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Article

A Systematic Review of Architectural Design Collaboration in Immersive Virtual Environments

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Abstract: Emerging applications of immersive virtual technologies are providing architects and designers with powerful interactive environments for virtual design collaboration, which has been particularly beneficial since 2020 while the architecture, engineering and construction (AEC) industry has experienced an acceleration of remote working. However, there is currently a lack of critical understanding about both the theoretical and technical development of immersive virtual environments (ImVE) for supporting architectural design collaboration. This paper reviewed recent research (since 2010) relating to the topic in a systematic literature review (SLR). Through the four steps of identification, screening, eligibility check, and inclusion of the eligible articles, in total, 29 journal articles were reviewed and discussed from 3 aspects: ImVE in the AEC industry, ImVE for supporting virtual collaboration, and applications of ImVE to support design collaboration. The results of this review suggest that future research and technology development are needed in the following areas: (1) ImVE support for design collaboration, particularly at the early design stage; (2) cognitive research about design collaboration in ImVE, toward the adoption of more innovative and comprehensive methodologies; (3) further enhancements to ImVE technologies to incorporate more needed advanced design features.

Keywords: architectural design collaboration; immersive virtual environments; systematic literature review

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1. Introduction and Background

Traditionally, most architects work and collaborate in face-to-face environments, and virtual collaboration only occurs occasionally, mainly during the latter design stages such as design review. Although the concept of computer-supported cooperative work (CSCW) in the design field has emerged and been extensively studied during the past few decades, in actuality, the area has not seen significant advances throughout that time. With emerging technologies such as immersive virtual environments (ImVE), architects and designers are able to collaborate virtually with more convenience and power. Since 2020, there has been an urgent global acceleration of remote working, leading to a rush of adoption of virtual technologies across most industries, including in the architecture and design sectors.

Design collaboration refers to team-based design activities working toward achieving the shared design goals. Effective collaboration during the initial design stage will lead to fewer problems during the latter, more complex design and construction stages [1]. Design collaboration with multiplicate problem-solving approaches can align different stakeholders' opinions toward a common baseline that can more optimally result in valuable project insights [2]. Tan [3] argues that design collaboration enhances reflection upon the actions of architects within a team. Citing the need for remote collaboration during pandemic times, Kim et al. [4] note that social networking services can increase idea clarification and the sharing of information to support active design collaboration. Combrinck and Porter [5] found that initial stages of design benefit directly from the collaboration between architects and end-users. Design collaboration occurring at the early design stage is significant for achieving design innovation and ultimately optimal design solutions.

Researchers have emphasised that digital modalities and collaboration affect the quality, efficiency, and accuracy of design [6–8]. Virtual collaboration environments enable distributed remote design collaboration, facilitating greater time and cost efficiency in design, and have become increasingly relevant and crucial since 2020. Early studies have explored the application of shared digital environments in design collaboration during the design phase [9–11], including the effects of those environments on designers. For example, Gu et al. [12] suggested that 3D virtual worlds support the production of considerable perceptual events during synchronous design collaboration. Recent developments in ImVE facilitate intuitive virtual interactions between designers, and also between designers and the design environments [13], leading to better spatial perception [14] that may be beneficial for the design process. ImVE refers to virtual environments in which the users can "immerse" themselves inside the computer-generated world and feel they are in fact an integral part [15]. This can be achieved by using head-mounted displays (HMD) or multiple projections [16]. Virtual reality (VR), augmented reality (AR), and mixed reality (MR) are typical categories of ImVE systems that allow different degrees of interactions between the physical and the virtual worlds supporting building projects with different complexity and diversity [17]: VR is a computing technique that immersively manipulates the user's senses to make him/her feel present in a simulated virtual environment [18,19]; AR on the other hand superimposes virtual information upon the real world in a graphical manner via digital computing platforms to deliver enhanced experiences of the real world [20]; and MR is a combination of AR and augmented virtuality (AV), with the potential to integrate virtual and augmented realities together [21].

In light of the increasing application of ImVE within the architecture, engineering and construction (AEC) industry, it is important to critically understand how ImVE supports design collaboration. This study has reviewed the recent (since 2010) research in this area, to reveal the current body of knowledge and different applications of ImVE for supporting design collaboration, as well as potential future research directions to further advance the field.

2. Research Method- Systematic Literature Review

This study adopts the research method of systematic literature review (SLR) to review current research on design collaboration in ImVE and synthesise further knowledge about the field. SLR is an authoritative procedural method that synthesises and delineates the boundaries of knowledge in a research domain [22,23]. In accordance with common SLR research conventions, this study adopted a four-stage SLR to review the published articles related to design collaboration in ImVE, comprising a widespread literature search, full text assessment, meta-synthesis, and critical content analysis. The following sections elaborate on the details and steps of SLR. The article retrieval process is shown in Figure 1 below. Through the 4 steps of identification, screening, eligibility check, and inclusion of the eligible articles, ultimately 29 articles were selected for analysis from the initial 1106 papers identified. The relatively small number of articles that were closely related to the topic shows that architectural design collaboration in immersive virtual environments has not been extensively explored in the field, and this in turn supports the needs for this review and for future research.

2.1. Selection of Databases and Literature Search

The SLR process should be reinforced by a detailed and impartial search in specifying relevant research. A choice of database selection that ensures a broad coverage of research must be identified and used. In this regard, this study uses Scopus and Web of Science (WoS), the two most significant platforms for article retrieval. These two databases offer a wide coverage of literature and are feasible for conducting organised queries. Past reviews have used similar databases for article selection in the AEC industry [24,25]. Firstly, prominent keywords related to architectural design collaboration and ImVE were identified, and in the next step, a number of keywords having similar semantic meanings were merged. The resulting search string used for this study was as follows:

[TITLE-ABS-KEY ("architectural design" OR architecture) AND TITLE-ABS-KEY ("collaboration" OR "design collaboration") AND TITLE-ABS-KEY ("virtual reality" OR "augmented reality" OR "mixed reality" OR "immers* techn*" OR "virtual environment*")]. A total of 689 articles from *Scopus* and 417 articles from *WoS* were identified via the search.

