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FROM INFORMATIVE TO CO-DESIGN: THE ROLE OF IMMERSIVE VIRTUAL REALITY FOR USER-INVOLVEMENT IN HEALTHCARE FACILITY DESIGN

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Shahin Sateei, PhD student,
Department of Architecture and Civil Engineering, Chalmers University of Technology, Sweden
shahin.sateei@chalmers.se

Mattias Roupé, Associate Professor
Department of Architecture and Civil Engineering, Chalmers University of Technology, Sweden
mattias.roupe@chalmers.se

Mikael Johansson, Researcher
Department of Architecture and Civil Engineering, Chalmers University of Technology, Sweden
jomi@chalmers.se

SUMMARY: *The design of a new hospital is often recognized as a complex process involving diverse stakeholders, where the outcome directly impacts healthcare operations. To improve these outcomes, collaborative practices such as participatory design and co-design are frequently used to gather end-users' wants, needs, and operational knowledge. Recently, immersive Head-Mounted-Display (HMD) Virtual Reality (VR) has emerged as a tool that can enhance these processes by offering a better understanding of spatial scale and design details compared to traditional visual representations. However, while previous studies have focused on how immersive HMD VR improves spatial comprehension during design reviews, less attention has been paid to how specific interactive features—such as object interaction and multi-user capabilities—can facilitate collaboration and accelerate problem-solving. This paper aimed to gain an understanding of how these interactive features in immersive HMD VR can support various collaborative practices in hospital design projects. We present findings from six real-life hospital projects, spanning multiple design phases and utilizing different immersive HMD VR systems, to explore how interactive features affect user understanding, involvement, and engagement. Our results reveal that in the two cases where both object interaction and multi-user capabilities were available, participants could in real-time iteratively adjust layouts, including structural elements and loose furnishings, to test scenarios simulating real-world workflows. This enabled them to explore multiple spatial configurations and evaluate their impact on functionality. Multi-user collaboration facilitated simultaneous design reviews, promoting task-driven design evaluations and reducing revision lead time from weeks to hours. In cases where only free exploration of the virtual environment was available, participants primarily used immersive HMD VR to identify previously unrecognized design issues, evaluate sightlines, test logistical flow, and gain a clearer understanding of room scale. These insights highlight how varying levels of interactivity in the virtual environment impact user engagement, spatial understanding, and collaborative design processes. Additionally, we propose a classification framework for end-user involvement in VR-supported design reviews.*

KEYWORDS: *Virtual Reality, design review, collaborative practice, interactive features, user-involvement.*

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1. INTRODUCTION

Hospital projects are commonly characterized as complex in terms of facilitating a mutual, cross-disciplinary understanding of the building design. Moreover, the way people work during the operational phase has been linked to the building design (Lundin, 2021; Mourshed & Zhao, 2012). Furthermore, the design of a healthcare facility can influence the efficiency of healthcare operations and thereby influence the quality of patient care services (Salonen et al., 2013; Støre-Valen et al., 2014). Therefore, it is important to clarify the underlying premises and mechanisms that determine how stakeholders such as healthcare staff and facility managers can be effectively involved and engaged. This is specifically applicable in helping the design team better understand how to translate the needs of end-users' (e.g., healthcare staff and their representatives), namely their operational knowledge and experience with design outcomes that reflects their wants and needs (Huisman et al., 2012; Joseph & Rashid, 2007; Pilosof, 2021). A deeper understanding of the premises and mechanisms behind end-user involvement has led to increased adoption of collaborative practices, such as participatory design and co-design (Caixeta et al., 2019; Fröst et al., 2017). Even so, there is no consensus on what distinguishes these various collaborative practices (Kujala, 2003; Magnusson et al., 2003). In an effort to address this lack of consensus, recent studies have explored the degree to which various definitions of collaborative practices can be linked to different levels of user involvement (Caixeta et al., 2019; Fröst et al., 2017).

However, although classifying collaborative practices helps us understand what is required for each level of user involvement, there is a lack of emphasis on the visual and informational medium used. In this context of end-user involvement, 2D drawings and 3D models are the most commonly used information and visualization media during the design review stage. These information and visualization media have been shown to be inefficient when facilitating spatial understanding among end-users (Paes et al., 2017; Ventura et al., 2020). As a result, difficulties with interpretating the design prevents a mutual understanding among stakeholders of the design (Kleinsmann & Valkenburg, 2008; Paes et al., 2017). Consequently, this impediment makes it difficult to develop design proposals that support the needs of healthcare staff in undertaking daily tasks at work (Carthey, 2021).

As a response to this need for mutual understanding, immersive Head-Mounted-Display (HMD) Virtual Reality (VR) has been used as an alternative visualization and information medium to 2D drawings and 3D models (Liu et al., 2020; Nikolic et al., 2019; Ventura et al., 2020). Additionally, immersive HMD VR has been observed to help healthcare staff and their representatives to better understand how the building design supports their daily work requirements (Sateei et al., 2021). An explanation is that interpreting lines and symbols on 2D drawings during design review has been shown to be perceived as abstract by end-users (Dadi et al., 2014). Compared to 2D drawings and 3D models viewed on a flat screen, immersive HMD VR provides the stereoscopic visualization combined with a fully enclosed visual environment, which enhances users' understanding of volumetric qualities (e.g., room size) and identifying hidden sightlines (Abouelkhier et al., 2021; Chowdhury & Schnabel, 2020; Dadi et al., 2014). The stereoscopic visualization together with the real-time head and positional tracking allows users to get immediate feedback on their own position and movements in relation to objects in the virtual environment. Moreover, the use of interactive features, such as multi-user and object interaction (Jr et al., 2017), has shown to further enhance end-users' sense of "being there" in the virtual environment and not in the physical world (i.e., sense of presence) (Sra & Schmandt, 2015). The use of interactive features makes it possible to adopt task-based scenarios during design review to better understand how the building layout supports building occupants' daily work tasks (Nikolić & Whyte, 2021; Roupé et al., 2020).

Nevertheless, there is a lack of studies that explore how immersive HMD VR and interactive features can facilitate the different collaborative practices in the design process (Horvat et al., 2022; Lapointe et al., 2021; Liu et al., 2020). As a result, a knowledge gap has emerged between researchers and practitioners on how to best achieve certain levels of user involvement via immersive HMD VR. Therefore, this study investigates, based on six real-life case studies, how immersive HMD VR with support for interactive features supports different types of collaborative practices. The aim of the paper being to gain a broader understanding of how different interactive features influence end-user involvement, and consequently, collaborative practices in healthcare facility design. Thus, the current study will present a classification of end-user involvement when immersive HMD VR is used as a visual and informational medium. The research thus seeks to pursue a greater understanding of the following research questions:

1. How do various interactive features in the virtual environment influence end-user involvement during building design review?
2. How can immersive HMD VR used in collaborative practices be classified according to different levels of end-user involvement?

As such, the paper has the following structure: the first part, section 1 presents related works to establish an understanding of the current research. Section 2 describes the methodology in which Caixeta et al.'s (2019) classification of user involvement will be mapped and applied as the theoretical framework for the presented case studies. Section 3 details the results of this mapping process. Section 4 discusses the result and the mapping of Caixeta's (2019) classification as well as the developed classification for this study. Additionally, this discussion will include an outline of the study's limitations. Lastly, section 6 presents the conclusion for this work as well as recommendations for future study.

2. RELATED WORK

2.1 Virtual Reality as visual and information medium

Virtual Reality (VR) allows users to engage with and experience a computer-generated environment in a way that simulates real-world perception (Y. Zhang et al., 2020). The extent to which a system creates this simulated experience is referred to as *immersion*. Immersion relies on factors such as field-of-view vision, motion tracking, and users' ability to interact with the world, and as such, refers to the *technological capability* of a VR-system (Slater & Sanchez-Vives, 2016). The purpose of VR-systems having these technological factors is to enable users to perceive and interact with the virtual environment via natural bodily movement and interaction (e.g., head turning, bending down to examine an object from a different angle), in what is known as natural sensorimotor contingencies (O'Regan & Noë, 2001). When a VR-system accurately responds to natural bodily movements, it reinforces immersion by ensuring that the virtual environment behaves in accordance with real-world expectations of such actions. Different VR-systems achieve immersion in different ways, depending on how the virtual environment is presented to the users, whether through wearable displays such as Head-Mounted-Displays (HMD), or stereoscopic large-scale projections found in different types of cave automatic virtual environment (CAVE) systems. The main differences between immersive HMD VR and CAVE relates to their hardware properties. Users' perception and immersion can be affected, for example by screen resolution and contrast, field-of-view and latency. In addition to immersive VR systems, there are also non-immersive systems, commonly referred to as desktop VR. These setups present a 3D virtual environment on standard computer monitors, rather than utilizing stereoscopic real-time tracking of head movements and body positioning as seen in headset-based or projection-based systems. Furthermore, interaction in desktop VR is typically carried out using a keyboard and mouse instead of natural body movements. Additionally, this means a lack of field-of-view and depth through stereoscopic display. As a result, the experience is generally less immersive compared to that offered by immersive VR systems (Slater & Sanchez-Vives, 2016). Moreover, 360-degree VR, a system based on a rendered panoramic image viewed from a fixed viewpoint, offers users a static yet immersive visual experience. It enables visual exploration of the environment in all directions, but without the ability to interact with or change perspective through physical movement. In contrast to fully immersive VR systems, where real-world head movements dynamically alter the virtual viewpoint and generate depth cues through parallax (i.e., the relative motion of nearby and distant objects), 360-degree VR maintains a fixed spatial relationship within the scene. The viewpoints in such systems are predetermined and remain unchanged regardless of user movement. Consequently, the lack of dynamic depth cues can diminish the sense of immersion compared to systems with real-time positional tracking (Deering, 1992).

Overall, the degree of immersion experienced by users can vary depending on the type of VR-system used. For instance, in comparison studies between immersive HMD VR and CAVE, it has been found that HMD VR can offer a more immersive experience (Havig et al., 2011; Pala et al., 2021; Prabhakaran, Mahamadu, & Mahdjoubi, 2022). For instance, in CAVE systems, users remain partially aware of the physical environment - such as screen edges or their own body - which can create conflicting spatial cues and reduce immersion (Mestre, 2017; Vasconcelos et al., 2019). In contrast, the full visual enclosure of the user in immersive HMD VR ensures that all the spatial cues and visual stimuli align with the virtual environment, causing users to become more immersed with immersive HMD VR than CAVE systems.

As immersion increases, so does the potential for users to feel what scholars describe as a “sense of presence” in the virtual environment (Slater et al., 2022). Presence in the literature is described as the subjective illusion of “being there” in the virtual environment, where the brain interprets sensory input as if the virtual environment were real. This experience emerges when a VR system effectively replaces real-world sensory perceptions with virtual ones, leading users to respond to the virtual world as they would in a real-world setting (Slater et al., 2022; Slater & Sanchez-Vives, 2016). In the context of building design review, immersive HMD VR provides users with increased spatial cues (e.g., size, depth, and object position), which has been shown to strengthen their sense of presence in the virtual environment (Paes et al., 2021). Moreover, studies suggest that an increased sense of presence could improve end-users’ performance in tasks related to the review and evaluation of architectural design proposals (e.g., identifying more design issues, navigation, completing tasks in less time), when compared to traditional methods of involving end-users (Heydarian et al., 2015; Paes et al., 2017).

