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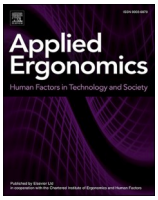

Investigating the relationship between three-dimensional perception and presence in virtual reality-reconstructed architecture

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ABSTRACT

Identifying and characterizing the factors that affect presence in virtual environments has been acknowledged as a critical step to improving Virtual Reality (VR) applications in the built environment domain. In the search to identify those factors, the research objective was to test whether three-dimensional perception affects presence in virtual environments. A controlled within-group experiment utilizing perception and presence questionnaires was conducted, followed by data analysis, to test the hypothesized unidirectional association between three-dimensional perception and presence in two different virtual environments (non-immersive and immersive). Results indicate no association in either of the systems studied, contrary to the assumption of many scholars in the field but in line with recent studies on the topic. Consequently, VR applications in architectural design may not necessarily need to incorporate advanced stereoscopic visualization techniques to deliver highly immersive experiences, which may be achieved by addressing factors other than depth realism. As findings suggest that the levels of presence experienced by users are not subject to the display mode of a 3D model (whether immersive or non-immersive display), it may still be possible for professionals involved in the review of 3D models (e.g., designers, contractors, clients) to experience high levels of presence through non-stereoscopic VR systems provided that other presence-promoting factors are included.

1. Introduction

This paper investigates the relationship between 3D (three-dimensional) perception and presence in Virtual Reality-reconstructed architecture. Virtual Reality (VR) typically refers to technology that can immerse a person into a three-dimensional computer-generated simulated environment (Sherman and Craig, 2003). The term itself was coined by Jaron Lanier in 1989, who used it to refer to "three-dimensional realities implemented with stereo viewing goggles and reality gloves" (Krueger, 1991). However, Steuer (1992) broadened the definition to focus on the user experience in VR, specifically, the feeling of presence or the sense of being in an environment. This definition of VR as a presence experience allows for the distinction among different VR systems according to the level of presence provided. In turn, Wann and Mon-Williams (1996) connect human perception to presence and point out that a system must satisfy criteria that arise from human perception to be considered a Virtual Environment (VE). Both Steuer's and Wann and Mon-Williams's definitions do not rely on a system's technological apparatus and appear better aligned with the general purpose of VEs in most contexts of use, i.e., to deliver lifelike experiences. As such, in the context of VR applications in the built environment, VR can be defined as the experience of feeling present in a fictitious or envisioned environment through its representation.

Basically, VR systems include a 3D digital model, a display, interaction devices, and software to stitch all these components together. These, however, can vary largely, especially when it comes to the display type, which can be projection-based or head-mounted (HMD), monoscopic or stereoscopic. Furthermore, VR systems can be non-immersive or immersive. Usually, in low-end non-immersive systems, the display mode offers monoscopic views of a digital model, and interaction devices are limited to a simple mouse and keyboard. In high-end immersive VR (IVR) systems, a user's movements in the real world

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are tracked by sensors while the display delivers stereoscopic views of a model (Bertol, 1997). Stereoscopic displays have been demonstrated as an efficient technique for enhancing the illusion of depth (Chiuhsiang and Widyaningrum, 2018).

VR has become a popular technology in the AECO/FM (Architecture, Engineering, Construction, Operation and Facility Management) sector due to the perceived benefits associated with its ability to represent the scale, depth, and volume of spaces (Henry and Furness, 1993; Castronovo et al., 2017). These benefits are often associated with the realism of simulations. Immersive VR, in particular, is expected to provide users with "a realistic perception of the simulation" (Fernando et al., 2013) and "simulate the experience of moving through and interacting with the virtual space as if it was real" (Bassanino et al., 2010). In summary, the main goal of VR applications in built environment fields is to describe and resemble environments that do not exist in the real world (Bertol, 1997).

Therefore, realism is one of the major achievements and contributions of VR technology to the field. However, the VR equipment does not create a realistic experience; instead, it allows people to construct the scene by themselves, similar to when looking around a physical environment. In effect, human visual intelligence is responsible for creating and qualifying visual experiences in the computer-generated world (Hoffman, 1998). It follows that sensory processes and perceptual criteria dictate user experience and the effectiveness of virtual environments (Wann and Mon-Williams, 1996). In other words, what makes a VR experience more compelling (or lifelike) might be its ability to allow users to form more realistic mental images – i.e., "percepts" or "constructs" (Kosslyn, 1994; Hoffman, 1998; McGinn, 2004) – that are somewhat more similar to the ones they would create when in the physical world.