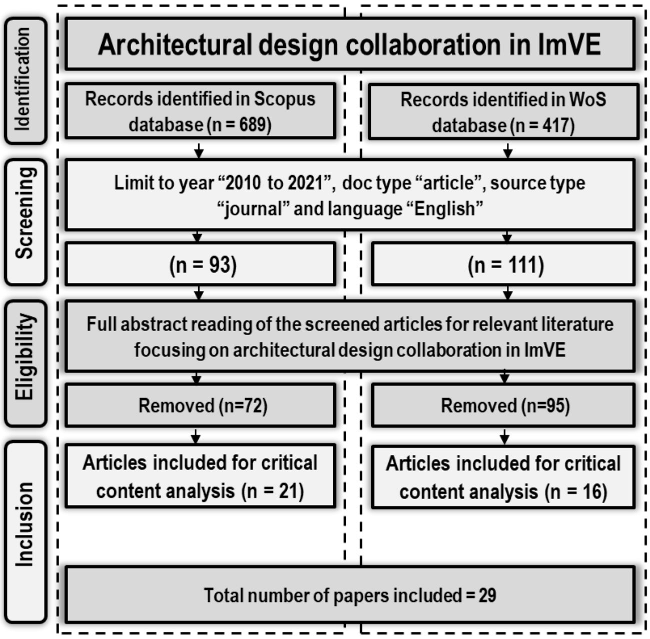

Figure 1. Article retrieval process (data was collected in March 2022).

2.2. Screening of Articles

The screening of the articles provides and constitutes the benchmark utilised in the SLR process for filtering the pool of articles. At this stage, this filtering was performed based on year, document type, source type, and the language of articles. The applied filtering procedure is as follows: [(LIMIT-TO (YEAR, "2010-present") AND (LIMIT-TO (DOCTYPE, "ar") AND (LIMIT-TO (SRCTYPE, "j") AND (LIMIT-TO (LANGUAGE, "English")]. The articles considered for this study were limited to recent ones (from 2010, in accordance with the prominent boom of ImVE). In relation to document type and source type, only peer-reviewed journals articles were considered for the study; since journal articles go through a more rigorous peer review process and provide more in-depth knowledge than other research articles such as conference papers. Finally, non-English language articles were filtered out. This stage resulted in a total of 93 articles from Scopus and 111 articles from WoS.

2.3. Eligibility and Inclusion Criteria of Articles

In this step, eligibility and inclusion criteria were developed to narrow down the articles relevant to the specific focus of this study: criteria such as abstract review, keywords, evaluation of conclusions, and results were applied to the articles from the previous step. Papers with a focus on ImVE but for health care, manufacturing, and other domains were removed at this stage. This stage resulted in a total of 21 articles from Scopus and 16 articles from WoS. Articles which were identified as duplicates in both search engines were then merged. In the end, a total of 29 articles were for this study, which is a significant number for critical content analysis. This sample size is favourable compared with other similar reviews.

2.4. Meta-Synthesis and Critical Content Analysis of Articles

Meta-synthesis refers to the analysis of metadata within the pool of articles in the SLR process [26]. It augments the SLR process by extracting the metadata from each article and is utilised to provide a basis for organising a framework for the study [27]. Information such as journal name, year of publication, focus of research, and limitations constitutes metadata and was organised in a tabular format into an Excel file. This comprehensive table can be described as an "idea thought matrix supplemented by components of analysis" [26]. The articles were then categorised further into research themes, emphasising commonalities among them to form clusters from among the retrieved articles; this process is called critical content analysis, and it facilitates establishing the current status quo and developing future trends in the domain of study [28].

3. Results

3.1. Publication Trend of Architectural Design Collaboration in ImVE

The articles in this study were limited to those from the year 2010 to present, due to the rise of ImVE only being significantly noticeable over the last decade, and this focus is more likely to deliver the latest advancements and status quo in the specific subject area. Figure 2 depicts the annual trends in research publications on the topic. From the figure, we can see that the period of time between 2010 to 2013 only has up to 3 articles per year, as this period marks the inception of ImVE in the architecture field (where architects found ImVE to be a novel design collaboration tool and could engage clients and other stakeholders in a more intuitive way). In 2014, the social media company Meta promoted its Oculus VR headset, which resulted in a substantial amount of awareness to the public. However, this did not result in increasing number of research publications in this area, due to a number of reasons; firstly, there were significant barriers encountered by the AEC industry for adopting ImVE devices including low battery life, tracking issues, interoperability concerns, and relatively high degree of skills required from users [17], and secondly the AEC industry comprises of large number of small and medium-sized enterprises (SMEs) that lacked interests in adopting ImVE due to the relatively high costs, capital required for training, and other significant obstacles [24]. A surge in the number of papers is seen from 2017 on the use of ImVE for design collaboration. This is because technological advancements seen in the latest ImVEs have resolved major prior concerns and issues. Further surge in demand resulting from the COVID-19 pandemic has brought such applications of ImVE to the broader industry. Virtual collaboration has never carried more necessity and meaning than in the recent times of the COVID-19 pandemic, which saw a general upwelling of interest among researchers since 2020 [29]. Such upward trends in this area makes this study especially timely and valuable in its analysis of the status quo, emergent themes, and future research directions for design collaboration in ImVE. Note that in Figure 2 the upward trend is not seen in the 2022 data point, as this study's data collection was only completed in March 2022.

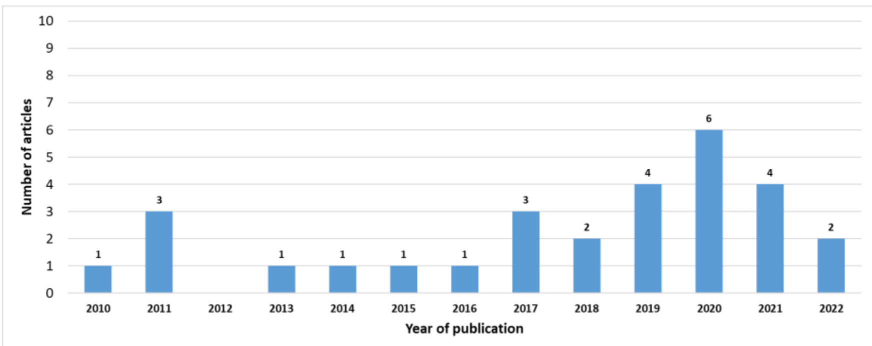

Figure 2. Annal publication trend of articles for design collaboration in ImVE.

3.2. Distribution of Journals for Publishing the Topic

The 29 articles included in this study were published across a total of 17 journals. Table 1 lists the journals, and the number of articles published. Six journals published at least two articles each, with the top contributing journals being *Automation in Construction* (7) and *Journal of Information Technology in Construction* (4). The analysis of journals provides a summary for researchers who may conduct similar kinds of studies. Other main journals include *Visualisation in Engineering, Frontiers in Robotics and AI,* and *Journal of Higher Education Theory and Practice*. Together, they have illustrated the applications and benefits of ImVE from a wide range of perspectives, such as automating the design collaboration process, providing better visualisations for end users, and promoting the use of information technologies within the AEC field.