Although visual simulation via immersive HMD VR helps end-users conduct design review more efficiently, the use of various interactive features, such as multi-user (Prabhakaran, Mahamadu, & Mahdjoubi, 2022; Z. Zhang et al., 2023), object interaction (Khalili, 2021; Roupé et al., 2020; Wolfartsberger, 2019) and ability to freely explore the virtual environment (Berg et al., 2017; Haahr & Knak, 2022, Roupé et al., 2014) seems to further enhance end-users’ ability to examine design proposals. In this study, we define object interaction and exploration as part of what Jr et al. (2017) refer to as *fundamental interaction tasks*. These tasks are what the authors consider users to need to accomplish objectives in a 3D environment: *object selection, object manipulation, travel* and *system control*. Specifically, object interaction in our study encompasses *object selection* (i.e., identifying and selecting objects) and *object manipulation* (i.e., adjusting an object’s position and rotation). Jr et al. (2017) also define *exploration* as a subclass of the *travel* task. In *exploration*, users do not have an explicit movement goal, but instead navigate the environment to gather spatial information, observe objects, and develop an understanding and build knowledge of the virtual space (Jr et al., 2017).

Similarly, multi-user via immersive HMD VR is another interactive feature that helps multiple users to engage within the same virtual environment simultaneously. In terms of defining multi-user in virtual environments, it has varied over the years. While earlier studies tended to have more device-oriented definitions around collaboration, based on the technologies available at the time (e.g., conferencing technologies, early immersive HMD VR prototypes) (Benford & Fahlén, 1993; Carlsson & Hagsand, 1993; Chinowsky & Rojas, 2003), later studies defined multi-user experience in virtual environments as part of a set of criteria related to collaboration between users (transition between shared and individual activity, shared context, awareness of others, negotiation and communication and flexible and multiple viewpoints) (Churchill et al., 2012; Churchill & Snowdon, 1998). In this study we adopt a more recent definition of multi-user interaction that describes Collaborative Virtual Environment (CVE) systems – such as immersive HMD VR – as *a computer-based, distributed, virtual space or set of places. In such places, people can meet and interact with others, with agents, or with virtual objects* (Churchill et al., 2012). Applying this definition to the context of design reviews, several studies highlight how a multi-user feature influence stakeholders’ understanding of the design proposal being reviewed. For instance, design team members can better understand how the building design affects healthcare staff when having a shared frame of reference when using immersive HMD VR (Bjørn et al., 2021; Roupé et al., 2020). Additionally, multi-user features have been shown to reduce overall time spent on decision-making related to design approval. When managers and clients do joint design review via immersive HMD VR, adjustments in the design proposal can be immediately assessed and approved in the virtual environment by the client (Truong et al., 2021). Consequently, there is less misinterpretation of the design and instead a more collaborative understanding that emerges.

In our study, the term interactive features specifically refers to fundamental interaction tasks, including *exploration*, *multi-user* capabilities and object interaction (selection and manipulation of objects). These interactive features have been observed to enhance individual user engagement but also play a crucial role in collaborative design review settings. For instance, Berg et al. (2017) demonstrated with two real-life cases how clients exploring design proposals prior to review would result in numerous design issues being identified. The authors argue how these identified design issues can help design team members make more informed decisions and guide the design process. Similarly, previous work by Truong et al. (2021) observed how use of remote multi-user feature during design review encouraged an increased use of non-verbal gestures (e.g., pointing and waving to grab attention of other users) and an overall more coordinated decision-making process. Nevertheless, recent studies emphasize the lack of consensus in the literature on how interactive features in immersive HMD VR systems influence design review (Horvat et al., 2022). While studies have aimed to understand how immersive

HMD VR influences design review in the context of user-involvement and specifically collaborative practices such as co-design (Lapointe et al., 2021), there is still a lack of real-world case studies and understanding of which interactive features that are considered important during design review, which prevents researchers from fully understanding how immersive HMD VR affects collaborative practices.

2.2 User-involvement and collaborative practices

In the field of building design, terminologies such as user-involvement, co-design and participation are widely used and as certain researchers acknowledge, used arbitrary and interchangeably (Caixeta et al., 2019; Räisänen et al., 2024). In addition to make discussions around the phenomena itself less coherent, the lack of conceptual consensus can also lead to user-involvement taking place on a premise of false expectations (Choguill, 1996), which risks causing end-users (e.g., building occupants) to be viewed as alibis in the design process (Olsson et al., 2006). As a result, insufficient involvement results in loss of important feedback that is needed to ensure that the design satisfies the wants and needs of end-users.

As a response, efforts have been made to establish frameworks for user-involvement. These have historically been illustrated as a ladder, where each step of the ladder corresponds to a different level of user-involvement, with the top reflecting the higher levels of user-involvement (Choguill, 1996; Wulz, 1986). Still, these illustrations have been criticized for their linear, hierarchical model of involvement as well as unclarity in what the different levels require, in terms of method and type of users (Tritter & McCallum, 2006). In particular, it is the mismatch between expectation users have of influencing decisions when involved and the method used to involve, which makes user involvement more susceptible to failure. As also highlighted by Tritter and McCallum (2006), with existing classifications of user involvement, e.g., (Arnstein, 1969), overlooking methods used for involvement, users are prevented from framing problems and are limited to taking part of pre-defined solutions.

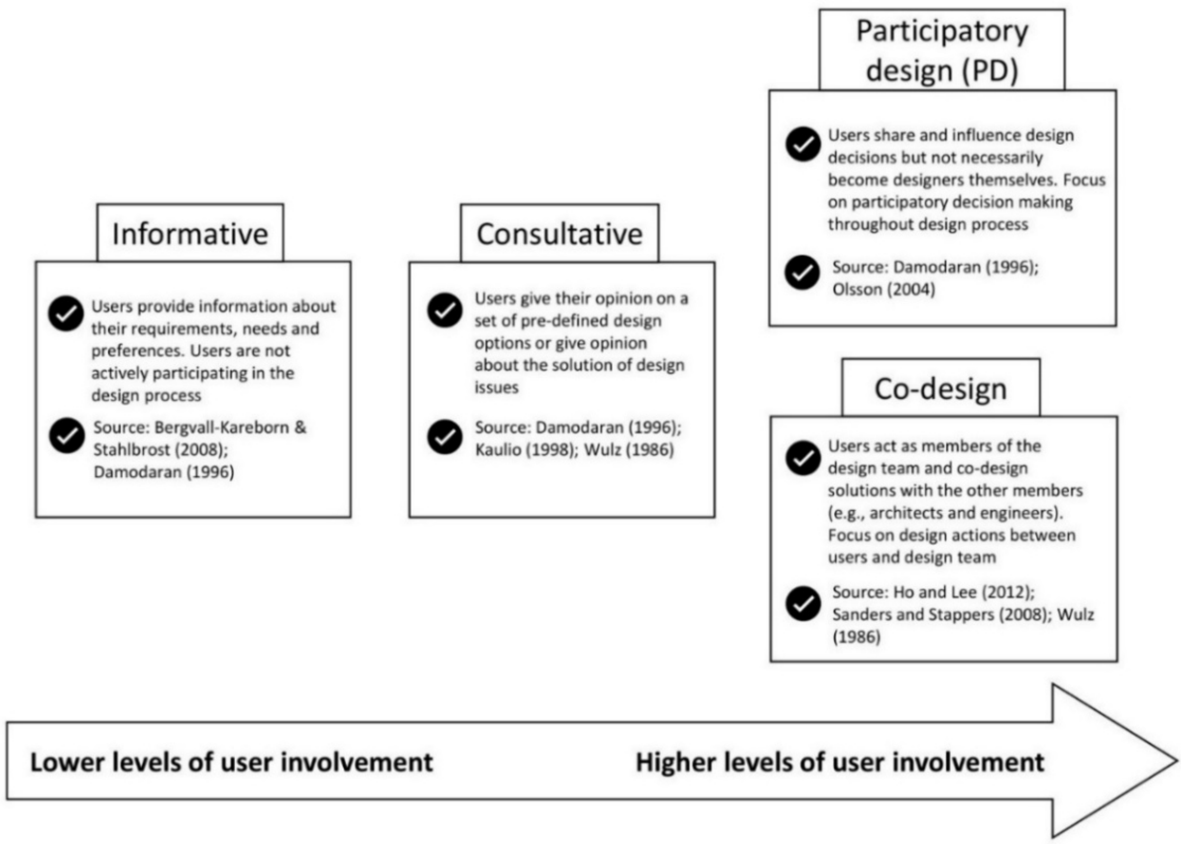


Figure 1: Classification of user involvement in building design. Illustration adapted from Caixeta et al (2019).

In an effort to address this, Caixeta et al (2019) reviewed 37 journal articles from various domains (e.g., architecture design, product development, information technology etc.) to define how user involvement can be classified in the building design domain. The classification is presented according to three different levels of involvement: *informative* (Bergvall-Kåreborn & Ståhlbrost, 2008; Damodaran, 1996), *consultative* (Damodaran, 1996; Kaulio, 1998; Wulz, 1986) and *participatory design/ co-design* (Ho & Lee, 2012; Sanders & Stappers, 2008; Wulz, 1986) (see Figure 1 below). No level is considered better than the others, but instead, the emphasis is placed on how the various levels can satisfy distinct needs in different contexts. Although both Participatory Design (PD) and co-design are set at the same level of higher involvement, Caixeta et al (2019) distinguishes between the two collaborative practices by describing how involvement of users via PD focuses more on promoting democracy in decision-making and can take place throughout the design process, whilst co-design focuses more on building operability and is more appropriate for early phases of the design process. In this context, the level of involvement is defined as the *range of influence that users or their representatives have over the final products* (Bergvall-Kåreborn & Ståhlbrost, 2008; Caixeta et al., 2019). In our study, we extend the classification of user involvement proposed by Caixeta et al. (2019) to explicitly include the role that interactive features of immersive HMD VR play in facilitating different collaborative practices.

2.3 Integrating Virtual reality-sessions with collaborative practices

A small number of studies have explored how immersive HMD VR systems can facilitate collaborative practices (e.g., participatory design, co-design) by increasing end-users' spatial understanding. For example, Loyola (2019) and Johansson & Roupé (2022) observed that end-users immersed in the virtual environment were able to identify and address design issues that the design team previously were unaware of. This observation of immersive HMD VR eliciting ideas and thoughts about the design seem to be further reinforced by the availability of interactive features such as object interaction, multi-user and teleportation. Specifically, studies have found that these interactive features can help bridge the gap between the intention of involving end-users and their actual engagement in the design process via participatory design (PD) (Ehab et al., 2023; Mahamadu et al., 2021). Beyond PD processes, Roupé et al (2020) investigated how to facilitate a co-design process in healthcare design by using the design object interaction tool known as Virtual Collaborative Design Environment (ViCoDE). ViCoDE provides multiple user-interfaces (e.g., multitouch table, immersive HMD VR, projector screen) and interactivity options (e.g., multi-user, object interaction via the multitouch table). The study observed how the visual understanding the healthcare staff gained from VR, together with the ability to do object interaction, allowed them to conduct task-based scenarios in the virtual environment (e.g., testing logistical flow of different furnished rooms). As a result, the healthcare staff were able to become part of the design team by developing different design proposals together with the architect. The authors argue how these task-based scenarios helped the healthcare staff better understand specific design challenges, enabling them to change the design and evaluate how well different design layouts could support their daily working tasks. This aligns with research on collaborative virtual environments which emphasize the role of synchronous interaction in enhancing engagement and collective decision-making (Whyte & Nikolić, 2018; Truong et al., 2021).

Taken together, studies investigating the use of immersive HMD VR in collaborative practices show the importance of a shared context that allows users to perceive and understand the activities of each other (Bullinger-Hoffmann et al., 2021), an awareness of others in the same virtual environment (Truong et al., 2021) and be able to negotiate and communicate ideas with each other (Prabhakaran, Mahamadu, Mahdjoubi, et al., 2022), transitioning between shared and individual activities as well as being able to have multiple viewpoints (Ibayashi et al., 2015). Nevertheless, current studies have mainly focused on either visualization without including interactive features (Alizadehsalehi et al., 2020), presenting a methodology for how immersive HMD VR can be used (Ventura et al., 2020) or detailing technological implementation (Coburn et al., 2017; Du et al., 2018).

