, we discuss the potential of VR to enhance design-thinking skills using a thematic-analysis approach based on a creative enhancement structure (Thornhill-Miller and Dupont, 2016) (Table 2). Based on this discussion, we aim to determine how VR enhances design-thinking ability, its potential opportunities, and the related challenges. The overall information

TABLE 2 Themes and publications under each theme.

Theme	Publications	Numbers
Self/Self-perception	Skibina and Taratukhin (2021), Chen et al. (2022)	2
Collaborations	Kan and Gero (2008), Lee and Do (2009), Merrick et al., 2011; Gül (2014), Rive and Karmokar (2016), Petrykowski et al. (2018), Roupé et al. (2020), Skrupskaya et al. (2021), Whewell et al. (2022)	9
Environmental elements	Georgiev et al. (2017), Siau et al. (2010), Dosi et al. (2019), Abdelhameed (2014), Sopher et al. (2019), Buruk and Hamari (2021), Vosinakis and Koutsabasis (2013), Jenek et al. (2021), Gu et al. (2010), Maurya et al. (2019), Keller and Stappers (2001), Cindioglu et al. (2022), Zhu and Du (2021), Stark et al., 2010; Olmos (2006), D'Souza et al. (2011), Charlton et al. (2018)	17
Problem-solving process	Abrishami et al. (2013), Fogli et al. (2017), Gräßler et al. (2017), Yamada et al. (2017), Aydin and Aktaş (2020), Chang et al. (2020), Lin et al. (2020), Abhari et al. (2021), Earle and Leyva-de la Hiz (2021), Jee Hyun Lee et al. (2021), Jee Hyun Lee et al. (2021), Ren, 2021; Chang (2022)	13
Integration of technologies	Nishino et al. (2001), O'Dwyer et al. (2007), Chandrasekera and Yoon (2015), Maurya et al. (2019), Zimmerer et al. (2020), Fan and Pong (2020), Caputo et al. (2017), Yoshida et al. (2000), Shih and Kuo (2017), Schkolne et al. (2001), Tabrizian et al. (2017), Liu et al. (2021)	12

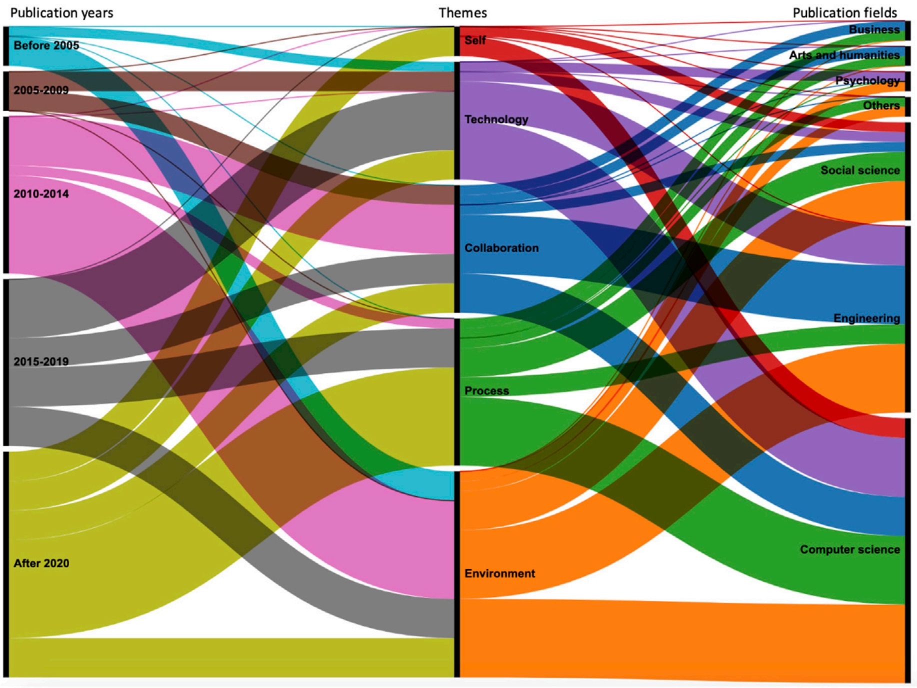

FIGURE 7
Relations among publication years, themes, and publication fields.

about the year of publication, themes, and publication fields are shown in Figure 7.