Table 1 categorises the 29 articles about architectural design collaboration in ImVE that have been reviewed. The table also organises these current studies in terms of the type of technology, focus of design collaboration, main research content, and project stage in which ImVE has supported design collaboration. The results of the review are further discussed in Section 4.

Table 1. Reviewed articles on design collaboration in ImVE.

No.	Journal	Author & Year	Article Title	Type of ImVR	Focus of Design Collaboration	Main Research Content	Project Stage
1	Automation in Construction	[30]	A multi-user collaborative BIM-AR system to support design and construction	BIM and AR	Multi-stakeholder collaboration	Presented a BIM-AR system that provides the ability to view, interact with, and collaborate with 3D and 2D BIM data via AR with geographically dispersed teams.	Multiple stages
2	Automation in Construction	[31]	From BIM to extended reality in AEC industry	Extended reality	Technologies for construction collaboration between stakeholders	Explored outsourcing patterns for technologies among construction project stakeholders.	Multiple stages
3	Automation in Construction	[32]	Virtual reality applications for the built environment: Research trends and opportunities	VR	Design collaboration, multi-user virtual construction	Review paper; reviewed VR applications in AEC.	Multiple stages
4	Automation in Construction	[33]	OpenBIM-Tango integrated virtual showroom for offsite manufactured production of self-build housing	BIM, VR, and AR	Early involvement of stakeholders and end-users	Streamlined the design process and provided a pared-down agnostic openBIM system with low latency and included concurrent user accessibility.	Design stage
5	Automation in Construction	[34]	Zero latency: Real-time synchronization of BIM data in Virtual Reality for collaborative decision-making	BIM and VR	Improvement of collaboration in AEC industry	Proposed a BIM VR real-time synchronisation system based on an innovative cloud-based BIM metadata interpretation and communication method.	Design stage
6	Automation in Construction	[35]	Immersive virtual environments versus physical built environments: A benchmarking study for building design and user-built environment explorations	Immersive virtual environments	End-user involvement	Explored the use of immersive virtual environments during the design, construction, and operation phases of AEC projects.	Multiple stages

Table 1. *Cont.*

No.	Journal	Author & Year	Article Title	Type of ImVR	Focus of Design Collaboration	Main Research Content	Project Stage
7	Automation in Construction	[12]	Technological advancements in synchronous collaboration: The effect of 3D virtual worlds and tangible user interfaces on architectural design	3d virtual worlds and tangible user interface	Design collaboration	Presented and evaluated two current advancements of collaborative technologies for architectural design.	Design stage
8	Journal of Information Technology in Construction	[36]	The impact of avatars, social norms and copresence on the collaboration effectiveness of AEC virtual teams	VR	Virtual team collaboration on AEC project	Review paper; examined collaboration effectiveness of global virtual engineering project teams.	Multiple stages
9	Journal of Information Technology in Construction	[37]	Virtual Reality for the built environment: A critical review of recent advances	VR and virtual environment applications	Benefits for collaboration	Review paper; presented a classification framework to reveal the scholarly coverage of VR and virtual environment.	Multiple stages
10	Journal of Information Technology in Construction	[38]	Case studies using multiuser virtual worlds as an innovative platform for collaborative design	Multi-user virtual worlds	Collaboration between designers	Investigated the innovative use of emerging multiuser virtual world technologies for supporting human–human collaboration and human–computer co-creativity in design.	Design stage
11	Journal of Information Technology in Construction	[39]	Framework for model-based competency management for design in physical and virtual worlds	Virtual worlds	Design collaboration	Explored differences and commonalities in competencies for design in the physical and virtual worlds by examining design input, process, and outcome.	Design stage
12	Journal of Construction Engineering and Management	[24]	State-of-the-Art review on Mixed Reality applications in the AECO industry	MR	Multi-user collaboration	Review paper; reviewed MR technology applications in the AECO industry.	Multiple stages

Table 1. *Cont.*

No.	Journal	Author & Year	Article Title	Type of ImVR	Focus of Design Collaboration	Main Research Content	Project Stage
13	Journal of Construction Engineering and Management	[40]	Virtual collaborative design environment: Supporting seamless integration of multitouch table and immersive VR	VR	Multi-stakeholder collaboration	Presented the design and evaluation of a virtual collaborative design environment.	Design stage
14	Applied Sciences (Switzerland)	[41]	Developing a BIM-based MUVR treadmill system for architectural design review and collaboration	BIM based Multi-user VR	High-level immersion in architectural design review and collaboration	Presented a system framework that integrates multi-user virtual reality (MUVR) applications into omnidirectional treadmills.	Design review
15	Applied Sciences (Switzerland)	[25]	End-Users' Augmented Reality utilization for architectural design review	AR	End-user involvement in design review	Investigated how the AR system affects architectural design review from users' perspectives.	Design review
16	Applied Sciences (Switzerland)	[42]	Trends and research issues of Augmented Reality studies in architectural and civil engineering education—A review of academic journal publications	AR	Collaboration between academia and practice	Review paper; reviewed AR in AEC education, with a focus on collaboration promoting optimal connection between general pedagogy and domain-specific learning.	Multiple stages
17	Journal of Engineering, Design and Technology	[43]	Multiuser immersive Virtual Reality application for real-time remote collaboration to enhance design review process in the social distancing era	Immersive VR	Collaboration in design review	Explored design review process conducted among participants remotely located.	Design review
18	International Journal of Digital Earth	[44]	Immersive Virtual Reality for extending the potential of building information modeling in architecture, engineering, and construction sector: systematic review	Building Information Modelling (BIM) and Immersive VR	Communication and collaboration in design, construction, operation, and maintenance phases	Review paper; reviewed most commonly adopted technologies, applications, and evaluation methods of VR.	Multiple stages