With previous research focusing primarily on visual realism, technological implementation, or methodological frameworks, there remains limited understanding of how immersive HMD VR with support for interactive features affects collaborative practices. With the literature also emphasizing how certain behaviors are difficult to observe in a laboratory setting (Geszten et al., 2023), field studies in end-users' real-world environment become necessary. By better understanding how immersive HMD VR systems with support for interactive features affects end-user involvement, a better understanding can be gained for how to develop a design review planning cycle that enable collaborative practices to take place (Horvat et al., 2022; Lapointe et al., 2021).

3. METHOD

3.1 Presentation of case studies

Six cases were reviewed to more accurately understand how immersive HMD VR facilitated the involvement of end-users in the design process. The end-users consisted of healthcare staff, project managers and facility managers. Concerning the choice of cases, the strategy was to select healthcare design projects that were taking place in different phases of the design process, varying from preparation and brief to technical design. Furthermore, the cases were chosen based on the type of operations planned (e.g., somatic, and psychiatric) as well as their willingness to share information and data with this study. Background information regarding these case studies have been analyzed based on the following criteria: 1) purpose of use, 2) design phase, availability of interactive features and number of VR sessions as well as 3) outcomes resulting from having used immersive HMD VR in the design process.

Five of the six cases used Head-Mounted-Display (HMD) VR system whereas case E (see Figure 2 below) used Virtual Collaborative Design Environment (ViCoDE). In this study, immersive VR is primarily represented by HMD systems. While other immersive VR systems, such as CAVE, also exist, the decision to focus on immersive HMD VR was based on its accessibility, cost-effectiveness and adoption in real-world design review workflows (Johansson & Roupé, 2024; Özcan Deniz, 2019). Although CAVE systems theoretically could have been considered, practical factors such as limited support for multiple users (typically only a single user is accurately tracked with a correct stereoscopic field-of-view, causing distorted visuals for other users), and a lack of commercially available solutions supporting multi-user tracking (Agrawala et al., 1997; Coburn et al., 2017), make immersive HMD VR a more logical choice for our study. Also, recent studies show how immersive HMD VR enable multiple users in the same model, with users being either co-located or remote (Johansson & Roupé, 2022; Truong et al., 2021). Therefore, cases involving immersive HMD VR systems were chosen to reduce the likelihood of hardware-related factors having affected the multi-user experience.

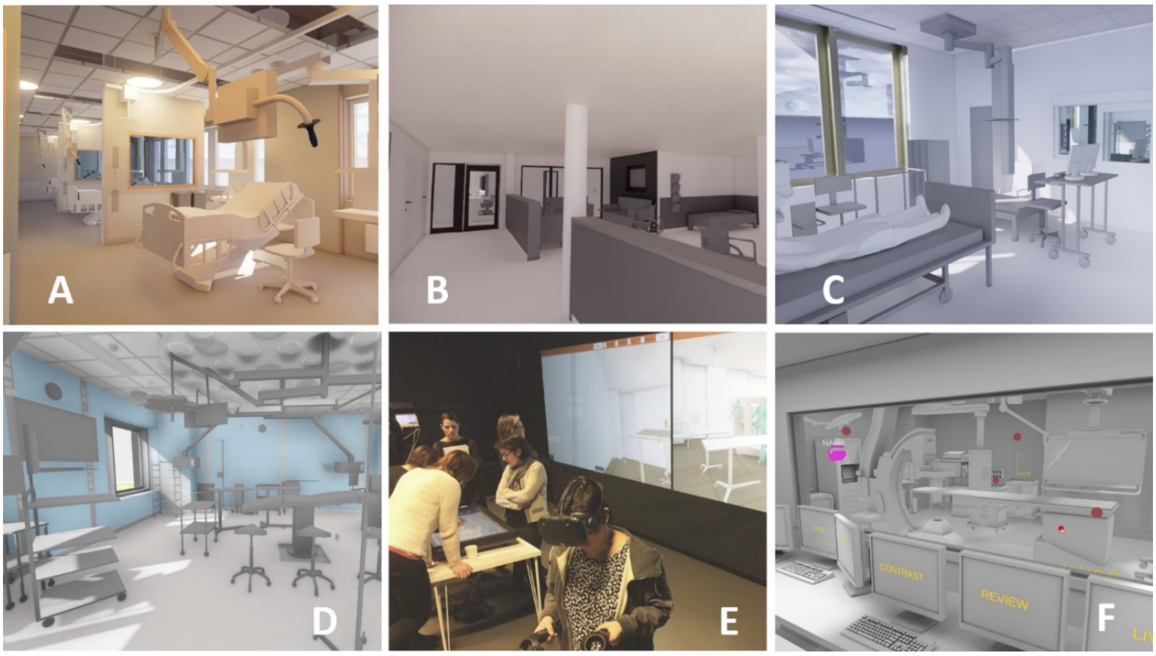


Figure 2: Screenshots from inside the VR-models as well as the set-up for case E with the multi-touch table together with immersive HMD VR (ViCoDE) (Sateei et al 2021).

The immersive HMD VR systems consisted of a VR-ready computer to smoothly run the VR-models. Connected to the PC was a VR-headset (e.g., HTC Vive, Oculus rift) with external sensor mounts for accurate position detection and to set the boundaries for the space that users can physically move within. Lastly, handheld controllers enable users to navigate the virtual environment via teleportation, a Virtual Locomotion Technique (VLT) (Al Zayer et al., 2020). This means that when users teleport, they are instantaneously repositioned to the target location, by aiming with the controller and selecting the specific location. Finally, in one case (case F), controllers allowed users object interaction of spatial components (e.g., placement and furnishing of spatial components).

ViCoDE features seamless integration of several immersive HMD VR systems and a multitouch table, together with a projector screen, that facilitates collaborative design work with immediate, real-time feedback (i.e. object interaction). The multitouch table client uses a top view to visualize the facility. Users can pan and zoom in this view using the same standard multitouch interaction features found in most smart phones. Different Building Information Modelling (BIM) based components (e.g., static avatars, furniture, medical equipment) coming from the Swedish national healthcare database, PTS (program for technical standard), can then be added to the scene by drag-and-drop. Once added, a component can be repositioned, rotated, or removed, using the multitouch interface. The component is then instantly updated in all the other connected user interfaces (e.g. projector screen, immersive HMD VR).

3.1.1 Object interaction, exploration and multi-user

As previously described in section 2.1, object interaction and exploration are considered *fundamental interaction tasks* (Jr et al., 2017). In this study, object interaction specifically refers to tasks such as selecting and manipulating objects (e.g., placement, rotation), while exploration refers to users browsing and gathering information about the virtual environment. These tasks are what the authors consider users to need to accomplish objectives in a 3D environment: *object selection, object manipulation, travel* and *system control*. Object interaction in our study encompasses *object selection* (i.e., identifying and selecting objects) and *object manipulation* (i.e., adjusting an object's position and rotation). Also, we focus on manipulations that preserve the shape of objects (i.e., spatial rigid object manipulation (Jr et al., 2017). *System control* addresses changing the mode of the VR-system. Menus and toolbars are examples of system control techniques that enable users to perform a particular action, e.g., object selection and manipulation. The available tool menu inside the VR user-interface in F and the multitouch table in case E, showing available medical equipment to be placed into the scene, is considered the system control of the VR-system in these cases. Adding and removing medical equipment (object creation/deletion), can be understood as a combination of the fundamental tasks. For example, object creation, in this context adding medical equipment into the virtual environment, can be accomplished by selecting an item from the tool menu in the VR user interface (*system control*). Moving and rotating the selected medical equipment into a desired position in the virtual environment is then considered *manipulation*. Similarly, object deletion (i.e., removal of existing and added medical equipment) might be accomplished by selecting an object (*selection*) and the selecting the delete command from the menu that appears (*system control*). Therefore, object interaction in our study refers to *object selection, object manipulation* and *system control*.

Jr et al. (2017) also defines exploration as a subclass of the travel task. In exploration, as done in all cases when identifying design issues, users do not have an explicit movement goal but instead navigate the environment, gather information about objects and locations (design issues), and build knowledge of the space they explore (Jr et al., 2017). While some VR sessions were structured as design reviews, this study does not explicitly analyze *wayfinding* , defined as the planning and decision-making related to user movement, or its related travel subclasses, *search* (i.e., traveling to a specific goal or target location) and *maneuvering* (i.e., adjusting the viewpoint within a limited area to perform a task). Although these behaviors may have taken place during design review sessions, the available data does not provide sufficient evidence to systematically distinguish them from general exploratory behavior. Therefore, while design review was a key purpose of immersive HMD VR use in several cases, the analysis focuses on exploration as a broad mode of engagement rather than differentiating between targeted search, maneuvering, and general spatial browsing. Given this, wayfinding and its related travel subclasses were not included in the analysis.

Apart from object interaction and exploration, multi-user interaction was also present in our study**.** Multi-user interaction refers to the ability of multiple users to simultaneously engage within the same virtual environment, facilitating real-time communication and shared spatial awareness (Prabhakaran et al., 2022; Z. Zhang et al., 2023). This aligns with research on collaborative virtual environments (CVE), which emphasize the role of synchronous interaction in enhancing engagement and collective decision-making (Whyte & Nikolić, 2018; Truong et al., 2021). In our study, multi-user interaction was evident in cases E and F (see Figure 3), where participants collaboratively influenced spatial configurations within the virtual environment. As stated in section 2.1, we adopt Churchill et al.'s (2012) definition of Collaborative Virtual Environment (CVE) systems. This definition emphasizes a shared virtual space allowing users to meet and interact simultaneously. In the context of our study, this definition is relevant as it aligns closely with our investigation of multi-user features in immersive HMD VR, particularly regarding how stakeholders collaboratively explore, evaluate, and make joint decisions during healthcare facility design reviews. Thus, adopting this definition enables a deeper analysis of collaborative dynamics observed in our real-world case studies. The above description of interactive features in Immersive HMD VR is summarized in Table 1.

Table 1: Interactive features in immersive HMD VR for design review.

Interactive Feature	Definition	Related Tasks and characteristics	Characteristic enabler and outcome	References
Exploration	User's ability to *freely navigate* the virtual space to observe and understand	- Travel / Exploration - Identify and evaluate	- Free movement and browsing the environment - Wayfinding - Identify logistical flow - Identify sightlines - Spatial understanding - Identify room size - Triggering thoughts about the design	Jr et al., (2017) Berg et al., (2017) Haahr & Knak (2022) Roupé et al., (2014)
Object Interaction	*Object selection & manipulation in the virtual environment* *System control*	- Selecting objects - Moving & rotating objects - Adjusting spatial configurations	- Selecting objects - Moving/rotating objects - Adjusting spatial configurations - Adding creating/deleting object	Jr et al., (2017) Khalili (2021) Wolfartsberger (2019) Roupé et al. (2020)
Multi-user Interaction	Real-time engagement of multiple users in a shared virtual environment	- Collaboration - Shared spatial awareness	- Shared frame of reference - Avatar embodiment - Communication (verbal/non-verbal) - Joint decision-making	Churchill et al. (2012) Roupé et al. (2020) Prabhakaran et al., (2022) Z. Zhang et al., (2023) Truong et al. (2021)

Figure 3 below shows which specific phases of the design process that VR was used in, and the available interactive features used in the different cases, based on the definitions from Jr et al (2017) and Churchill et al (2012). Time-line phases are based on RIBA Plan of work (Ostime, 2022).