4.1 Altering aspects of self and self-perception

VR technology has been long used to enhance creativity by altering the aspects related to self and self-perception, such as the use of avatars, which forms the core of this approach. The use of an avatar is an improvement over several other computer-mediated modes of communication because it enables both verbal and non-verbal communication, in addition to providing a completely new level of self-expression and intricate engagement. According to the "Proteus effect," the features of the avatar strongly impact the behavior of an individual, regardless of their interaction with others; this implies a possibility of fundamental alterations in self-perception (Yee and Bailenson, 2007). In addition, "ghost engineering" claims that, by modifying our body perception and recognition, the cognitive function can be altered according to our desire (Narumi, 2021). More importantly, existing studies have recognized the critical role of altering an individual's self and self-perceptions to enhance their skills.

To enhance a creative person, Thornhill-Miller and Dupont (2016) proposed several potentials such as role-playing techniques, creating empathy and imagination, and varying emotions and arousal based on findings from related research (Thornhill-Miller and Dupont, 2016). In ghost engineering, several approaches are employed to modify the virtual body. The "transformation" represents the experience of becoming someone or even something else, which is similar to generating empathy. The experience of manipulating multiple bodies is possible using VR technology. The "body multiplexing" impacts one's balance of thoughts and communication. Moreover, in the case of a "merged body," a single body is operated by several people (Narumi, 2021). Although the effects of these methods still require empirical tests, the potential to enhance design-thinking skills by altering self or self-perception has been theoretically established.

However, in our reviewed publications, only two articles focused on altering the aspects of self and self-perception (Skibina and Taratukhin, 2021; Chen et al., 2022). One publication discussed the augmentation of design skill from the perspective of empathy. This study intended to investigate the origins of consciousness and empathy to extend empathy methodologies in design thinking for assisting individuals in achieving global understanding. The research suggested the "empathy mirror" of VR-assisted individuals to understand the system from the inside (Skibina and Taratukhin, 2021). Empathy is crucial in design-thinking skills and human-centered design to avert empathy-related product failures (Dam and Siang, 2021). As established, VR is closely associated with empathy, embodiment, and perspective-taking (Ahn et al., 2016). Compared to other aspects, self-perception and empathy are the most neglected aspects to date.

Another study discussed VR, cognitive load, creative components, and performance. The findings suggested that VR can significantly affect professional cognition and motivation, which indicates the direct impact of VR on cognition (Chen et al., 2022). Existing studies have proven the direct impact of VR on one's ability by altering cognition. For instance, creative avatars with creative professional appearances can improve creative performance (Buisine et al., 2016). Thus, more empirical studies are required on this aspect because the influence of VR on design-thinking skills remains unclear.

Furthermore, studies that altered the aspects of the self and self-perception are limited to empathy or cognition improvement. According to our previous discussion, several possible approaches can be employed to improve creativity by altering self-perception. For instance, further research is required to test "body multiplexing" or "merged body." In the OriHime-D project, disabled people collaboratively shared an avatar robot to serve customers in a café. This approach can mitigate the physical limitations of a single person and create value along with a sense of fulfillment (Takeuchi et al., 2020). Consequently, we can expect an enhancement in collaboration by altering the aspects of self and self-perception using various methods.

In summary, relatively few studies discussed the modification of aspects related to self and self-perception, and they primarily focused on empathy and cognition. Thus, further research is required on the application of VR to enhance design research and empathy, considering research topics besides empathy, such as collaboration through "body multiplexing" or "merged body."

4.2 Optimizing interactions and collaboration with others

Recently, VR has been suggested to enhance creativity by optimizing interactions and collaboration with others. In certain cases, co-creative design occurs online with virtual teams working together, wherein telecommuting and tele-collaboration are not rare occurrences. However, most methods of virtual collaboration are faceless and asynchronous, which creates a slew of inefficiencies and misconceptions along with an environment of less interpersonal and task-oriented participation (Schroeder et al., 2001). Thornhill-Miller and Dupont (2016) suggested that VR can provide benefits without the associated drawbacks because the sensation of immersion and synchronous co-presence with others provided by virtual worlds can significantly improve interpersonal and work engagements as well as creativity.

In the reviewed articles, nine studies primarily focused on enhancing creativity using VR by optimizing interactions and collaboration with others. These studies discussed two types of benefits. The most widely discussed benefit of VR is that it provides computer-mediated collaboration tools, which are broadly classified into computer-mediated communication (CMC) and collaborative virtual environment (CVE) technologies (Lee and Do, 2009). These publications reported that the VR system can be more time- and cost-effective because it entails shorter cycles between new proposals and feedback from end users (Roupé et al., 2020). As VR sketching or prototyping tools are more intuitive and require less effort (Gül, 2014), it strongly supports human–human interaction and HCI (Merrick et al., 2011). In teamwork scenarios, VR aids engagement and promotes motivation (Whewell et al., 2022; Skrupskaya et al., 2021) because of its advantages in sharing, interaction, and collaboration (Rive and Karmokar, 2016). In particular, VR displays immense potential in brainstorming and prioritization (Petrykowski et al., 2018). Compared with traditional 2D digital collaboration, VR positively impacts efficiency and engagement as a CVE.