Table 1. *Cont.*

No.	Journal	Author & Year	Article Title	Type of ImVR	Focus of Design Collaboration	Main Research Content	Project Stage
19	Journal of Computational Design and Engineering	[45]	Evaluation framework for BIM-based VR applications in design phase	BIM and VR	Multi-user collaboration	Developed an evaluation framework for BIM-based VR applications focused on the design phase of projects.	Design stage
20	Journal of Higher Education Theory and Practice	[46]	Innovation in architecture education: Collaborative learning method through Virtual Reality	VR	Collaborative learning	Review paper; reviewed VR encounters and long-term collaborative learning approaches.	Design education
21	Construction Innovation	[47]	Using Virtual Reality to facilitate communication in the AEC domain: A systematic review	VR	Multi-stakeholder collaboration	Review paper; explored how VR has been applied for communication purposes in AEC.	Multiple stages
22	Environment and Planning B-Urban Analytics and City Science	[48]	Architectural design creativity in multi-user virtual environment: A comparative analysis between remote collaboration media	VR	Multi-user virtual environments	Investigated the affordance of multi-user virtual environments for the production of novel and appropriate solutions in remote collaboration.	Design stage
23	Frontiers in Robotics and AI	[49]	Laypeople's collaborative immersive Virtual Reality design discourse in neighborhood design	VR	Virtual participatory urban design	Protocol study; explored design communication and participation of laypeople in a virtual participatory urban design process.	Design stage
24	Advanced Engineering Informatics	[50]	Overlay design methodology for virtual environment design within digital games	VR	Design collaboration	Protocol study; explored the use of overlay design methodology for the creation of virtual environments within digital gaming contexts.	Design stage
25	Visualization in Engineering	[51]	Virtual Reality-integrated workflow in BIM-enabled projects collaboration and design review: A case study	BIM and VR	Collaboration in design review	Developed and tested a VR integrated collaboration workflow.	Design review

Table 1. *Cont.*

No.	Journal	Author & Year	Article Title	Type of ImVR	Focus of Design Collaboration	Main Research Content	Project Stage
26	Journal of Digital Landscape Architecture	[52]	Using Virtual Reality as a design input: Impacts on collaboration in a university design studio setting	Immersive VR	Student learning and group collaboration	Presented the application of immersive VR to assist landscape architecture students in design.	Design education
27	Co-Design	[53]	Enablers and barriers of the multi-user virtual environment for exploratory creativity in architectural design collaboration	Multi-user virtual environment	Architectural design collaboration	Explored the design collaboration process using multi-user virtual environment and sketching media in face-to-face and remote collaboration modes.	Design stage
28	Computers in Industry	[54]	Mutual awareness in collaborative design: An Augmented Reality integrated telepresence system	AR	Design collaboration	Proposed a new computer-mediated remote collaborative design system, TeleAR, to enhance the distributed cognition among remote designers.	Design stage
29	IEEE Transactions on Visualization and Computer Graphics	[55]	A spatially Augmented Reality sketching interface for architectural daylighting design	AR	Collaboration between designers and end-users	Presented an application of interactive global illumination and spatially augmented reality to architectural daylight modelling.	Design stage

4. Discussion

During past decades, emerging immersive virtual technologies have significantly changed the nature of collaboration in the AEC industry at various stages of a building project including design. Technological advancements create new design environments for designers and make virtual collaboration possible, which also have an impact on designers' thinking processes as well as on the design solutions they produced [56]. This section discusses the current state of theoretical and technical developments about immersive virtual technologies, and their applications in supporting design collaboration from various perspectives, as revealed from the critical review.

4.1. Immersive Virtual Technologies and It's Attributes in the AEC Industry

One of the most significant obstacles for current design technologies has been the immersion of the relevant stakeholder in the design representation during different stages of the project. Table 1 shows that the term "immersive" is increasingly being seen in design collaboration research since 2015. Prior to 2015, researchers used alternative terms such as "virtual worlds", and "multi-user virtual worlds". Despite possessing numerous advantages for streamlining the process of design, design technologies have not provided adequate immersive presence for its users. The importance of presence when visualising a design solution is significant in the AEC industry for realising the aesthetic appearance of a space, simulating the functionality of the design, and enabling users to effectively experience the place in terms of other factors such as safety and ergonomics. Advancements in digital design technologies including ImVE have supplied architects with a myriad of opportunities, for visualising the appearance and performance of their designs [57].

Recent broader adoption of computing technologies have enabled designers to more readily utilise ImVE in practice. Conceptually, an ImVE system can be predominantly classified into four categories of elements, namely devices, platforms, applications, and tools (Figure 3).

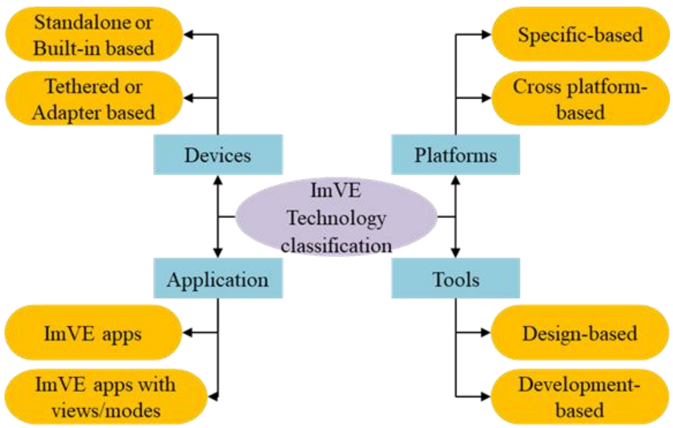

Figure 3. The conceptual model of an ImVE system.

The first category elements in the model is devices, which can be subdivided into standalone or built-in, and tethered or adapter based. The VR Quest series by Meta is a typical example of a standalone VR device, although it can also be optionally tethered to give it more rendering power. The Oculus Rift seriesis a more recent tethered models that needs to be connected to a computer through a cable. One of the earliest examples of adapter-based devices is Google Cardboard, which simply wraps around a smartphone. In relation to AR, examples such as Microsoft HoloLens act as a standalone device incorporating high-level computing capabilities. On the other hand, Holokit act as adapter based AR device using Apple ARKit enabled smartphones. There has been continuous advancement among ImVE devices with companies such as HTC, Microsoft, and Meta developing high-end devices with significant enhancements to the visual field of view, storage capacities, ergonomics, and graphics rendering to name a few. The second category of elements relates to the software platforms that serve as the basis for devices to work; such platforms can be subdivided further into specific and cross platforms. Companies such as Meta, HTC, and Magic Leap provide their own proprietary software platforms for their devices to function, while cross platforms (sometimes referred to as open platforms) allow different hardware devices to function on the same software platform. Steam VR, Windows Mixed Reality (WMR), and WebXR are examples of such open or cross platforms. The third category pertains to ImVE applications, which are subdivided into ImVE applications alone and ImVE applications with views and modes. The difference between those two relates to their real-world integration and communication. Most typically, VR applications are without real-world integration, while AR/MR applications possess real-world interaction capabilities. Finally, the fourth-category elements relate to ImVE tools that are either design based or development based. Tools such as Tilt Brush, Quill, and Aero are design oriented and are common among designers such as architects. Development tools such as Unity and Unreal Engine are significant tools for creating VR and AR visualisations respectively.