Since human perception runs on input from different sensory channels (Gifford, 2002), it is reasonable to assume that the more interfaces of interaction with the virtual world, the more closely a VR system would simulate perception, provided that sensory input delivered via interfaces are compatible with each other and consistent with real-world stimuli. As per Bertol (1997), the difference between non-immersive and immersive VR resides precisely in the multiple interface modes that make interaction and perception of the simulation more realistic in the immersive system. Other scholars argue that the most evident difference is the level of presence provided, which the immersive system aims to enhance by employing stereoscopic visualization and intuitive interaction (Steuer, 1992). In reality, various insufficiently explored and intricate technological and human factors would determine the quality of user experience in VR. For example, direct interaction methods seem to improve visual perception accuracy (Chiuhsiang and Woldegiorgis, 2017). The technique used to transition from the real to the virtual world may affect users' presence levels (Soret et al., 2021). Another example is a self-avatar, which can also increase the sense of presence and improve distance estimation by possibly acting as an important scale cue (Alshaer et al., 2017).

Perceptual realism and presence may vary largely across VR systems (Bertol, 1997). However, regardless of how immersive virtual environments are (from non-immersive to "fully-immersive"), research reinforces the expectation of a direct association between users' 3D perception and presence while interacting with the simulation. Nonetheless, the existence and configuration of such a relationship are still unclear. Often, scholars suggest that this could even be a two-way association where 3D perception and presence would cyclically impact one another. On the one hand, empirical evidence shows that immersive virtual environments promote accurate 3D perception (*3D representation* > *3D perception*) (Kalisperis et al., 2006; Zikic, 2007; Paes et al., 2017; Paes et al., 2021) and great levels of presence (*3D representation* > *presence*) (Steuer, 1992; Wann and Mon-Williams, 1996; Slater and Wilbur, 1997; Witmer and Singer, 1998; Paes et al., 2021). On the other hand, at the same time, the literature also suggests that presence is a precursor of perception (*presence* > *3D perception*): "an essential component for the complete perceptual experience" in the virtual world (Bertol, 1997), improving visual perception by enhancing the observer's attention and visual search abilities (Kalisperis et al., 2006; Oren et al., 2012; Heydarian et al., 2015). In a deliberate assumption, Henry and Furness (1993) state that the sense of presence enhances people's ability to perceive space.

As per Slater and Wilbur (1997) and Zikic (2007), there is not much information on the factors that affect 3D perception in virtual environments, and evidence about its relationship with the sense of presence is somewhat conflicting. On the one hand, a few empirical studies that have looked into the relationship between presence and distance perception in virtual environments (e.g., Thompson et al., 2004; Kalisperis et al., 2006; Interrante et al., 2006; Renner et al., 2013) showed that accurate distance estimation might not necessarily be evidence of great levels of presence. People may still perform well in estimating distances in virtual environments that do not offer the conditions for great levels of presence (Interrante et al., 2008). On the other hand, Slater and Wilbur (1997) state that presence has been found to correlate positively with the vividness of simulations (which includes both pictorial and depth realism).

2. Problem statement and research objective

This study's motivation stirs from the long-lasting assumption in the literature that more realistic virtual environments (in terms of 3D representation and user's 3D perception) – such as stereoscopic visualization-based ones – are inherently more immersive (hence delivering greater levels of presence), despite the lack of empirical supporting evidence. Thus, this research revolves around a single though rather intricate research question (given its elementary nature): the relationship between two key cognitive responses in virtual environments, namely, 3D perception and presence.

The general research hypothesis is that there is an association between those variables in virtual environments. Thus, the research objective is to test whether that is true. While 3D perception and presence have been investigated separately, their direct relationship has not been thoroughly examined to date (some previous attempts include Slater and Wilbur, 1997; Thompson et al., 2004; Kalisperis et al., 2006; Interrante et al., 2006; Interrante et al., 2008; Renner et al., 2013), although supported by theory and suggested in the literature, as discussed in more detail in section 3.3. The association is tested in two different virtual environments: non-immersive and immersive. The expected association tested is unidirectional, that is, 3D perception affecting presence.