As a CMC, VR can simultaneously support collaboration in creative design thinking. According to an empirical study conducted in international projects, VR can enhance digital skills and engagement and assist with cultural competence and global mindfulness (Whewell et al., 2022). Furthermore, contemporary designs require communication between multiple stakeholders. For instance, the meta-design framework encourages the involvement of more relevant groups such as end users. As such, VR systems have been proven to support creative and design processes shared between multiple stakeholders by facilitating understanding, participation, communication, knowledge sharing, and collaboration (Roupé et al., 2020).

Non-etheless, certain publications have reported the drawbacks of VR technology. In a 3D virtual-world setting, users developed fewer design ideas than in face-to-face (F2F) settings because of the limited use of gesturing (Kan and Gero, 2008). Additionally, this empirical study suggested that teams worked together longer in distant settings because the communication efficiency reduced when the participants could not directly interact with each other, as in the F2F setting. The findings suggested that the current CVE failed to support effective collaboration (Lee and Do, 2009). Owing to the limitations of technological development, virtual collaboration cannot be as efficient as F2F collaboration; however, it may be more efficient than other traditional online collaborations, and therefore, a hybrid method of interaction is required (Skrupskaya et al., 2021). In addition to the disadvantage of technological limitations, VR systems may negatively impact users' cognitions, considering user familiarity (Gül, 2014), because the lack of experience in using VR may yield negative results (Jensen, 2017; Evans and Söderlund, 2021; Qian, 2021).

4.3 Optimizing environmental conditions and influences

The most prominent benefit of VR is that it provides complete control of the environment at a low cost (Thornhill-Miller and Dupont, 2016). By modifying the environment, several direct and indirect elements may impact creativity.

Thornhill-Miller and Dupont (2016) concluded that creativity could be influenced in four ways. First, the environmental elements were proven relevant to creativity, such as light, color, and plants (Dul and Ceylan, 2011). The researchers clarified that visual and audio elements (i.e., color and sound) may affect creativity. For example, yellow, orange, pink, red, or red violet are recognized as inspiring colors, and music as well as silence or the absence of noise positively affects creativity (Dul and Ceylan, 2011). Second, appearance metaphors, referring to problem solving, can contribute to creativity at the cognitive level (Slepian et al., 2010). Third, the broadened exposure and expanding experiences to multiple cultures can enhance creativity (Leung et al., 2008). Lastly, the inclusion of other elements, e.g., individuals tend to be more innovative when exposed to scenes with complex unexpected or unusual events (Ritter et al., 2012). Thus, VR offers an eminent opportunity to enhance the creative design process by modifying the environment.

Among the reviewed articles, 17 articles focused on the impact of the virtual environment on design-thinking skills as a major benefit of VR. The environment is provided directly by VR, and the surroundings can be visualized in a manner that varies completely from traditional 2D representations. Several publications have stated the potential of novel visualization in the virtual world. The ideation process can be visualized through a navigable semantic network expected to generate more creative ideas through exploration, unexpectedness, and reflection in the virtual world (Georgiev et al., 2017). Although exploration in VR is somewhat accidental (Buruk and Hamari, 2021), users' communication with environments inspires designers to imagine a suitable atmosphere (Keller and Stappers, 2001). Moreover, the virtual environment exhibits a nature of interactions that facilitate the design of creative tasks to gain design-thinking skills (Siau et al., 2010). Consequently, VR can increase design productivity, creativity, and design exploration through idea generation (Cindioglu et al., 2022), as well as support design convergence (Sopher et al., 2019). When users are equipped with a technology that enables them to directly execute the design activities and modify a virtual prototype, they are more interested in the design tasks, more satisfied with the design process, and produce more creative results (Maurya et al., 2019). Specifically, enhancing creativity by optimizing environmental conditions and influences has been widely discussed in spatial and architectural design. Virtual simulation can promote the decision-making confidence of the top management and head physicians (Dosi et al., 2019), and dynamic design tools (VR) can assist in realizing more advanced design-related decisions (Jenek et al., 2021).