Based on data from the online market data portal Statista, the market size of ImVE is predicted to increase vastly in the coming years, from 30.7 billion USD in 2021 to 296.9 billion USD in 2024. This is indicative of the future demand for ImVE and its related technologies and applications across many industries. Figure 4 shows the main ImVE types and their usage comparison data obtained from Statista for actual 2020 and predicted 2024. From the figure, we can see that in 2020, all VR-related technologies were utilised more than AR-related technologies. Among them the VR standalone HMDs were the most popular immersive technology (accounted for 43.76%). However, for 2024 the prediction is that AR-related technologies combined will be utilised more than VR combined, and among the AR technologies the AR standalone HMDs will have the highest usage (accounted for 31.28%). AR represents the superimposition of the virtual information over the real world to construct the synthetic environment aiming to enrich reality [58]), and the growing trend of research shifting away from VR and toward AR/MR can also be noticed in the ImVR literature that was reviewed (Figure 5). In the figure, we can see that although most of the reviewed articles focused on VR-related ImVE technologies, in recent years, there is a visible increase of AR/MR utilisation in design collaboration. The growing application of AR technologies for design collaboration may due to the fact that AR technologies were based on early VR technologies that had been developed to extend VR technologies, focusing on the capability of augmenting the real world with virtual information, allowing real and virtual information to coexist and at a same time making user interactions more intuitive through references to reality [59].

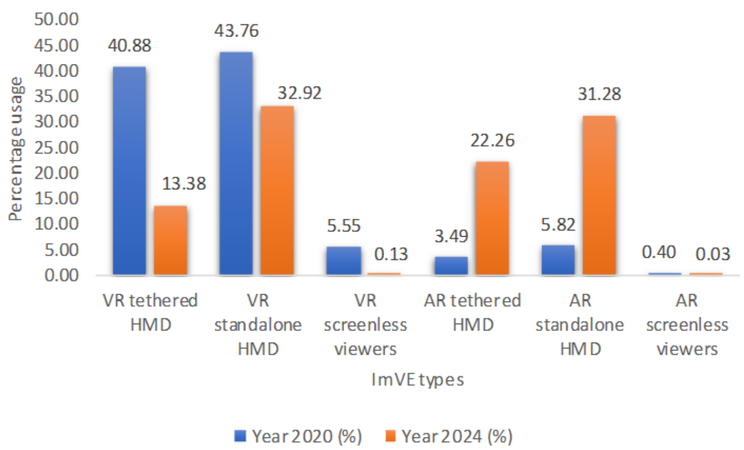

Figure 4. Main ImVE types and their usage comparison (Source: Statista).

Some of the main attributes of ImVE include presence, immersion, and interactivity [60,61]. Presence describes the complete feeling of being in an immersive simulated space, wherein the user is psychologically immersed in the virtual environment in a manner that they temporarily escape their real world [62–64]. The immersion level is affected by the sophistication of the simulation in terms of the quality of its visual representation, consistency, freedom of movement of the user, and physical interaction/feedback functionality within the ImVE. The interactivity level indicates to what extent a user is able to alter the ImVE in real-time [65]. Additionally, immersive AR technologies are able to augment real world spaces with overlayed virtual information in a manner such that real and virtual information can coexist simultaneously to enable enhanced intuitive user interactions [59].

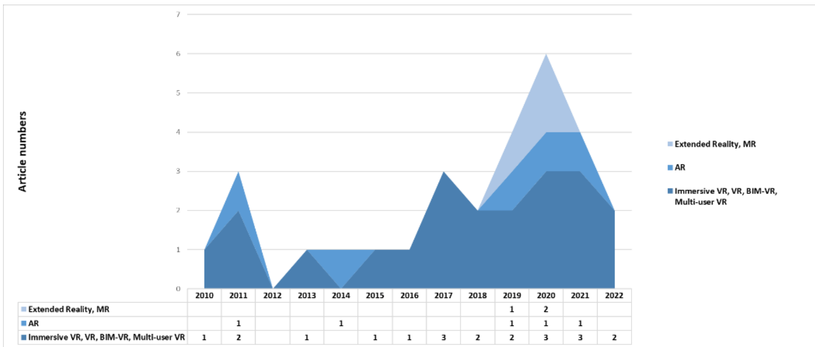

Figure 5. Types of ImVE technologies the review articles focused on.

4.2. ImVE in Supporting Virtual Collaboration

Virtual collaboration tools currently in use within the AEC industry largely focus on design review or construction scheduling, such as Unity Reflect Review, Resolve, Trezi, Fuzor, and BIM 360. A few recently emerging tools are intended for use in the design ideation stage, including Wild, Mindesk, and Arkio. For design ideation purposes, most tools support importing 3D models from commonly used architectural design software such as Revit and SketchUp. Mindesk and Arkio support the use of Grasshopper, which is a popular parametric design tool for design ideation in architecture. Arkio provides functions including real-time Boolean operations, sun studies, smart guides for geometry alignment and creation, integrated street maps, etc., which can support a range of design ideation purposes. For design collaboration, Wild provides native digital sketching tools for both ideation and as (speech to text) annotation for design review. Mindesk allows teams to collaborate on the same parametric model in multi-user VR sessions. Arkio on the other hand focuses on supporting multi-user model modification during design collaboration. All of the aforementioned virtual collaboration tools enable access via VR including desktop VR options that are convenient for users without headsets. Wild and Arkio also allow mobile access for users. Another virtual collaboration tool Hyve 3D, is primarily focused on providing 3D sketching in immersive design environments, to support both ideation and remote collaboration. Hyve 3D requires a Macbook, iPad Pros, and a 4K projector but a VR headset is not needed to have the immersive experience. Table 2 summarises the main ImVE used for virtual design collaboration in the AEC industry. In addition, generic communication and collaboration tools are also used in the AEC practice, including Teams, Zoom, Slack, etc. Some of those generic tools also provides certain visual collaboration functions, for example, Miro has a 2D digital whiteboard for supporting brainstorming, Asana can assist with project workflow planning with a visual timeline and calendar, and as Jira can be linked to Navisworks and allow the display of 3D models. From the table, we can see that there are recently developed design collaboration tools utilising ImVE technologies, some of which are focused on application at the early design stage. However, they are not yet widely adopted throughout the AEC industry. Furthermore, the review results suggest that academic research has fallen behind the technological advancement, and there is a lack of understanding of how the recently developed ImVE technologies support design collaboration, particularly at the early design stage.