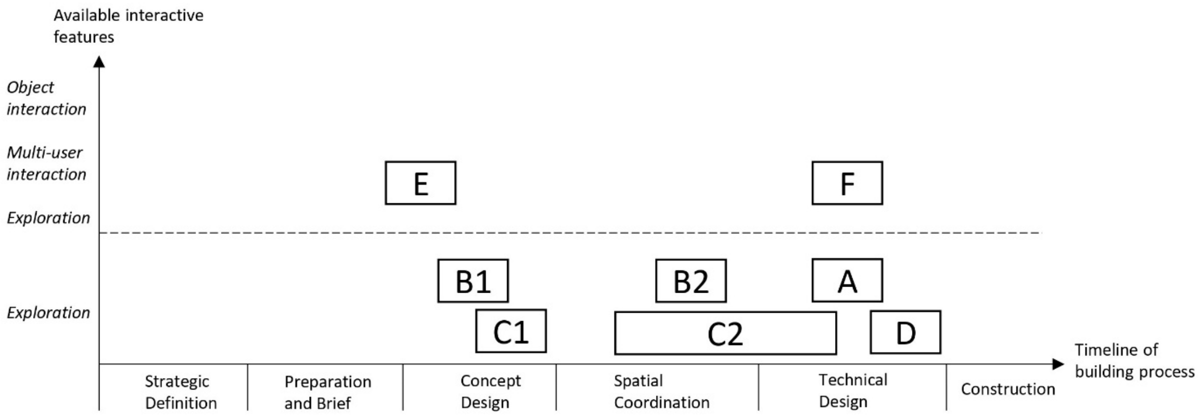


Figure 3: Graph illustrates how the observed cases map onto the various phases of the design process according to the RIBA Plan of work and available interactive features.

In the context of available interactive features, all cases consisted of VR-models that enabled users to freely explore the virtual environment to identify design issues while two cases (case E and F) enabled users to use the object interaction and multi-user features, as in Table 1. In regard to multi-user and as stated in section 3.1.1, we have adopted Churchill et al.'s (2012) definition of multi-user collaboration as users interacting simultaneously within the same virtual environment. Based on this definition, both Case E and Case F involved multi-user VR settings where participants were in the same model and could see each other's avatars in real time.

Furthermore, the level of detail in the virtual environments varied among the cases. For instance, in case A, the virtual environment was not only photorealistic but also characterized by a high level of detail. In contrast, other VR environments had varying levels of detail, which did not have the same level of (photo) realism as case A (see Figure 2).

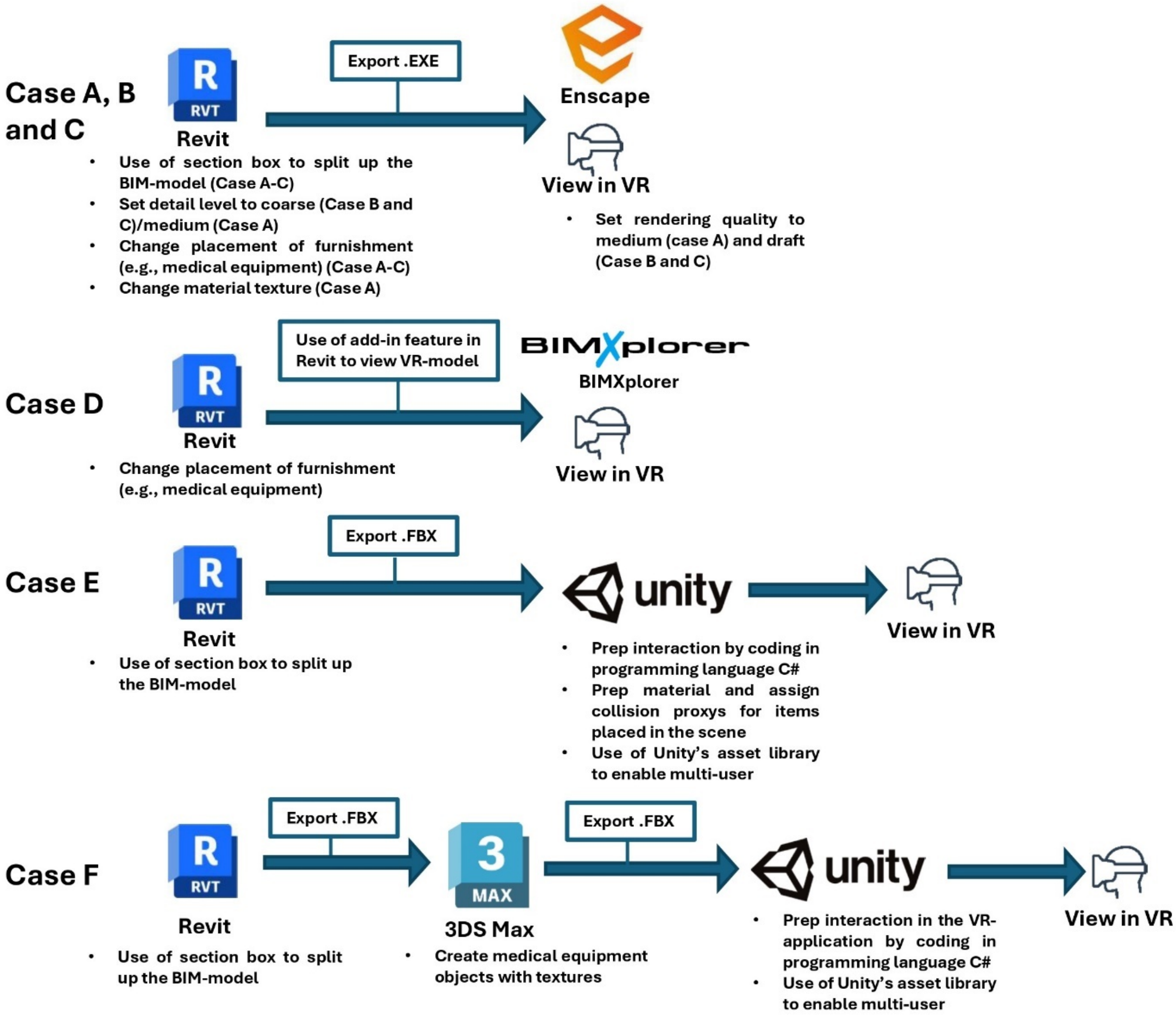


Figure 4: Software workflow for the different cases, showing how the BIM-model was transferred to a VR environment.

3.2 Transfer of BIM model to VR-environment

For case A, B and C, the commercially available software Enscape was used via an addin in the BIM authoring software Revit (see Figure 4 below). For Enscape to provide a sufficiently high frame rate without causing motion sickness and to improve the import speed from Revit, the BIM model had to be geometrically simplified. In Revit, this simplification consisted of using the section box to split up the BIM-model and reduce it to the area intended for design review as well as setting the detail level to coarse/medium, depending on the number of objects in the sectioned area (i.e., loose and fixed furnishing). After having simplified the BIM model in Revit, an .EXE file was created via the Enscape addin feature. Opening up the .EXE file, the rendering quality was set to medium (case A) and draft (case B and C) to further improve the rendering performance, before viewing the BIM model in a VR environment. Additional pre-processing step was made in case A when changing the material texture of the sectioned BIM-model prior to exporting the .EXE file. Lastly, after each design review session in VR, changes such as placement, addition, and removal were made to the available loose and fixed furnishings in Revit based on comments provided by end-users.

For case D, the high-performance VR-viewer BIMXplorer (Johansson & Roupé, 2024) was used on a federated BIM-model via the add-in feature in Revit. Compared to the other cases presented in this study, case D required no need for geometrical simplification or other pre-processing steps except for changing the placement of furnishings in Revit after each design review session. As such, immersive HMD VR was readily available via the Revit add-in, despite case D being a federated BIM-model containing all of the project's 21 sub models (arch, MEP, structural etc.) and not a sectioned architectural BIM-model as the other cases in this study.

For case E and F, the Unity software was used to develop a custom-made VR-viewer for the BIM-model with support for multi-user and object interaction. In both cases the architectural BIM-model first had to be reduced to the area intended for design review, before creating a .FBX export file. In case F the export of the .FBX file was opened in the 3DS Max software for further optimization of the geometry as well as creating the medical equipment furnishings. Following the optimization step, a .FBX file was transferred to Unity where the programming language C# was used to prep interaction in the VR-viewer as well as make use of Unity's asset library to enable multi-user. The same pre-processing steps were applied in case E, along with an additional pre-processing step to prepare materials and assign collision proxies for items placed in the virtual environment. Lastly, after having pre-processed the models in case E and F in the Unity software, the models were transferred to the virtual environment.

3.3 Participants

To achieve sample representativeness, interviewees were selected based on the following criteria: 1) role in the design process, 2) prior experience with design review with traditional visual and information media (e.g., 2D drawings, 3D models, physical mock-up rooms), and 3) involvement in ongoing healthcare design projects.

The participants interviewed were stakeholders and specialists from healthcare and construction projects, e.g., healthcare staff (HS), architects (arch), BIM coordinators (BC), facility managers (FM), project managers (PM) and project leaders (PL). In total 32 participants were interviewed; i.e. *Case A* – ICU unit (PL=2, FM=2, Arch=1, HS=3), *Case B* - Psychiatric clinic (Arch=1, PL=1, HS=1), *Case C* (PL=2, FM=1, HS=3, Arch=2, BC=1), *Case D – Children's clinic* (BC=1), *Case E – Robot assisted surgical room* - ViCoDE (PL=2, FM=1 HS=6) and *Case F – radiology room* (BC=1, PL=1).

It is also important to note that all non-design team participants (i.e., healthcare staff) had no or little experience with using VR. While some of the participants had experienced VR in an entertainment context (i.e., gaming, social media), none had used it for design review purposes. However, all participants were experienced with design reviews with 2D drawings and 3D models. Similarly, the design team members (i.e., BIM coordinator and architects) in case A and E had limited experience in design review with VR and had used it mostly for informative purposes, while design team members in case F had previous experience of using VR for design review purposes.

3.4 Interviews

This study used semi-structured interviews as they enable a thematic approach to be applied during the interviews but also offer flexibility with adjusting the interview questions to gain a conversational depth (Qu & Dumay, 2011). Focus was then on assessing the participants' views about: (1) background information (e.g., design phase, number of held VR-sessions), intention with using VR and current experiences with user-involvement when using 2D drawings and 3D models, (2) available interactive features in the VR-models and how these influenced participants' ability to understand and provide feedback and (3) participants' experience with using VR during the design process compared to 2D drawings and 3D models and what outcome that was gained after the held VR-sessions.

Some of the interviews took place via videoconferencing platform Zoom after VR had already been used (cases B, D and F), while in other cases (case A, C and E) face-to-face during an on-site visit. For cases where video observation was made, these semi-structured interviews were conducted prior and immediately after design review with VR was done. The interview questions were sent in advance to the interviewees, with interviews lasting 30-45 min. Interviews were audio recorded, transcribed, and sent to the interviewees for clarification and subsequent approval. The interviews were conducted between January 2020 and April 2021.

3.5 Video recordings

Observations via video recording were made in Case A, C and E. The decision to include video recordings only in these cases was primarily based on the availability of previously recorded material. Specifically, recordings were made from 3 out of 5 total VR sessions in Case A, 2 out of 30 VR sessions in Case C, and 1 out of 2 VR sessions in Case E (using the ViCoDE system).