VR can also create virtual environments where users' sensorial perception is enhanced. The spatial and 3D perceptions in VR enhance spatial imagination required for interior design (Zhu and Du, 2021) and landscape design (Tabrizian et al., 2017; Ren, 2021). The content and meaning of architectural expression have been expanded by VR technology (Ren, 2021). However, spatial design is not the only design field which benefited from visual perception enhancement through VR. In the VR space, the design prototype could be projected in its use situation. This assists the user test stage in design thinking to extract precise user impression (Yamada et al., 2017). Additionally, design convergence can be supported in immersive virtual environments (Sopher et al., 2019). The attractive, stimulating virtual experience motivates designers and boosts their creativity (Aydin and Aktaş, 2020). Another advantage of prototyping in VR is multisensory inputs. Shared music, sound effects, and visuals in virtual space are the typical inputs for design creativity (Rive and Karmokar, 2016). However, our reviewed literature covers few other sensorial perceptions. Only one study attempts to explore the five senses in VR to enhance design thinking. Designers can see the world differently, find hidden patterns, and connect seemingly unconnected phenomena in VR environments (Liu et al., 2021). Currently, the main VR application is visualizing the prototypes and interacting with them using tangible user interfaces (Chandrasekera and Yoon, 2015). Using multisensory inputs other than audio and visual elements in virtual world is worth exploring in future studies.

Design Studio is another form of VR implementation in the design process. As a traditional approach of gaining design skills, studies have described methods for using virtual worlds incorporating the use of prospective tools and workplaces (Vosinakis and Koutsabasis, 2013). Compared to physical means, a virtual design studio is an effective training tool that enables faster and real-time design actions to enhance "learning by doing" (Olmos, 2006). In this case, VR is a virtual design environment that is more convenient to use than a traditional design environment.

Nevertheless, technological inefficiencies inevitably limit the effects of the VR experience, and virtual worlds present technical as well as behavioral challenges (Siau et al., 2010). Thus, we should aim for a comprehensive improvement of VR technology, especially real-time rendering, functional structure, and interactions (Zhu and Du, 2021). For instance, the brick-collage style causes noise and disturbance (Olmos, 2006), and we should enhance rendering and other related technologies to achieve superior styles, while maintaining the speed and stability of the system. In addition, the research highlights the demand for more functions in the VR environment to enable designers to start without specific or certain design ideas (Abdelhameed, 2014).

Other disadvantages or unresolved issues cited in the reviewed articles include pedagogical design and communication problems.

As educational content gradually adjusts with the rapid technological growth, virtual design environment tools must be further studied in the context of a university (Jenek et al., 2021). One study determined that a VR interface considerably increases logical, kinesthetic, and naturalist skills; however, it intrudes on verbal and intrapersonal skills (D'Souza et al., 2011). Thus, certain hybrid modeling methods have been proposed for collaboration between designers and engineers (Stark et al., 2010).

4.4 Facilitating guidance or gamification of the problem-solving process

Although VR can enhance design-thinking skills by facilitating the guidance or gamification of the problem-solving process, the application of VR technology to this aspect is underestimated. Thornhill-Miller and Dupont (2016) suggested that each step of the traditional problem-solving procedure can be transformed into a digital form and conducted in a virtual world, where resources and opportunities are provided to participants to more efficiently explore, modify, or evaluate their ideas.

In this review, 13 studies emphasized the enhancement of the design process. VR can augment all the steps of the design-thinking process with various methods, including the development of design concepts, examination of design concepts, enrichment of design environment, simulation of design scenarios, validation of design solutions, and improvement of design logic (Abhari et al., 2021). VR aids the entire process, focuses on a macroscopic view, and stimulates cognitive action and interaction (Lee et al., 2019). VR corresponds to the concept of experiential learning as it initiates with concrete experiences (Chang et al., 2020). Further, VR significantly affects the way of thinking and cognition in the design process, as reported in various articles. In addition to assisting designers with iterative and flexible thinking (Lee et al., 2019; Lee J. H. et al., 2021), VR instills a sense of accomplishment and confidence among the users (Chang et al., 2020). In addition, VR positively influences the cognitive and affective domains in the engineering design process (Chang, 2022). More importantly, VR can significantly improve the overall creative design process because it increases enjoyment, motivation, and self-efficacy, which promotes involvement in design (Chang et al., 2020). The design process using VR is attractive and stimulating (Aydin and Aktaş, 2020). As a result of the enhanced cognition and thinking ability coupled with a more enjoyable process, participants experienced joy using VR and generated a high number of ideas (Gräßler et al., 2017). The game-like immersive VR interface has been proven to offer further augmented opportunities in global AEC design (Abrishami et al., 2013) as well as in engineering design (Chang, 2022).