Table 2. Virtual design collaboration tools in the AEC industry (Source: respective official website of each individual platform).

Virtual Design Collaboration Tools	Project Stages	Collaboration Means	Interoperability	Accessibility	Design Support
The Wild (https://thewild.com/)	Multiple stages	Annotation (speech to text) for design review	Revit, SketchUp, BIM 360	VR, desktop or mobile	Sketching, Inspection of object BIM data
IrisVR (joined Wild) (https://irisvr.com/)	Multiple stages	Optimised *Revit* to VR workflow, multi-user meetings, collaborative tracking, annotation, other user controls, BIM coordination.	Revit, Sketchup, Navisworks, Rhino	VR or desktop	Inspection of elements, tape measure, scale model mode, sun studies
Generic communication tools such as Zoom (https://zoom.us/), Teams (https://www.microsoft.com/en-au/microsoft-teams/log-in (accessed on 12 September 2022)), Slack (https://slack.com/intl/en-au/in (accessed on 12 September 2022)), Miro (https://miro.com/), Asana (https://asana.com/).	Multiple stages	Multi-user meeting, 3D model viewing, 2D shared white board, visual timeline, calendar, chat box	-	-	3D model viewing, 2D drawing sharing.
Fuzor (https://www.kalloctech.com/)	Multiple stages with a focus on construction	Multi-user view	Revit, Rhino	VR, desktop or mobile	Flythrough and walkthrough videos
BIM 360 (https://www.autodesk.com/bim-360/in (accessed on 12 September 2022))	Multiple stages with a focus on construction	Multi-user model modification	BIM	Desktop	Model modification
Hyve3D (https://www.hyve3d.com/)	Ideation	Multi-user model modification, sketching	Can import model from Revit, SketchUp, but primarily focus on sketching	Need iPad Pro, Macbook Pro, and 4K projector, but does not require a headset	3D sketching simultaneously in complementary (orthogonal) representations.

Table 2. *Cont.*

Virtual Design Collaboration Tools	Project Stages	Collaboration Means	Interoperability	Accessibility	Design Support
Arkio (https://www.arkio.is/)	Ideation, modelling	Multi-user model modification, sketching	Revit, SketchUp, BIM 360, Rhnio	AR/VR or mobile	Parametric design, sketching, real-time Boolean operations and parametric volumes, sun studies, PC spectator mode, see inside with sections, smart guides, integrated street map, and instantly enable 3D buildings from OpenStreetMap, etc.
Mindesk (https://mindeskvr.com/)	Ideation, design review	3D/surface modelling, multi-user model modification, navigation, selection, review and co-presence and use of body language for communication	Revit, Rhino, Grasshopper, Solid works	VR or desktop	Parametric design, Unreal Studio and OBS Studio for VR
Theia BigRoom (upcoming) (https://www.theia.io/bigroom/in (accessed on 12 September 2022))	Design review	Multi-user meeting, 3D sketching tools, whiteboard drawing tools, ideation boards, task lists and post-it notes	BIM	VR, desktop or mobile	Unreal engine, interactive sun + sky.
Unity Reflect review (https://unity.com/products/unity-reflect-reviewin (accessed on 12 September 2022))	Design review	Walkthroughs in VR and AR, annotation, and filter BIM data to effectively communicate design intent to stakeholders	Revit, SketchUp, BIM 360, Navisworks, Rhino	AR/VR, desktop, or mobile	Sun studies, overlay models in 1:1 AR at scale (marker-based or tabletop)
Resolve (https://www.resolvebim.com/)	Design review, facility management	Annotation (speech to text), multi-user meeting	BIM	VR or desktop	Annotate by measuring and sketching, issue tracking integration with BIM 360, inspect BIM properties
Trezi (https://trezi.com/)	Manufacturing	Multi-user meeting	BIM	VR or desktop	Model modification, design review

4.3. Applications of ImVE in Supporting Design Collaboration

ImVE provides opportunities for designers and other stakeholders to work collaboratively in a shared virtual environment. In the AEC industry, ImVE combining with standard design and collaboration platforms specific to the sector such as BIM have significantly enhanced communication and collaboration across design, construction, operation, and maintenance stages [44]. This study reviewed recent research on design collaboration in ImVE. As shown in Figure 6, 15 out of 29 articles focus on the design stage, 10 articles discuss collaboration across multiple stages including design of a building project, and 4 articles focus on design review. Collaboration research focussing on the design stage in ImVE covers a wide range of topics including the development of various VR environments or frameworks to support design collaboration [40,45], cognitive exploration on how designers collaborate in VR environments [49,50], and in an education context, virtual design studio through VR collaboration [46,52]. Articles focussing on design review discuss various directions including developing a BIM-based multi-user VR system for architectural design review and collaboration [41], investigating how AR affects architectural design reviews based on the user's perspectives [25], and integrating VR into collaboration workflow [51]. For articles focussing on collaboration in ImVE across multiple stages or in the general AEC context, some present relevant ImVE applications [44,47] and other advance technical developments of ImVE, especially by combining with BIM, to facilitate collaboration [30,35]. The review of the 29 articles has identified 3 main application areas of ImVE in supporting design collaboration: (1) design review with end-users and other stakeholders in ImVE; (2) visual data in BIM-based ImVE for supporting design collaboration; and (3) cognition and education in collaborative ImVE. These three application areas will be further discussed as follows.

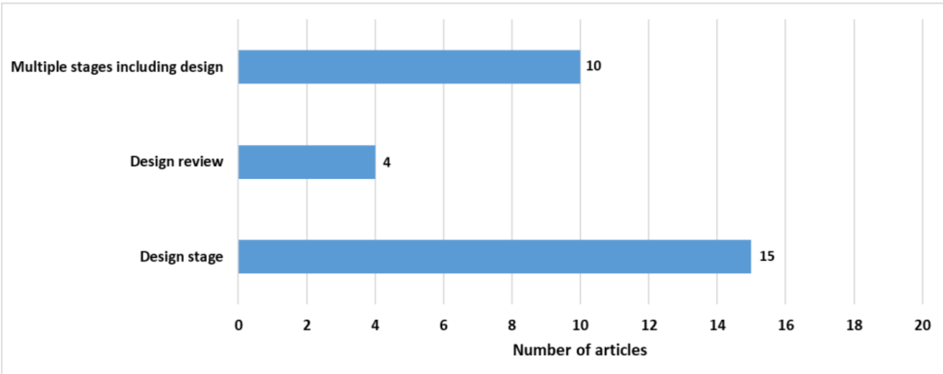

Figure 6. Number of articles focusing on different project stages.