The ViCoDE workshops were recorded with two stationary video cameras which were placed in elevated positions to capture the participants' collaboration, movement, and use of the different user-interfaces (e.g., multitouch-table, immersive HMD VR) in the workshop room. The collected corpus of video data consists of 3.45 h of video data which was transcribed for further analysis and later compared with the field notes and interview data to reinforce the observations made. The video data were analyzed in a qualitative manner by drawing attention to the detail of the natural occurring interactions with the various technologies available in the setting and between the participants as they developed the design of the operating theater. The verbal interaction between the participants was transcribed by one of the researchers. The transcription was added as subtext in the video data. Due to the limited space in this paper, a fragment of approximately 21 min of video data was selected from the broader corpus of 3.45 hours of video data of case E to illustrate the collaboration, the verbal and nonverbal interactions, and the different behavior of the participants during the workshop. The fragment selected for detailed analysis presented in this paper was extracted from the final part of the second workshop.

Case A and C used the same principles of video-based study methods and video observations were made in a total of 2.45 h, with 45 min selected from case A and 30 min from case C. This was done to illustrate the communication between design team members and end-users and specifically how the design review was influenced by the use of immersive HMD VR. The selected parts were extracted from the second workshop in case A and the fifth workshop in case C. In Case A and C, the recordings focused on how end-users used exploration as an interactive feature to navigate and interpret the design proposal. These sessions did not involve multi-user functionality, and therefore, interactions were limited to individual users providing feedback based on their own experiences within the virtual environment. In contrast, the recorded session in Case E included multi-user as interactive feature within the VR environment, where participants could see each other's avatars and interact in real time. As such, Case E was the only case among the three where the video data enabled observation of collaborative practices occurring within the virtual environment, in line with Churchill et al.'s (2012) definition of multi-user interaction.

Consequently, while the video recordings contributed insights into end-user engagement across all three cases, the classification model developed in this study is specifically focused on collaborative practices observed *within* the VR environment, and not interactions surrounding external displays (e.g., projectors or laptop screens). Due to the lack of systematic video data across all cases, interactions occurring outside the virtual environment - such as co-located discussions based on projected VR views - were not included in the analysis.

3.6 Data analysis technique

The interview and observational data collected were analyzed using thematic analysis, known as one of the most efficient methods for analyzing qualitative data and capturing valuable information (Braun & Clarke, 2006). This analysis aimed to gain a more accurate understanding of how each theme aligned with the theoretical framework of our study. The cases were mapped according to the different levels of involvement in Caixeta et al.'s (2019) classification. The strategy of selecting themes was based on gaining a better understanding of: (1) how VR is used in the context of design activities and collaborative practices, and (2) how interactions between participants is influenced by VR and (3) how VR influences end-users' ability to express their wants and needs about design proposals.

Subsequently, the researchers conducted separate analyses and observations of the collaboration, conversations, and behavior of the participants during the workshop. Following these initial analyses, collaborative data review sessions were conducted to further scrutinize the preliminary observations and develop thematic categories.

4. RESULTS AND ANALYSIS

4.1 Summary of results

The main findings from the case studies are summarized in Table 2, categorized according to: (1) purpose of use, (2) the design phase(s) in which VR was adopted, the availability of interactive features, and total number of VR sessions, and (3) outcomes resulting from VR implementation. Subsequent sections discuss these findings further by addressing how VR and its interactive features were used as a visual and information medium, and by mapping these practices onto different collaborative levels of user involvement (i.e., informative, consultative, participatory design, and co-design).

4.2 VR as visual and information medium in the design process

4.2.1 Design phase and interactive features

Observations indicate that the specific design phase can impact users' degree of user-involvement. Moreover, the level of influence users experience in the design process is further facilitated by the interactivity level in the VR-models, i.e., availability of interactive features. For example, one participant commented that *VR needs to be further developed to enable all involved parties to be in the same virtual space be able to review design requirements simultaneously [PL, case B]*. The level of interactivity was particularly noticed in case E where object interaction helped architects and healthcare staff at a rapid pace develop several different design proposals, with the design changes showing up simultaneously on all the different user-interfaces, i.e., multi-touch table, VR headsets and projector screen. As a result, a mutual understanding emerged between the architect and the healthcare staff on room size and choice of furnishings layout.

The different participants discussed, tested, and validated the new operating theaters in the immersive HMD VR system, reaching a consensus on how the new design layout could best support the healthcare staff's daily working tasks (see Figure 5 below). As a result, the architect commented on how reducing the size of the preparation rooms led to the realization that they *probably could manage to fit two of the new operating theaters to the overall design of the building [Arch, case E]*. In this case the users had the ability to change furnishing and wall placement in the VR models (i.e., object interaction) compared to VR models where participants were unable to do so (case A-D).

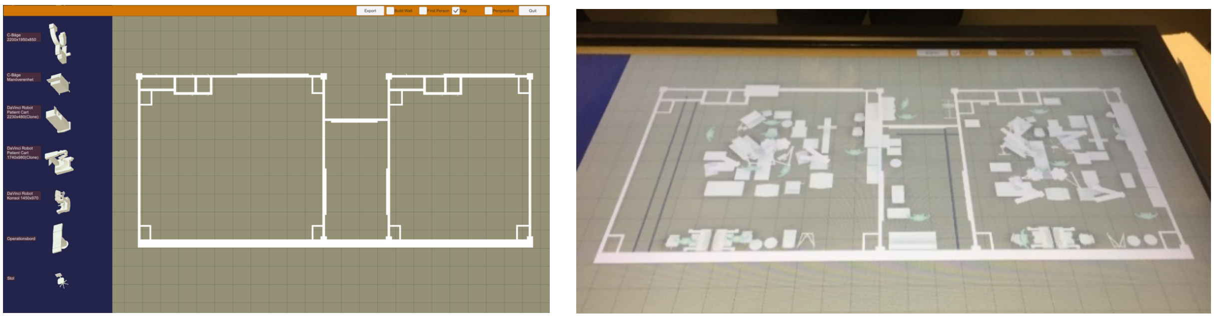


Figure 5: By adding furnishings to the empty space (left picture) and having the ability to change the size of the available layout, different real-time scenarios could be tested to attain the best solution (right picture) (Case E).

Figure 6 below illustrates the different types of design issues that were identified in the different cases, with design issues identified in earlier design phases being related to structural changes, whilst later phases are categorized as non-structural changes. For both these types of changes, the different cases required a different number of workshop sessions to identify and resolve the same type of design issues, whether these were structural or non-structural. Specifically, with participants using the interactive features available to them in the different cases, design review of the same type of design issues varied timewise between the different cases.

Table 2: A table showcasing the observed case studies. Notice that case E and F enabled users to interact with the virtual environment.

Case and project type	Purpose	Design phase, interactive features and number of sessions	Outcome of implementing VR
Case A. The ICU unit for a whole hospital floor	Explore how alternative visual- and information mediums could provide better understanding for future workplace and validate design requirements	***Technical design phase*** • Freely exploring the virtual environment • Single-user 4 VR-sessions	• Users discovered and addressed previously unrecognized issues (e.g., placement change of lift handling equipment, elevation of windows between patient rooms)
Case B1-B2. The psychiatric ward, including patient rooms, administrative area and dining area	Inform healthcare staff of the design of the new facility and provide healthcare staff with an accurate insight into their future workplace	***Concept design & Technical design phase*** • Freely exploring the virtual environment • Single-user 2 VR-sessions	• Users showed preference for seeing future workplace in VR instead of 2D drawings and 3D models during staff-days • Decision to consider VR implementation in future projects beyond informative purposes
Case C1-C2. (various facilities) Rooms pertaining to various types of operations and common areas independent of a particular operation	Inform and explore how alternative visual- and information mediums could address certain design issues more accurately (e.g., sightline from ICU control room, logistical flow)	***Concept design, spatial coordination, and technical design phase.*** • Freely exploring the virtual environment • Single-user 30 VR-sessions	• Understanding regarding design issues linked to hidden sightlines, test of logistical flow and understanding of room-scale were achieved more accurately and faster compared to earlier reviewing sessions with 2D drawings and 3D-models • Users experienced VR as easier compared to 2D drawings and 3D-models when negotiating design requests with design team members
Case D. ICU unit and hyperbaric chamber	Explore an alternative visual- and information medium to validate set spatial requirements in final design review before construction documents were handed over	***Technical design phase*** • Freely exploring the virtual environment • Single-user 8 VR-sessions	• Change placement of non-structured elements (e.g., electrical outlets, medical equipment) • Addressed issues related to workflow logistics of room via static-scenarios in the virtual environment
Case E. (ViCoDE) – Unit of obstetrics and gynecology - Robot assisted surgical room	Explore an alternative visual- and information medium that can address design issues related to fitting a new surgical room in existing space	***Preparation and Brief and concept design phase*** • Freely exploring the virtual environment • Object interaction • Multi-user 2 ViCoDE-sessions	• Consensus on solutions between all parties was achieved • Users experienced design review in VR as more engaging and inclusive than 2D drawings and 3D-models
Case F. A single radiology room with an adjacent corridor and common area	Explore an alternative tool that can address design issues related to fitting a new radiology operation room in existing space	***Technical design phase*** • Freely exploring the virtual environment • Object interaction • Multi-user 3 VR-sessions	• Consensus on how to fit radiology room in existing space achieved after three VR-sessions • Compared to 2D drawings and 3D-models, interactive scenarios in VR were experienced by users as more understandable when testing logistical flow and spatial understanding of radiology room

By using interactive features allowing real-time object interaction (cases E and F), participants could resolve design issues more rapidly compared to cases limited to free navigation in the virtual environment (cases A-C). For instance, participants in case E, where structural changes (e.g., walls, room layouts) were explored, managed to identify and resolve significant structural design issues within hours. In contrast, participants in case C, facing similar structural issues, required *2-3 weeks of revision time between each VR-session [Arch, case C]* to update and revise VR-models. In case F, although changes were strictly non-structural (placement of electrical outlets, medical equipment), participants still benefitted from the interactive features, enabling rapid evaluation and immediate layout adjustments.

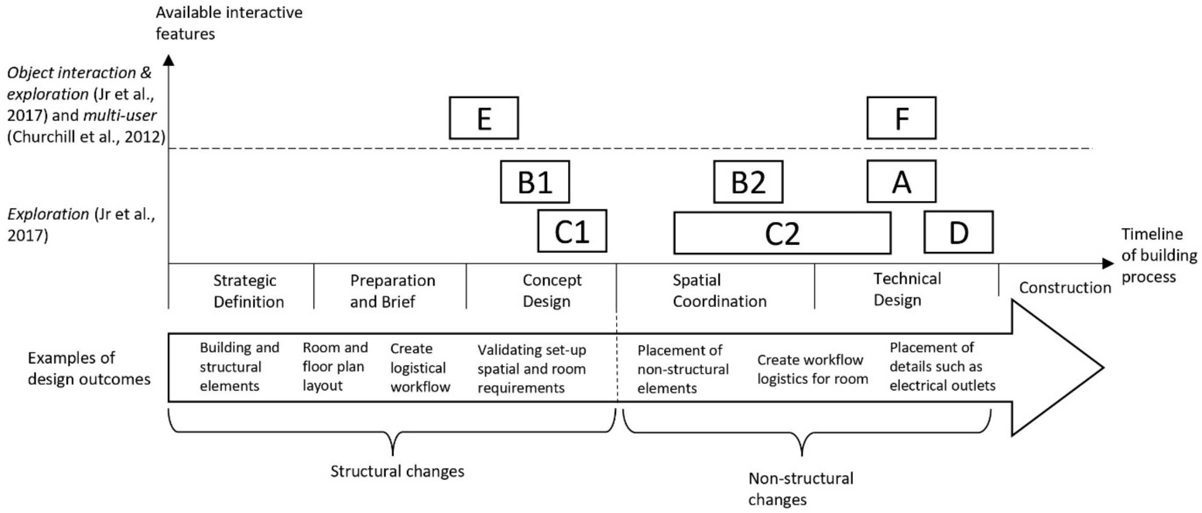


Figure 6: The figure illustrates the cases and the possibility and focus of influence the design outcomes when using VR.