However, certain studies reported that the software can be "complicated" and "confusing." Users scored extremely low on the pragmatic qualities of perspicuity, efficiency, and dependability (Aydin and Aktaş, 2020). In addition, VR is expected to be implemented with new interfaces and databases (Abrishami et al., 2013) because tangible user interfaces and physical object manipulation create more engagement among users (Fogli et al., 2017). Thus, VR offers immense potential in facilitating the guidance or gamification of the problem-solving process with more advanced interfaces and reliable systems.

4.5 Offering an arena for integration of other technologies of creativity enhancement

The fifth way that VR can enhance creativity is labeled "VR and converging technologies of enhancement" (Thornhill-Miller and Dupont, 2016), i.e., VR facilitates the integration of other technologies or approaches for learning and cognitive enhancement.

Among the reviewed publications, 13 studies focused on integrating other approaches or technologies. The most discussed technology is 3D modeling or simulation technology, which corresponds to the functionality of VR as a novel CAD tool. Accordingly, a modeling system has been developed based on interactive evolutionary computation (IEC), and its potential for use in creative design has been demonstrated (Nishino et al., 2001). In addition, a virtual structural environment system has been integrated into VR, which enables students to construct simple structural models (O'Dwyer et al., 2007). Another study discussed the validation of design workplaces based on an ergonomic approach (Caputo et al., 2017). VR simulation or modeling is one of the fundamental purposes of integrating approaches into technologies.

Moreover, several existing studies have proposed a new interface. Users prefer tangible interfaces (Chandrasekera and Yoon, 2015) in the virtual world because tangible interfaces are more immersive. The VR + TUI tool increased the motivation and appeal for generating concepts (Maurya et al., 2019). A certain study discussed multimodal interfaces (MMIs) comprising a synergistic combination of speech and pointing/grabbing gestures (Zimmerer et al., 2020). More recently, researchers in this field have attempted to stimulate all senses of human beings to enhance the design experience. Interactive media with multiple approaches to trigger the designers' senses provide a clear advantage, especially in the case of triggering sensations such as touch, hearing, and smell (Liu et al., 2021). The novel interaction combined with multiple senses renders the design process more tangible and easier to imagine.

In this context, tracking technology is essential in VR environments. We reviewed several articles to discuss technologies applicable to VR. A framework has been developed for tracking custom-made physical items in a multiuser environment, which consists of three aspects: tracking hardware, software stack, and VR hardware (Fan and Pong, 2020). The existing research attempted to physically connect the path of the hand to its shape by being immediately realized as geometry (Schkolne et al., 2001). The development of tracking technology renders the VR experience more adaptive and reliable in real cases, which should be considered for further research in future.

The benefits of integrating new technologies constitute the primary motivation for future research. We can conclude from our reviewed articles that the VR modeling tool is easy-to-use for individuals with relatively less knowledge and experience in modeling (Nishino et al., 2001). This is because the natural and intuitive process of the physical design interfaces motivates specialists from other disciplines or even the general public to readily participate (Tabrizian et al., 2017), which enables users to act more naturally than in a traditional CAD system (Yoshida et al., 2000). Thus, users are not hindered by unfamiliar interfaces when collaborating with designers (Shih and Kuo, 2017), which assists designers to focus on generating innovative concepts and obtain fast validations without considering the feasibility of behavioral concepts (Maurya et al., 2019). Moreover, an extensive amount of data can be acquired because virtual simulation significantly reduces the cost of implementation (Caputo et al., 2017).

The relevant technological issues are also discussed in this section. A tool with more complex interaction elements is required (Maurya et al., 2019), and its reliability and flexibility should be improved with the integration of MMIs (Zimmerer et al., 2020) because it yields inferior user experience.

5 Discussion: Future research directions in VR and design-thinking skills

VR has been used for cognitive enhancement for a variety of purposes, such as cognitive training and memory improvement (Manera et al., 2017; Kim et al., 2019). In this review, we identified the primary methods through which design-thinking skills are enhanced with the assistance of VR technologies. The enhancement methods cover the perspectives of the self, environment, process, collaboration, and technology integration (Thornhill-Miller and Dupont, 2016). VR technology has been widely applied as a CAD tool for 3D modeling, prototyping, or simulations for design review or idea testing. In addition, several publications have upheld VR as a novel computer or engineering technology. Design-thinking skills incorporate a wide range of concepts in multiple steps, and only a handful of research have studied certain design-thinking steps. Although numerous theoretical approaches have been developed to enhance design thinking, empirical studies should test more approaches or ideas. We identified aspects that have been thoroughly explored as well as underestimated by existing studies. Future research directions in VR and design-thinking skills are outlined in this section to increase the efficiency and usefulness of future VR systems toward design-thinking enhancement.