4.3.1. Design Review with End-Users and Other Stakeholders in ImVE

In current practice, architects have embraced ImVE in the participatory process to engage with end-users and to obtain their feedback. For instance, Pour Rahimian et al. [33] consider VR an effective tool for end-user engagement due to the advanced visual communication of building design, and a dynamic feedback initiator. Whether by simulating the realistic scale of the building, or functional aspects of the design, or other end-users experiences such as safety, ImVE has enabled telepresence for different stakeholders including clients, end-users and authorities [56]. ImVE can be intimidating initially for new users especially outside the professional project team, as it involves various hardware and software setup. However, the benefits of ImVR are enormous, as it can leverage the showcase of virtual models to clients in a superior way [66], enabling them with a more thorough understanding of the design and better align the business- client requirements. As a result, design professionals including architects are increasingly using VR for design showcase [67].

ImVE delivers spatial information and at the same time allows collaborative communication. In the AEC disciplines, the goal of including clients during the design process beyond the final showcase—clients who often have limited spatial comprehension and limited specialist knowledge—is to improve both design quality and client satisfaction [33,68], and has gained increasing popularity in the sector. Similarly, Heydarian et al. [35] also find that ImVE is an effective tool in the design phase of a building project in terms of acquiring performance feedback from end users. These benefits are evident in all types of ImVE. For example, VR has been considered to engage clients to the project in an inclusive way [35], and could be more effective than the traditional approach for design review [43]. Lee et al. [25] suggest that AR is effective in reviewing the visual elements of a building and leads to a higher degree of satisfaction in terms of user experience. AR could be an effective platform to investigate evaluate the appearances of a virtual model and to examine the user experience in the design review process [25]. Sheng et al. [55] present an application of an interactive AR application to architectural daylight modelling in which designers and end users can review and have their input on the daylighting design. The involvement of end users leads to higher performing design and end user satisfaction. MR has shown potential in increasing the spatial understanding of end users [69], to allow the interpretation and translation of virtual content through wearable devices [70]. Enabling an end user to experience a realistic and immersive visualisation of a building project, has a different effect on an end user's cognition, and can reveal new possibilities. Unlike AEC professionals, end users are unable to be effectively related to two-dimensional drafting documents. Standard BIM models, despite having multiple advantages over drawings, still lack in leveraging the experiences of the end users to critically understand the design. It is therefore necessary to utilise BIM combing with immersive technologies in participatory design to adequately support end users' decision-making processes [71]. Combining BIM and immersive technologies can also bring many other benefits. For example, the ability to allow collaborators to interact with BIM models without being physically together at different stages of a building project, can be achieved via VR. Zaker and Coloma [51] further suggest that VR collaboration in the design review is beneficial for a wide range of disciplines involved.

Early design review and visualisation, optimisation of building performance analysis, and building maintenance and operations, are possible areas where MR integration can improve the delivery of the building project [24]. The rapid development in MR technologies has significant potential for the AEC industry by combining digital- and real-world information, which is beneficial for design collaboration [69]. MR collaboration can be face-to-face or remote. Face-to-face MR collaboration is achieved by using a shared coordinate system, where collaborators interact with the same set of virtual data information in person [72]. In remote MR collaboration, remote data sharing and remote collaboration are both accomplished utilising the MR platform [73]. Currently, MR collaboration has not been widely adopted within the AEC industry, and there is especially a lack of applications for remote MR collaboration, despite that such applications are likely to benefit AEC professionals to communicate and interact across distributed locations, due to its strong capability of integrating both digital- and physical-world information [24].

4.3.2. Data Visualisation in BIM-Based ImVE for Supporting Design Collaboration

BIM combining with ImVE enable collaboration among multiple parties via both two dimensional and three-dimensional models [74]. Data visualisation in BIM-based ImVE can effectively support and improve design collaboration; in particular, the data visualisation in immersive BIM-based VR environments during the design process can potentially facilitate a deeper understanding among collaborators [75], which can make real-time visualisation and communication more accurate during design [76,77]. Additionally, studies suggest that the barriers in BIM-VR data exchange need further exploration, which may otherwise limit applications of VR within the AEC industry [44]. For example, Du et al. [34] introduced a real-time synchronisation system for BIM-based VR, which is cloud-based, and updates changes to the BIM model and VR model simultaneously to facilitate effective data exchange.

BIM-based AR enriches the real world with digital data by providing more dynamic outcomes with real-time visualisations through a seamless management process [78], hence BIM-based AR environments have potential to benefit design collaboration, by supporting richer interactions and media representations [79]. Visualising and sharing of information by multiple users through AR can augment the real environment by embedding relevant digital data for supporting design decision-making. Overall, by combining the real and the digital, AR can improve designers' information processing and communication [80] and offer subsequent benefits in terms of project visualisation, monitoring, and control [81]. One example of a BIM-based AR system was developed by Garbett et al. [30], which allows distributed teams to view, interact and collaborate on both 3D and 2D BIM data via AR. The other immersive technology—MR—can also be used to enhance BIM model information and its visualisation, feeding mixed-reality representations back to the original BIM model during the design process [82]. BIM-MR integration can potentially further enhance the visualisation of the BIM model, along with supporting more context-aware interactions between the designers and between the designers and the design environment [33]. However, one of the main limitations in BIM-MR integration is the amount of data and details of a BIM model, which is at times not required and not appropriate for an effective corresponding MR application. Therefore, timely data-keeping, and dropping of non-required BIM data, should be addressed in future studies to improve the performance of BIM-based MR applications for design collaboration. Future data storage technologies supported by cloud computing will also help addressing this issue, and can expand the potential utilisation of BIM-based MR applications, to include large-scale collaborative projects, which tend to produce significant amounts of data. Data storage and transfer, together with other issues such as the accuracy of spatial registration, user interface, and multi-user collaboration have been suggested to be key areas for future MR research [24].

4.3.3. Design Cognition and Education in Collaborative ImVE

The exploration of design perception, design physiology, and design cognition and neurocognition in a collaborative environment can generate the knowledge needed in order to support improved design patterns, creativity, and reasoning among multiple users to support their designing and collaboration [83]. Research shows that ImVE aids designers' cognitive processes such as those related to working memory, design data search and access, spatial cognition, and attention allocation. Particularly, ImVE has a positive effect on users' perception and memory [75,77]. Hermund et al. [84] determined that immersive VR representations during the design process were less demanding on designers' cognitive load than traditional 3D visualisation on desktop computers. Design is not a linear process, since designers typically formulate a design problem and develop a design solution in parallel [85]. Studies indicate that ImVE can potentially lead to higher performance of designers particularly in problem finding [86], which can have positive effect in both the problem and solution spaces. In another study focusing on collaboration, Hong et al. [53] developed a multi-user virtual environment and track users' problem-solving measures in a shared design setting. Their results suggest positive effective of ImVE especially in increasing inspiration for new approaches to problem-solving among design collaborators.