As clarified above, in case F, despite participants having access to both object interaction and multi-user interactive features, design changes remained non-structural due to pre-existing spatial constraints. Still, these features allowed efficient evaluation and rapid decision-making for furnishing and equipment placement. To this point, retrofitting a new type of healthcare operations (radiology) into existing built space meant that due to design review taking place close to construction, that the use of the object interaction feature was limited to arrangement of furnishing. In other words, the spatial boundary conditions connected to structural changes (as observed in case E) are set in earlier design phases, whereas in the later design phases (case A, D), smaller, non-structural changes can be influenced (see Figure 6).

In contrast, interactive features such as object interaction were less restricted in case E, as structural boundary conditions were not yet finalized (e.g., floorplan, room layouts). Both cases E and F prominently featured task-based scenarios through active and simultaneous rearrangement and evaluation of furnishing layouts by participants. While cases A-D included tasks related to evaluating sightlines, logistical flow, and minor furnishing placement, these scenarios lacked the immediate interactivity and collaborative adjustment possibilities characterizing the scenarios in cases E and F. Instead, scenarios in cases A-D were limited to visually identifying design issues without real-time adjustments, thus requiring significantly more VR-sessions. All in all, the data shows how VR has been used for extraction of experience and practice related knowledge from healthcare staff throughout the different phases of the design process.

4.2.2 Explorative dimension of VR

Observations show that beyond the available interactive features, the design phase in which VR was used and the intention of using VR (i.e., design review or informative purposes), that there was an explorative dimension of using VR that participants in the different cases had not experienced when using 2D drawings and 3D models.

"It (VR) triggers thoughts in the users. Even if they understand 2D drawings, it does not necessarily translate into the questions you need to ask yourself around how it should be designed to get the most efficient outcome. They (end-users) are not relying on somebody else when exploring and finding things and do not feel uncomfortable

about asking someone else. They wander around and notice things and we get this great feedback that no other method has provided us with. [BC, case F]"

Figure 7: From case A, the resolved design issues (left), which then were incorporated into the final design (right).

The above quote aligns with observations made in case A, where VR was used for both informative as well as design review purposes. This exploratory approach to using VR was the most apparent in the first VR-session and later shifted, depending on the purpose, to a more structured procedure for design review purposes. The explorative aspect became particularly evident when the initial informative purpose of using VR shifted towards active identification and resolution of specific design issues. For instance, in case A, VR was initially used primarily to familiarize healthcare staff with the proposed design, but this subsequently led to discovery and addressing of critical design issues such as window elevation between patient rooms and the placement of lift handling equipment, which were then incorporated into the final design (see fig 7).

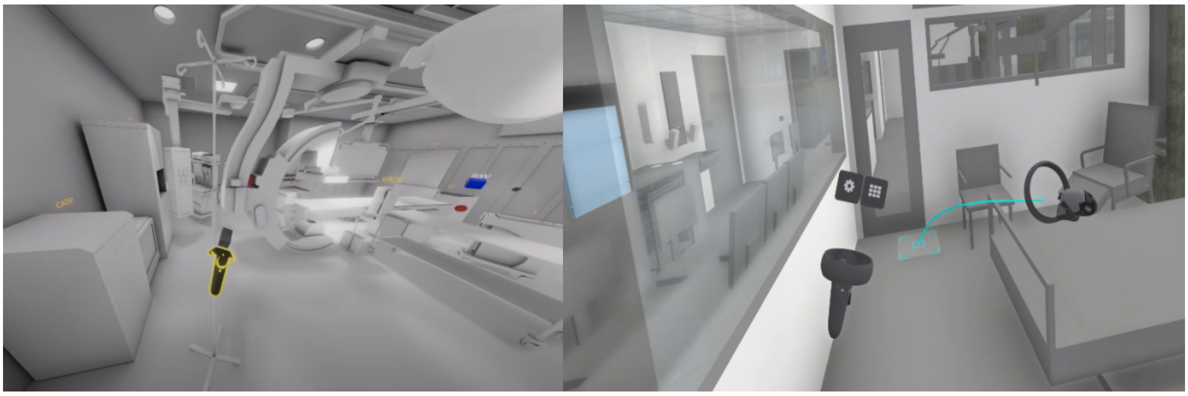


Figure 8: Healthcare staff moving medical equipment in the VR-model for case F (left) and in case D navigating the virtual environment via teleportation (right).

Also, as indicated by the quote above, participants in case F were less reliant on design team members when conducting design review with VR compared to when 2D drawings were used in case F. This independent exploration of the virtual environment among end-users was also observed in several of the other cases as well where the healthcare staff expressed how they were "*able to identify design issues that they previously had taken for granted were already addressed [HS, case A]"* and similarly observed by the BIM-coordinator responsible for the VR-workshops that "*they (healthcare staff), despite their hectic work schedule, were more likely to show up to the design review session as they find it more engaging and understandable than 2D drawings [BC, case C]"*. To this point, the increased engagement observed in the studied cases suggest that use of VR not only help end-users such as healthcare staff to explore the virtual environment more independently but also encourage them to participate in future workshop sessions (see fig 8). For instance, in the two sessions VR was used in case E, the same healthcare staff participated throughout both sessions and similarly, healthcare staff and project leaders in case D participated in multiple workshops out of the 8 sessions in total that took place.

4.3 Mapping cases to general classification of user-involvement

In the following sub-sections, the different VR case studies are mapped according to the different definitions of collaborative practices described in Caixeta et al.'s (2019) classification.

4.3.1 Informative

Case B, with its informative use (i.e., VR used during informative "staff-day") was mapped to an informative level of user-involvement, due to that the design team did not incorporate their comments into the design. In this setting, the healthcare staff paid more attention to the VR medium than the available 2D drawings and 3D models.

Similarly, case C1 involved VR being used for informative purposes with healthcare staff and facility managers not providing feedback to design team members. Therefore, these end-users had no formal role in the project, although this changed later when VR was used to gain feedback on the design. Similarly, case A had the first out of four VR-sessions being informative, with following sessions using VR for design review purposes.

4.3.2 Consultative

In case A, VR was initially used for informative purposes and later used for design review. The level of involvement was therefore informative, for the first session, as well as consultative when VR was used in the remaining three VR-sessions for design review purposes. However, the involvement was limited to a consultative level due to end-users not actively being involved in generating new design proposals but instead commenting on design issues that were discovered in each session.

Similarly, end-user involvement in case D, could be argued to be limited to a consultative level. Although VR was used very late in the design process and there was an absence of structured procedures to the design review, end-users still had the opportunity to provide feedback and input to the design. However, it could be argued that the late design phase made it difficult to use this feedback in a structured way and thereby conduct the design review session more systematically (scenario-based approach). Still, by allowing users to freely explore the virtual environment, the result from the case showed that smaller, non-structural design issues could be found, discussed, and subsequently addressed. This result highlights that it was difficult to understand 2D drawings and 3D models, that had been used up until VR was used.

4.3.3 Participatory design

Case C2 had the highest number of VR workshop sessions, each characterized by clearly structured procedures (e.g., pre- and post-session evaluations and BIM coordinator facilitating the design review). Due to the iterative feedback process and the close collaboration between end-users and the design team, this case aligns clearly with participatory design as defined by Caixeta et al. (2019). However, participants in these sessions could only freely explore the VR environment without directly implementing real-time changes themselves (e.g., not support for object interaction as interactive feature); they relied on the design team to incorporate their feedback. According to Caixeta et al.'s (2019) definition, participatory design is characterized by close collaboration and active involvement of users where they are able to "*share and influence design decisions"*, yet without these users becoming "*part of the design team"* responsible for co-creating proposals. This definition aligns well with the characteristics observed in case C2.

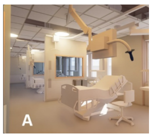
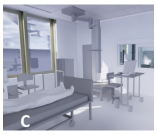
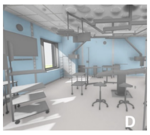
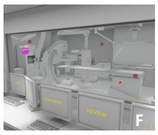
4.3.4 Co-design

Interestingly, VR in case F was used in the same design phase as case C2, A and D which all used VR for design review. However, the high level of available interactive features (e.g., multi-user and object interaction, users able to influence furnishings in the VR model) and structured procedure, led to higher levels of involvement from an end-user perspective. By enabling task-based scenarios in the virtual environment, users were able to revise the design proposals in real-time, towards a suitable design proposal that would fit the existing space. In regard to healthcare staff in case F being able to evaluate and making joint changes to the design in real-time, healthcare staff can be considered "*members of the design team and co-design solutions with architects"* (Caixeta et al., 2019). In case F the available interactive not only supported *Exploration* but also supported *Multi-user* and *Object interaction*, see Table 2. Even though the healthcare staffs' ability to influence the design were limited to non-structural design, the ability to make joint changes to placement of medical equipment and test for example the logistical flow makes case F a co-design case.

With case E, the level of user involvement that was enabled via ViCoDE suggests the highest level of involvement. As observed in case E, the end-users become part of the design team and design team members gaining an advisory role, which supports the definition of co-design according to Caixeta et al. (2019). Similar to case F, the task-based scenarios when design review, facilitated a co-design setting among end-users. Case E also supported interactive features *Exploration, Multi-user* and *Object interaction*, see Table 2. Different from case F, however, was the level of influence participants had during the VR-sessions. Specifically addressing design issues connected to structural layout and establishing the floor and room layout. This level of influence on design outcome is also consistent with the definition of co-design provided by Caixeta et al. (2019) which states that a co-design level of user-involvement is primarily achieved in the early design phases due to the addressed design issues being of operational character and how design issues in later design phases requires experience of the design process that is beyond end-users' knowledge and design experience.

In summary, cases B and C1 involved an informative level of user involvement, as participants provided no direct input influencing the design outcome. Cases A and D reflected a consultative level, where end-users commented on identified design issues but did not actively generate design proposals. Case C2 represents participatory design, characterized by close collaboration between end-users and the design team, although real-time interactions were limited. Lastly, cases E and F reached a co-design level of involvement, as end-users actively participated in generating design solutions through real-time VR interactive features (e.g., *Exploration*, *Multi-use* and *Object interaction*), with case E addressing structural design issues and case F primarily focusing on non-structural adjustments, see Table 3 below.

Table 3: Collaborative practices mapped to the different cases studied.

	Case A	Case B	Case C	Case D	Case E	Case F
Informative	✓	✓	✓			
Consultative	✓			✓		
PD			✓			
Co-design					✓	✓

This mapping process suggests that immersive HMD VR as a visual and information medium has the following effect on end-user involvement:

- Triggers new thoughts about the design which can help design team members better understand end-users' daily working tasks.
- Interactive features enable flexible end-user involvement – both sequentially (individual exploration followed by group discussion) and simultaneously (real-time collaborative design evaluation.
- End-users can more clearly articulate their operational knowledge when design review procedures in VR are clearly defined and structured (e.g., guided interactions and systematic VR-model preparation).

These observations suggest the need for a more contextual understanding of how VR affects collaborative practices. Specifically, to achieve the intended level of involvement when using VR, it is important to consider both the interactive features within the VR model and the structured procedures (i.e., clearly defined design-review tasks, facilitation during VR sessions, and preparation of VR models) that define collaborative practices. Therefore, in the following discussion a classification for user-involvement when using VR is presented and how interactive features such as *Exploration*, *Multi-user* and *Object interaction* support different collaborative practices.

5. DISCUSSION: CLASSIFICATION OF USER-INVOLVEMENT

The results of this study are discussed in regard to end-user involvement when immersive HMD VR is used in collaborative practices. First, the use of interactive features and how it affects end-users' ability to understand and evaluate the design is discussed, which related to research question 1. Second, classification of collaborative practices when immersive HMD VR is used, is covered, which relates to research question 2.