5.1 Research from art, humanities, and society perspectives

Further research is required from the perspectives of art, humanities, and sociology. Most articles were published by journals related to the fields of computer science and engineering. Although certain studies discussed the applicability of VR in fields of arts, humanities, and sociology, further research is required to deeply understand the prospect of VR in these fields.

Although few studies have mentioned the art aspects in design thinking skills, design thinking is considered to naturally build bridges between arts, sciences, and other subjects (Henriksen, 2017). In all the studies that we reviewed, only one articles mentions that VR has the potential to promote the development of design with the Ninth Art, in which the author discussed the exhibition art design in an indoor space (Zhu and Du, 2021). Moreover, design thinking is intwined with art thinking to promote innovation activities (Robbins, 2018). Therefore, future studies are expected to explore arts and art thinking in using VR to enhance design thinking skills, especially study how art thinking leads to highly revolutionary designs.

Pedagogical implication is a critical research direction under this topic, and several studies have focused on gaining design-thinking skills through educational methods and targeted students. Educational content is gradually adjusting with the rapid growth in technology (Jenek et al., 2021), and further research is required on developing learning content in the virtual world and gradually implementing virtual learning tools into the pedagogical design. Learning preference is another critical element with pedagogical implications. Existing research classified learners into kinesthetic learners and visual learners, assuming that kinesthetic learners prefer a tangible interface and *vice versa*. As such, the findings suggested that both kinesthetic and visual learners benefit from tangible interfaces (Chandrasekera and Yoon, 2015), and thus, this research direction should be further explored. In addition, virtual design environment tools must be studied from the perspective of a university (Jenek et al., 2021) because the dearth of educational experience is a fundamental problem that affects experimental results (Jensen, 2017; Evans and Söderlund, 2021; Qian, 2021), and unfamiliarity results in cognitive load (Chen et al., 2022).

In addition to pedagogical implications, the aspects of design or design thinking require a more rigorous intervention. In the reviewed articles, although the researchers stated the words "design thinking" or "design skills," most studies implemented a narrow understanding that addresses design as the prototyping activity. Only a handful of studies have considered design skills as an entity and discussed all design-thinking processes (Gräßler et al., 2017; Aydin and Aktaş, 2020; Lin et al., 2020). Considering the design activity and methodology, empirical studies should focus on establishing the foundation of design instead of developing computer or engineering systems to complete this research field.

5.2 Research on cognition process in virtual design

Further clarification of the cognition process in the virtual world will help in developing a VR system that directly enhances design cognition. In this regard, a few articles among the reviewed publications discussed certain cognitive elements. For instance, VR applications significantly impacted extraneous and germane cognitive load but did not affect intrinsic cognitive load (Chen et al., 2022). Meanwhile, both VR applications and cognitive load can predict creativity components and creative performance (Chen et al., 2022). In addition, VR stimulates cognitive actions and interactions to help designers with iterative and flexible thinking (Lee et al., 2019); this can be explained by the aspects of cognitive action. The immersive VR design tool activates physical and perceptual actions in design cognition and enhances flexible cognitive action among various levels of cognitive actions (Lee J. H. et al., 2021).

Flow and motivation are additional cognitive factors that may occur in a virtual environment and significantly impact creativity. The motivation and flow states exhibit a strong positive correlation such that the immersive virtual design environment facilitates the creativity of the participants of the design process more than the non-immersive one (Obeid and Demirkan, 2020). Furthermore, VR can increase enjoyment, motivation, and self-efficacy, which promotes involvement in design (Chang et al., 2020).

In addition to enhancing cognition processes, VR can provide opportunities to learn design cognition better. VR has been discussed as a research tool to enhance design experiences along with the study of design cognition, from the aspects of its continuous and multifaceted record, objective evaluation, direct observation, and active engagement (Neroni et al., 2021). The data collected *via* VR design is applicable for studying design cognition for further cognition enhancement.

These studies relevant to cognition processes are in the initial stage, especially in terms of the effect of VR on altering cognition and enhancing the design-thinking process through variations in cognition. The underlying mechanisms should be explored in future. Importantly, these clarifications of the cognition process can stimulate further research on the alteration of aspects related to self and self-perception in the virtual world. Although this aspect forms a considerable approach for enhancing design through VR, it remains underestimated as per our previous discussion.