Advances in design computing and cognition research have provided a number of methodological approaches to studying both human–human and human–agent communications and interactions in ImVE [38]. For example, Roupe et al. [40] developed a virtual collaborative design environment that enhances the communication, collaboration, understanding, and knowledge sharing of participants. They conducted two collaborative design workshops to explore the collaboration behaviours of designers in a virtual collaborative environment, utilising direct documented observations and semi-structured interviews with participants, to explore their experiences and views about their collaborative design processes. Leon et al. [1] developed a pre-BIM conceptual design stage protocol for cognitive design studies in collaborative virtual environments, and its coding scheme included team formation, introduction of the brief, discussion of project requirements, solution synthesis and brainstorming, solution evaluation, consensus, and final solution. For design collaboration in ImVE, communication tools have mainly consisted of a few forms of text-based tools, voice chat tools, visual sharing tools and avatars, which can potentially improve the communication efficiency of design collaboration in the AEC industry [47]. In one example, based on participatory observation in a virtual collaboration environment it has been found [36] that the use of avatar movement is effective for communicating non-verbal information that enhances the effectiveness of collaboration. Other studies focusing on various communication approaches during collaboration in ImVE, include Kim et al. [50] which applied an overlay design methodology in studying virtual environments based on protocol studies of participants' collaborative design process, and found that method can effectively assist with communication, doubling the collaboration segments among team members and reducing the overall time needed to complete their design compared to use of traditional design method. Another example is Wang et al. [54] development of a computer-mediated remote collaborative design system TeleA. Via measurement of participants' physiological movements such as gestures, facial expressions, fine motor movements and bodily postures and distances, as well as observation of their emotional states, that study suggested that developed system had a positive effect on designers' communication and collaboration, especially for distributed cognition and mutual awareness.

Furthermore, previous studies have also explored design collaboration in ImVE in the context of architectural education focusing on teaching and learning. For instance, Rauf et al. [46] discussed the application of VR in architectural education to support collaborative learning, and identified the effect of VR applications from various collaborative levels including student-instructor, student-client and student-industry. Similarly, Diao and Shih [42] reviewed AR applications in the broader AEC education and suggested that collaborative learning enabled by AR can promote the connection between general pedagogy and domain-specific learning. George et al. [52] studied students' design processes in ImVE and found that VR is effective in enhancing students' understanding of design decisions by assisting them with rapid design prototyping.

Among various design studies, especially cognitive design studies on collaboration techniques and frameworks, the dominant majority have the overarching aim of streamlining the collaboration process to produce more optimal design output. ImVE has the potential to assist in producing creative design solutions during the collaboration. Particularly, design solutions appeared to be more creative in terms of both novelty and appropriateness in multi-user virtual environments than in traditional sketching environments due to the explicit communication cues for sharing the collaborative procedure and spatial information provided by the former [48]. Similarly, Chowdhury and Schnabel [49] also found that the more spontaneous exchange of visual information in a shared virtual environment is beneficial for producing optimal design solutions.

5. Conclusions and Future Research

This study has reviewed recent research on design collaboration in ImVE from the past ten years. The results demonstrate an increasing research focus on this area through the past decade. From a technical development perspective, immersive technologies are being rapidly developed and applied within the AEC industry to facilitate collaboration at various design and construction stages. Recent research on design collaboration in ImVE has focused on design review with end users and other stakeholders in ImVE, visual data/information in BIM-based ImVE in supporting design collaboration, and cognitive studies of design collaboration in ImVE. To date, current research provides us with some early understandings of design collaboration in ImVE as applied in the above-mentioned ways. However, academic research about ImVE support for design collaboration, is not keeping pace with the accelerating rate of its technological advancement. Generally there is a lack of critical understanding about design collaboration in ImVE, thus the following future research is needed.

First, additional studies regarding ImVE support for design collaboration, especially at the early design stage, are needed. Commonly used design collaboration platforms in the AEC industry such as BIM tend to be tailored to the later design and management stages rather than providing support for the conceptualising, interacting, and sharing of design concepts at the early stage [7,87]. Most virtual collaboration tools are focused on visualisation [31,88,89]. A few recent tools that support design ideation (such as Wild, Mindesk, and Arkio) provide limited design functions of sketching or parametric modelling, etc., and they have not yet been widely applied and tested throughout the design industry. Effective collaboration during the initial concept design stage will lead to fewer problems during the later stages such as developed design, detailed design, and design documentation [1]. In addition, effective collaboration is often supported by digital and network tools, for example, through social networking services for enhancing remote design collaboration [4]. There is currently a lack of critical understanding about the effectiveness of these virtual technologies and various emerging add-on tools for meeting the needs of design collaboration, especially at the early design stage [90].

Secondly, further cognitive research on design collaboration in ImVE adopting more innovative and comprehensive methodologies is needed. Current research has explored the design collaboration process in ImVE from various cognitive perspectives, including the creativity of design solutions (i.e., novelty and appropriateness) in multi-user virtual environments [48], design collaborators' problem-solving measures in multi-user virtual environments [53], and various explorations from design teaching and learning perspectives [42,46]. More comprehensive understandings about how architects collaborate in ImVE from a cognitive perspective, compared with face-to-face or more traditional computer-based collaboration, will allow us to identify the barriers of adopting ImVE for design collaboration, and designers' needs for future tools to better support design collaboration. Very recently, more innovative and comprehensive cognitive studies such as by adopting or combining design and neuroscience perspectives could possibly lead to a deeper understanding of designers' collaboration, through measurements of designers' biometric responses such as eye-tracking and electroencephalogram (EEG), to complement the existing knowledge about the impact of ImVE on designers' collaboration process.

Finally, the continuing development of new ImVE technologies with more advanced design features (such as intuitive parametric and generative design functions) is needed to better assist with designing during collaboration. Current limitations of collaborative ImVE in terms of design support include insufficient conceptual sketching and overly simplified modelling functions. The parametric design functions provided by some tools rely mostly upon external add-ons rather than within the collaboration environment itself. There is a clear need for an algorithmic design feature in collaborative ImVE [89]. Furthermore, there is also a lack of advanced design features such as those for analysing building performance, cost, and land use, which are essential for making more informed design decisions during architectural design collaboration.

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