5.1 Interactive features and end-user involvement

Our results indicate that, regardless of the design phase, intention of use, and the extent of available interactive features, immersive HMD VR enhances end-users' spatial understanding by allowing them to experience the virtual environment at a 1:1 scale. This enhanced understanding is further reinforced by specific interactive features - such as exploration, multi-user and object interaction capabilities - which provide opportunities for richer collaboration and more effective feedback. These features ultimately help the design team better grasp end-users' daily working tasks and needs.

In light of these results, several interpretations can be made. Firstly, our findings suggest that interactive features play a crucial role in bridging the gap between the intention to involve end-users and their actual engagement. Specifically, the availability of interactive features in the virtual environment can mitigate the issue of false expectations that end-users might experience in traditional design processes using 2D drawings and 3D models (Choguill, 1996; Kim et al., 2016). For instance, even without certain features that help end-users collaboratively interact (multi-user) or revise and create design proposals (object interaction), features such as free exploration still allow end-users to identify and address design issues they were previously unaware of, as observed in case A and C (Berg et al., 2017; Haahr & Knak, 2022). Moreover, features such as object interaction and multi-user capabilities not only accelerate the design review process (Wolfartsberger, 2019) but also facilitate different modes of end-user involvement—sequentially (e.g., design review with specific intentions across multiple VR sessions) and simultaneously (e.g., shifting purposes within the same session). Our findings indicate that interactive features like object interaction and multi-user capabilities correspond to higher levels of involvement, as they enable end-users to become integral members of the design team (Caixeta et al., 2019), contributing to the creation of design proposals alongside the design team. In contrast, independent exploration of the building design primarily results in user involvement focused on evaluating rather than creating the design. In summary, these interactive features can be viewed as enablers for varying levels of end-user involvement when using VR.

Secondly, with immersive HMD VR resulting in enhanced spatial understanding for end-users, its role can shift from being used purely for informative purposes to actively supporting design review (e.g., case A and C). This finding suggests that involving end-users earlier in the design review process could be beneficial. For instance, with task-based scenarios supported by object interaction and multi-user capabilities, immediate feedback from the building occupants can be gained regarding preferred design requests, resulting in shorter design review cycles (Roupé et al., 2020). Following this, users such as interior architects could be involved to further help facilitate building occupants' understanding of how different design layouts should be furnished and whether these requests align with spatial requirements that the design proposal needs to comply with. Consequently, a more collaborative understanding can emerge as a result of the shared frame of reference in VR (Truong et al., 2021). In this context, healthcare staff have the opportunity to review and share their knowledge of their daily working tasks with the design team, which allows seamless interpretation and discussion about the design in the virtual environment. It can be further argued that this shared context and understanding helps end-users to focus more on evaluating preferred design proposals rather than ensuring that they have interpreted the design correctly. Thus, there is a need to classify user-involvement more accurately when using VR.

5.2 Classification of collaborative practices when using immersive HMD VR

In this paper we have identified a research gap when it comes to investigating how implementation of immersive HMD VR with different interactive features can best be leveraged in different collaborative practices. Specifically, there is little knowledge around interactive features and the implications they have for design actions and subsequent design activities. This is supported by recent studies' effort to describe the need for identifying how certain interactive features are more suitable for various design context, type of design review as well as purpose of review (Horvat et al., 2022; Lapointe et al., 2021). This may be explained by the fact that it is important for practitioners to be provided with guidelines on what specific features can be helpful when involving end-users.

Therefore, our results suggest the need for a classification of end-user involvement that considers end-users' ability to express their wants and needs about the design. It could help facilitate a more purposeful approach to design review with VR and help practitioners more accurately choose an appropriate level of involvement, depending on design phase, implementation purpose and available interactive features in the immersive HMD VR system. Moreover, interactive features can help translate end-users' operational knowledge to an understanding that everyone involved can partake in. Our paper proposes that different interactive features can be leveraged to facilitate different levels of user-involvement. Specifically, our paper findings demonstrate a cumulative effect where different interactive features enable increasingly higher levels of end-user involvement. At an informative and consultative level, *exploration* (Jr et al., 2017) of the virtual environment is considered sufficient for end-users to independently identify design issues. At a participatory design level, adding *multi-user* (Churchill et al., 2012) capabilities enables end-users to jointly identify, discuss and collaboratively review design proposals. Finally, reaching co-design relies on the availability and simultaneous use of *exploration*, *multi-user* and *object interaction* (Jr et al., 2017). It should be noted that our classification is not based on measuring the interactive features per se, but instead on how the availability of interactive features supports or limits end-users' level of involvement during a design review session. In this sense, the outermost metric in our classification remains the level of involvement, not the features themselves.

Moreover, our classification builds on the assumption that collaboration occurs *within* the virtual environment. It also reflects the empirical scope of our study, which, due to a lack of systematic data on collaboration outside the virtual environment (case A,C and E), focuses on collaborative practices taking place within the virtual environment. In contrast, Caixeta et al. (2019) emphasizes collaboration through ongoing dialogue between stakeholders across different levels of involvement, without mapping those levels to specific technologies or methods. In our classification, we map the levels of user involvement based on how interactive features satisfy the different CVE criteria (transition between shared and individual activity, shared context, awareness of others, negotiation and communication and flexible and multiple viewpoints) (Churchill et al., 2012; Churchill & Snowdon, 1998). These are a set of criteria that Churchill et al. (2012) argues immersive VR-systems enable collaboration within virtual environments. Although they do not present the CVE criteria as a strict hierarchy, they highlight how a combination of met CVE criteria helps enable collaboration within virtual environments. Building on this logic, we propose a cumulative model in which interactive features are linked to increasing levels of user involvement based on how they progressively satisfy the CVE criteria. As more features become available, more of the CVE criteria described by Churchill et al. (2012) are fulfilled - enabling deeper and more participatory forms of collaboration within the virtual environment.

In our classification, each level of end-user involvement is linked to the interactive features that help fulfill the CVE criteria (Churchill et al., 2012). At the lower levels of user involvement (informative and consultative), exploration enables users to engage with the design individually, allowing spatial awareness and the ability to independently identify design issues. As a result, the criteria related to flexible viewpoints and individual activity are fulfilled, but not awareness of others or negotiation and communication (case A-D). Adding multi-user as interactive feature allows users to view each other's avatars and interact with each other in real-time, fulfilling further CVE criteria such as awareness of others and negotiation and communication (case E and F). By having multi-user and exploration available at the same time, all the CVE criteria are fulfilled. Users are able to transition from independent to shared activities (e.g., independently identifying design issues in different parts of the building design to jointly exploring and negotiating how to resolve identified design issues). In this context, we argue that multi-user as interactive feature is a necessity for facilitating higher levels of user involvement (PD and co-design). Finally, by adding object interaction users are able to, independently as well as jointly, make direct changes to the design team's developed design proposal (case E and F), resulting in users *acting as members of the design team* (Caixeta et al., 2019). We therefore argue that object interaction, when combined with multi-user and exploration, reinforces collaboration. Adding object interaction allows for an even higher level of user involvement than PD. Whereas multi-user enables shared exploration and discussion, object interaction gives end-users the ability to actively reshape the design layout itself. By making direct changes in the virtual environment, users are able to change the shared context itself, i.e., the design review space. As a result, users have the conditions to negotiate more efficiently as they can modify the design team's pre-defined design proposal and validate their own alternative design layouts together in real-time. Object interaction therefore enables end-users to move from participating in a pre-defined collaborative virtual environment (PD) to collaboratively designing it (co-design).

This distinction between PD and co-design also highlights one of the main ways in which our work differs from Caixeta et al. (2019). In Caixeta et al.'s (2019) classification, participatory design and co-design are not treated as separate levels of involvement, due to overlapping definitions and a lack of consensus in the literature. To this point, an argument can be made that our classification is stricter than Caixeta et al.'s (2019) general classification. Particularly when the aim is to involve end-users at higher levels of participation. For example, co-design within virtual environments (case E and F) can emerge only when different interactive features are available. At the same time, our stricter classification can help address concerns raised in earlier literature about the lack of attention to how chosen methods influence the quality of user involvement (Caixeta et al., 2019; Tritter & McCallum, 2006). Specifically, our classification highlights the importance of compatibility between end-users' expectations (identifying and resolving design issues) and the interactive features that enable those expectations to be fulfilled. When this alignment is achieved, immersive HMD VR does not simply support evaluation of the design proposal but allows end-users to frame design problems themselves (Tritter & McCallum, 2006). In the context of design review, this framing occurs especially when interactive features enable task-based scenarios. As observed in cases E and F, end-users such as healthcare staff are able to use their operational knowledge to jointly test scenarios simulating real-world workflows.

While our classification is based on available data across the six cases, we also considered possible configurations of interactive features not observed in the data. An example of such a configuration involves users having access to exploration and object interaction but not multi-user. While exploration allows users to navigate the space and individually design review as well as object interaction enabling direct changes to the design, the absence of multi-user means end-users cannot perceive others' actions, negotiate in real time, or share mutual frame of reference within the virtual environment (Johansson & Roupé, 2024; Truong et al., 2021). As a result, CVE criteria are only partially satisfied. On the one hand, end-users would be able to explore the design proposal by themselves (*individual activity*) and view design review spaces from different angles (*flexible and multiple viewpoints*). On the other hand, sharing identified issues (*communicate and negotiate*) and creating different layout configurations to evaluate real-world workflows (*shared context*), would all be done independently. The level of involvement would therefore be considered consultative. Consequently, in our classification, a setting where multiple users can jointly explore and identify design issues in a static virtual environment (exploration and multi-user) is considered to support a higher level of involvement and collaboration, compared to a setting in which a single user can modify the design (exploration and object interaction) but does so in isolation.

The circular shape of the arrow reflects the sequential and simultaneous levels of end-user involvement that immersive HMD VR provides as a visual and informational medium (e.g., shift in purpose of using VR, exploring the building design freely). The ability to explore the virtual environment, as observed in all cases, is illustrated across all levels of involvement in the classification and can be seen as a foundational feature upon which other interactive features are built. While basic exploration allows users to navigate and view the virtual environment, it does not offer the same interactivity within the virtual environment as features like object interaction and multi-user, which enable users to actively engage with and modify the virtual environment. For example, end-users might not have an explicit movement goal (Jr et al., 2017) (case A and B) when involved for informative purposes, but in cases where involvement takes place for design review purposes (case C-F), end-users navigate the virtual environment and identify issues either individually or collaboratively. If object interaction is also available, end-users can make changes directly to the design, allowing them to better negotiate and communicate their ideas with each other within the virtual environment (Churchill et al., 2012). Here, collaboration is understood as taking place in shared immersive spaces, rather than around external displays, as it allows participants to have a shared frame of reference and make changes to the design in real time. Task-based scenarios, such as evaluating sightlines or logistical flow from the perspectives of healthcare staff, help structure the design review and give participants a clear purpose for their actions in VR. When combined with multi-user capabilities, these scenarios support a workflow where participants can switch between jointly reviewing spatial solutions and individually exploring areas of concern (Churchill et al., 2012), resulting in a more focused and collaborative design review session.

The dividing line between the consultative and informative levels reflects whether end-users have a formal role in the project. In our classification, the interactive dimension of VR is considered integral to determining the level of user involvement. Specifically, we argue that the more interactive features are available (exploration, multi-user, and object interaction), the higher the level of user involvement that can be facilitated. Lower levels of involvement (i.e., informative and consultative) correspond to only exploration being available. In contrast, if higher levels of involvement are desired, additional interactive features such as multi-user and object interaction can be leveraged to enable participatory design and co-design. When exploration, multi-user, and object interaction are all available, users can jointly review, modify, and evaluate building design proposals in real-time.