5.3 Research on emphasizing and defining stages in design-thinking process

This review revealed that the prototyping and test stages of the design-thinking stage have been predominantly discussed in existing research because it is the first activity considered in design. However, VR is closely associated with empathy, such that the potential of using VR to conduct design research has been underestimated.

Only two articles focused on empathizing and defining in our reviewed publications, and the researchers discussed enhancement through altering the aspects of self and self-perception (Skibina and Taratukhin, 2021) and the integration of other technologies (Liu et al., 2021). Besides prototyping, the crucial design-thinking stages of empathizing and defining have been subject to limited discussion. The underlying mechanism of empathy and self requires clarification. Overall, empathy encompasses five dimensions: affective, cognitive, somatic, emotional, and compassionate empathy; however, the kinds of empathy triggered by VR remain unclear (Hu and Georgiev, 2020).

Excluding perspective-taking and embodiment, the other empathy strategies have not yet been tested. As reported, ambivalent emotional reactions are caused by various perspective-taking strategies and the unclear effects of virtual avatar embodiment. However, we can utilize an ergonomic strategy based on replicating users' surroundings, multisensory embodiment, and interaction data (Hu and Georgiev, 2020). Based on a deeper understanding of the empathy process, future research should cover all creative enhancement structures. Notably, VR empathy can trigger the correlation between empathy and virtual environment, multisensory technology, and collaboration.

5.4 Overcoming technological difficulties

All creative enhancement structures discussed in the previous section noted certain technological deficiencies. The incomplete maturity of current technology hinders VR from realizing its full potential in enhancing creativity.

Stability and reliability must be improved to ensure user experience. Current VR systems exhibit poor pragmatic qualities of perspicuity, efficiency, and dependability (Aydin and Aktaş, 2020). Thus, VR technology should pursue comprehensive improvement, especially in terms of real-time rendering, functional structure, and interactions (Zhu and Du, 2021). The CMC system in the virtual world is considerably worse than that in the F2F settings. The delay and misses of information in the virtual world reduced the efficiency of communication between participants working in remote teams (Lee and Do, 2009). Upon allocating task to students in a VR system, they still preferred to use traditional social networks as their communication tool (Bujdosó et al., 2017). Thus, considerable effort is required to overcome these technological difficulties and redesign the CMC system in the virtual world.

Novel HCI and multimodal experience are inevitable aspects of technological development for enhancing the virtual experience beyond real environments. In future, research should explore the application of new technologies to increase immersion and assist in creation. For instance, research has been conducted on integrating haptic interaction with natural materials (sandbox) into VR, although the delay and inaccurate tracking yields inferior user experience (Fröhlich et al., 2018). The LUCID design system implements MMI with haptic and auditory interactions to provide a more intuitive and natural design experience (Ye and Campbell, 2006). The MMI offers great potential but requires further improvement in terms of reliability and flexibility (Zimmerer et al., 2020). In future, research should consider new interaction methods to augment the users' five senses.

The advancement of devices is also a promising direction for technological research under this topic. In our reviewed studies, on the one hand, almost all used wired VR devices driven by computers, such as HTC Vive (Roupé et al., 2020; Lee L. H. et al., 2021) and Oculus Rift (Tabrizian et al., 2017; Jenek et al., 2021), to ensure the performance and visual effects. Google Cardboard VR, on the other hand, was an economical choice in some studies (Whewell et al., 2022). One study used a standalone device Oculus Go but highlighted its limitations in operating time and weak performance (Skrupskaya et al., 2021). A few studies utilized MR technologies, such as Microsoft HoloLens, because its built-in cameras can detect hand motions and gaze, which are key activities in design (Cindioglu et al., 2022). Researchers are also attempting to expand audio–visual capabilities by integrating tangible user interactions or other devices (Yoshida et al., 2000; Schkolne et al., 2001; Tabrizian et al., 2017). Further research is needed in applying novel VR devices combined with interfaces for a natural experience.

We are approaching the "Metaverse," wherein VR technology is essential. Considering the impact of Metaverse on social connection, it can potentially transform the future of design thinking (Robertson and Peters, 2021). In contrast to the more inclusive idea of cyberspace that represents the entire shared online space across all dimensions of representation, Metaverse refers to a completely immersive three-dimensional digital world (Dionisio et al., 2013). Using an avatar and AI technology, Metaverse has already achieved novel forms of team co-creation. For instance, Microsoft Teams has introduced avatars into the system; the avatars are animated based on voice data parsed by AI. Hand gestures and emojis have been implemented to render a more human-like experience (Warren, 2021). This technology works best with an immersive VR hardware, which is primarily used in desktop environment because this technology is not yet mainstream.