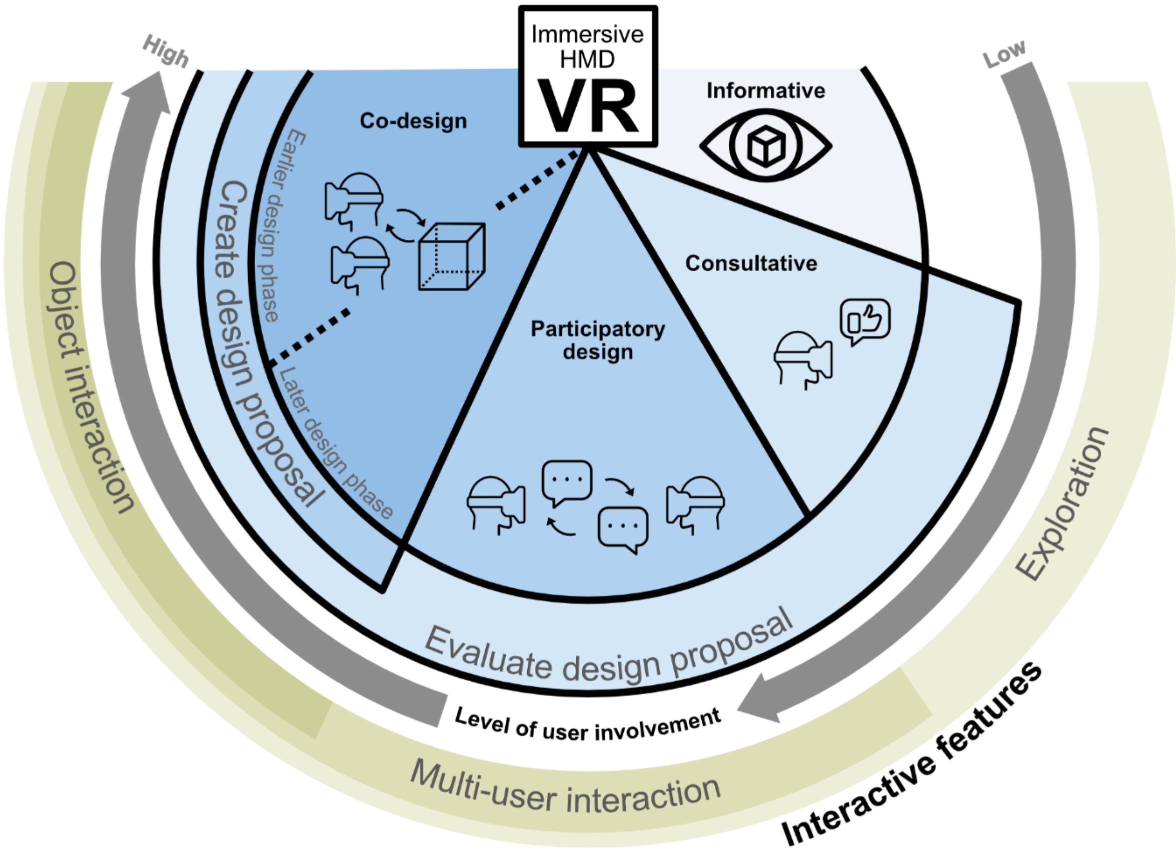


Figure 9: Classification of immersive HMD VR used in different collaborative practices. Notice how the increased level of interactivity corresponds to higher levels of user-involvement.

In these higher levels of user-involvement, users help generate design proposals via VR, rather than evaluating them, thus leading to increased levels of end-user involvement as end-users become part of the design team. This observation aligns with Caixeta et al.'s (2019) description of participatory design (PD) and co-design as collaborative practices at an equally high level of involvement, yet with different focus. Specifically, while PD puts emphasis on democratic decision-making and ongoing stakeholder engagement throughout the entire design process, co-design is described as more suitable for early design phases, focusing specifically on the operability and feasibility of proposed solutions. Our findings support this differentiation by illustrating how earlier design phases (e.g., preparation and brief) offer better conditions for co-design, enabling healthcare staff, by using a combination of freely exploring the virtual environment together with object interaction and multi-user features, to better understand how the building design could affect them, as spatial constraints (e.g., structural changes) have not yet been established. However, our study also shows that healthcare staff can, via the use of above features, also *become part of the design team* (Caixeta et al., 2019), in later design phases as well (case F). Although limited to non-structural adjustments due to existing boundary conditions, healthcare staff in case F were able to actively participate as design team members. They explored and tested different configurations of medical equipment placement. This allowed them to evaluate various aspects of the future radiology room in VR, such as sightlines, logistical flow, and room size. This difference in when in the design process co-design takes place is reflected in figure 9, by placing earlier phases of co-design above later phases in terms of level of end-user involvement. Therefore, we consider co-design taking place in early phases of the design process as the highest level of end-user involvement.

Lastly, it should be highlighted that the explorative aspect that is part of all the different levels of involvement refers to users' ability in immersive HMD VR, to explore design issues they previously were unaware of. As stated earlier, this explorative aspect may be reinforced when combined with object interaction and multi-user, allowing users to actively rearrange spatial layout. Specifically, in a co-design setting, where users are given the conditions to shape their own workspaces, this results in an intentional explorative process. Users are not only exploring and identifying issues in the architect's developed design proposal but also iteratively evaluating and refining different spatial configurations in real-time. For example, in Case F, healthcare staff jointly modified the placement of medical equipment and tested logistical workflows within the immersive VR model, which allowed them to evaluate and validate different room configurations. In this sense, co-design can be understood as a structured explorative process, where the act of making joint changes and developing the design proposal itself enhances spatial understanding and engagement among end-users. Therefore, a controlled, 360-degree view along a fixed pathway does not meet these criteria due to users being prevented from independently exploring the virtual environment. In contexts where the purpose of using immersive HMD VR shifts during a project (e.g., from informative to design review), it is the capability to freely explore the virtual environment that helps project members determine whether increased end-user involvement - such as moving from an informative to a consultative or participatory level - is necessary.

However, it is also important to acknowledge the need for a contextual definition of what user-involvement means in these processes. The general definition of user-involvement in building design used by Caixeta et al (2019), describes it as *the range of influence users or their representatives have over the final product* (Bergvall-Kareborn & Stahlbrost, 2008), though this definition is not applicable on our observations. One reason being that except for case A, there have not been any follow-up studies that validate whether addressed design issues in connection with VR-sessions were actually incorporated into the final hospital design. Another reason is that the interactive aspect of VR as visual and information medium has meant that user-involvement can take place both sequentially and simultaneously in the span of multiple design review sessions. Lastly, with the availability and combination of various interactive features, end-users can better understand how their operational knowledge and experience are connected to the design layout, thereby enabling them to express their wants and needs to the design team more accurately. These observations showcase how user-involvement via immersive HMD VR revolves around enabling conditions for end-user involvement and specifically help create a basis for decision making in the project where end-users' implicit and operational knowledge becomes understandable by all involved project members. Thus, our definition of end-user involvement when using VR as visual and information medium is presented as follows: *To what degree immersive HMD VR creates the conditions that enable end-users to express their wants and needs about the design.*

An interpretation that follows from this definition is that immersive HMD VR may help democratize the decision-making process by reducing end-users' reliance on the design team for spatial understanding. Furthermore, with earlier research emphasizing how VR is considered a pedagogical communication tool by both end-users and design team members (Sunesson et al., 2008), collaborative decision-making is more likely to emerge. As a result, it could then be argued that immersive VR may help mitigate team members' interpretative prerogative that typically emerge in traditional design processes (Henderson, 1998). In this democratization of the design process, it implies that participants can hold each other accountable during design reviews when decision-making is viewed as open and inclusive (Carthey, 2021). Also, the increased level of participation could help involved project members define and accept their own responsibilities in the dialogues that emerge in these processes (Manzini, 2016). This is supported by earlier studies investigating decision-making processes in healthcare design, observing how a project is more likely to achieve set desired outcomes when project owners accept their own accountability and responsibility in the project (Hamilton, 2016). Moreover, this would mean understanding how their design requests must consider the project's spatial boundary conditions and from a design team perspective, create the design review setting that help end-users better understand these constraints (e.g., task-based scenarios in VR, ability to influence spatial layout).

6. CONCLUSION

The aim of this paper has been to develop a classification for user-involvement in VR, which considers different interactive features (i.e., freely exploring the virtual environment, multi-user, and object interaction) and project-based factors (i.e., design-phase, purpose of use). There are two main results that can be extracted from our study: firstly, it shows that the immersive and explorative nature of VR triggers new ideas and enhances end-users' understanding of the design. This understanding is further enhanced by specific interactive features such as independent exploration, object interaction and multi-user. When combined, these interactive features help facilitate different levels of collaborative practices (e.g., PD, co-design). Secondly, VR is shown to help design team members better understand how to translate end-users' implicit operational knowledge and experience into explicit design proposals. These findings address the research gaps by identifying how different interactive features help with design understanding in the context of the studied cases, considering both the design phase and purpose of use. Also, by identifying the need for a contextual classification specific to immersive HMD VR (i.e., informative, consultative and participatory/co-design) a better understanding of how immersive HMD VR as visual and information medium can be used in collaborative practices. Thus, our paper presents the following contributions:

1. Based on Caixeta et al.'s (2019) classification, a new classification was developed for end-user involvement with immersive VR (i.e., informative, consultative and participatory/co-design), which incorporates the role of interactive features as enablers of different levels of end-user involvement
2. Validation of existing literature's findings that indicate that the enhanced spatial understanding end-users gain via immersive HMD VR creates better conditions for their operational knowledge and experience to be understood by design team members
3. Knowledge concerning interactive features which show how object interaction and multiple users in the virtual environment further enhances end-users' understanding of how their operative knowledge and experience is connected to spatial boundary conditions

The practical implication of this paper mainly concerns end-users (i.e., healthcare practitioners and facility managers) as well as design team members. For end-users, this classification of user-involvement can help them with setting requirements and thereby help set conditions for expressing their needs and wants in the project compared to a traditional design process. Similarly, by better understanding how their operative knowledge and experience are connected to the design (e.g., best-practice learning via scenario approach during design review) they can more confidently negotiate design ideas with the design team. For design team members, it can help them set appropriate level of involvement depending on design phase and intended use. Likewise, design team members can leverage interactive features in collaborative practices to accelerate decision-making and as a result, reduce the overall time of design cycles.

Lastly, our study has limitations that must be acknowledged. First, as a qualitative study, the findings may not be generalizable. However, our aim was to provide insights from real-life projects where immersive HMD VR has been used, which could inform future research. Subsequent studies could expand on real-world data while incorporating quantitative metrics such as object interaction frequency, structured questionnaires measuring cognitive load during design review and perform comparative analyses of identified design issues by healthcare staff and other stakeholders when using traditional visualization methods (e.g., 2D drawings) versus immersive HMD VR. Larger-scale, quantitative studies could further assess whether similar patterns emerge in other real-life projects.

Secondly, a key question is how multiple stakeholders can collaboratively develop design proposals while balancing project constraints, regulations, and spatial needs. For instance, healthcare staff prioritize logistical flow and patient integrity, facility planners focus on flexibility, and architects ensure accessibility and design vision. Understanding how they communicate, interpret, and negotiate design decisions in VR is crucial. A multimodal interaction methodology (Räisänen et al., 2024) categorizes communication into verbal, non-verbal, and material/digital modes, where interactive VR features like multi-user functions and object interaction play a role. Examining how stakeholders use these modes in VR could offer deeper insights into participatory and co-design processes in immersive environments.

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