The future Metaverse will aid humans in exceeding the limits of their abilities and maximize creativity and collaboration in the design process. As data acquirement is much easier in a virtual world, a creative method of using data may augment its potential in design. For instance, by acquiring human data, a socially aware system can benefit users in reading the climate by visualizing interpersonal relationships or hidden emotions. Moreover, with environmental data, VR can be used as a data visualization tool in architecture (Bartosh and Anzalone, 2019). Concurrently, the avatar can authentically represent users as well as transcend users. Upon modifying the facial appearance of the users, collaborations may become smoother (Nakazato et al., 2014). However, the core technology, VR, and other related technologies, including AI, blockchain, computer vision, networks, edge computing, user interactivity, and robotics, requires further improvement (Lee L. H. et al., 2021).

5.4 Hybrid of virtual and real worlds

Shifting the entire design-thinking process into a virtual space is unrealistic, especially in the near future. Thus, we will experience a hybrid design method to bridge individuals both in online and offline environments to completely utilize the resources from both virtual and real worlds in the near future. In this case, a hybrid type of interaction is expected to act as the future research direction. The hybrid type of interaction is the most practical approach to study because it enables certain activities to be completed through conventional distant contact methods, which enriches and diversifies the learning process to consequently promote educational quality (Skrupskaya et al., 2021).

In certain cases, a collaboration between virtual-world users and real-world participants is required; however, they cannot share the same perspective despite being present in the same physical space. Thus, researchers are developing methods to share the experiences of such participants.

In other cases, VR is used in certain stages of design thinking (e.g., the test stage), because it is an effective communication tool for design reviews. However, fieldwork should be conducted in the real world (Yamada et al., 2017). The virtual and real worlds are combined in the design-thinking process. More studies will be required to the assess the stage that is suitable for VR and to further refine the process if the user has to switch between the virtual and real worlds.

6 Conclusion

This study reviewed relevant publications to understand the mechanisms through which VR technology enhances design-thinking skills as an educational tool and/or a design-thinking toolkit. By reviewing publications from a wide range of disciplines and applications, we aimed to understand the extent to which design-thinking skills have been enhanced in virtual environments and provide future research directions for researchers to strengthen VR as a skill-enhancement tool for design thinking.

This review covered all stages of design thinking, with ideating and prototyping being the most discussed. HMD-enabled immersive VR emerged as the most popular device across most studies that targeted either a generalized population of individuals to improve their creativity or users with specialized professions such as engineering and product design. Most studies were published in journals or conferences on computer or engineering sciences, which constitute approximately 70% of the reviewed publications. Thereafter, we analyzed all publications according to five themes based on the creative enhancement structure of VR. In principle, VR can enhance design thinking by altering the aspects related to self and self-perception by optimizing the interactions and collaboration with others, optimizing environmental conditions and influences, facilitating guidance of gamification of the problem-solving process, and offering an arena for the integration of other technologies of creativity enhancement. This review discussed the potential as well as the limiting challenges of VR technology.

As demonstrated in this review, further research is required on the following aspects to achieve a comprehensive improvement in this field and enhance the positive effects of VR: 1) art, humanities, and societal perspectives; 2) cognition process in VR; 3) emphasizing and defining stage in design-thinking process; 4) technology improvement combined with Metaverse; 5) hybrid of the virtual and real worlds.

This study has several limitations. First, as we discussed in the literature selection part, the terminologies used by researchers vary and some studies in this field may have been missed. The keyword choice may cause selection bias. Secondly, the interpretation of research findings is also affected by the selected model. We may not have been able to cover all the points concerning VR for design thinking. Thirdly, outdated information may be included in this study because of the fast development of VR technology. Some technological difficulties that we discussed may have already been tackled, and new difficulties may be emerging. Future studies should consider the changes caused by the up-to-date technologies. Because VR presents a unique setting for enhancing design-thinking skills, further explorations are expected in the aforementioned research directions.

Author contributions

QL, KW, HU, and AM contributed to the concept and design of the study. QL collected the literature, performed the review, and created the first draft of the manuscript. KW, HU, and AM contributed to manuscript revision, restructuring, and completing the insufficient parts. All authors contributed to the article and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/frvir.2023.1137293/full#supplementary-material

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