Ultimately, this research aims at contributing to the body of knowledge about the factors that promote presence and its possible relationship to depth realism. This knowledge is essential to elicit the effectiveness of VR technology from the user standpoint and provide directions for developing and implementing increasingly effective VR systems. A better understanding of that relationship can foster a new generation of virtual environments in which 3D representations are manipulated to enhance presence levels and vice-versa. Developers may focus on delivering accurate 3D perception (through accurate depth representation techniques) to deliver highly immersive experiences.

3. Background

This section provides the theoretical background and rationale for the research question presented in the previous one.

3.1. Three-dimensional perception

Ultimately, the advantages of using VR technology to represent three-dimensional architectural artifacts are only relevant if the 3D perception of virtual environments is similar enough to the 3D perception of one's physical reality. It is only possible to conclude about the effectiveness and benefits of VR technology in the built environment

domain by satisfying such a condition (in contexts where realistic simulations are desirable). Thus, the effectiveness of VR applications in built environment fields such as design review (Paes et al., 2021), workforce training (Eiris et al., 2020), occupant training for active shooting (Lovreglio et al., 2022b) and earthquake (Feng et al., 2020) emergencies, and research on occupant behavior during fires (Lovreglio et al., 2022a) and earthquakes (Feng et al., 2022), might also be established in terms of the resemblance between human visual perception in the virtual environment and the correspondent physical environment, that is, the extent to which the virtual environment mimics one's visual experiences in the physical reality.

Naturally, the level of realism of a three-dimensional virtual environment is largely affected by the extent to which it is able to convey depth. Historically, the representation of depth has been pursued through various techniques (such as perspective constructions) to provide observers with realistic representations. Depth representation is expected to facilitate an understanding of the three-dimensional features of the depicted space (such as shape, size, volume, proportions and scale), which is a prerequisite for problem-solving and decision-making in architectural design (Bertol, 1997; Zikic, 2007). This relationship is illustrated in Fig. 1 below.

However, depth representation per se does not guarantee an accurate perception of an environment's three-dimensional structure. One must perceive depth from its representation. A given representation can only be deemed more realistic if one actually perceives three-dimensionality more accurately from it. Therefore, in reality, there is something between depth representation and realism of representation shown in Fig. 1, and that is precisely depth perception – used interchangeably with 3D perception in this study: a particular visual process within visual perception that accounts for the perception of depth of elements in space (see Fig. 2).

Visual perception is a sophisticated, creative and innate process through which people construct three-dimensional objects and entire worlds. Evolutionarily speaking, humans are trained to see things in three dimensions. When looking at a static figure of a house in perspective, for instance, the human brain will likely understand the house's three-dimensional shape from that flat representation (Marr, 1982; Hoffman and Singh, 2006). In the process of constructing three-dimensional scenes and objects, the visual system makes use of multiple "sources of information" or "visual cues", which provide information about size, shape, color, location, and other aspects of objects and spaces (Cutting and Vishton, 1995; Hochberg, 1998; Zikic, 2007).

Depth cues can be either geometric (e.g., distance, direction) or featural (e.g., color, texture) (Kimura et al., 2017) and further categorized into primary cues (stereopsis and parallax) and secondary cues (motion parallax, linear perspective, occlusion, size, texture, shading and shadow, light, color, among others) (Kelsey, 1993; Khuu et al., 2014). Provided by binocular vision, the binocular depth cues of stereopsis, parallax, and binocular disparity (the difference in the positions of binocularly visible objects) are deemed by many scholars the most relevant depth cues, although their relative importance is still unknown (England et al., 1992; Hubona et al., 1997; Hubona et al., 1999; Brooks, 2017).

There has been much debate on the term "spatial perception" adopted by some scholars in the field (e.g., Henry and Furness, 1993; Interrante et al., 2008) to refer to the process of visual perception of three-dimensional environments. The argument is that people do not perceive space per se but objects in space (Cutting and Vishton, 1995; Gibson, 1979). As an alternative, researchers have employed various terms to refer to the perception of the spatial configuration and three-dimensional arrangement of environments, such as "spatial understanding" (Schnabel and Kvan, 2003), "spatial cognition" (Kimura et al., 2017), "3D visualization" (Hubona et al., 1997), or yet, "spatial comprehension" (Zikic, 2007). In order to avoid misconceptions of nomenclature, this study adopts the term "three-dimensional perception" or simply "3D perception", as did Wann and Mon-Williams (1996), Norcia and Gerhard (2015), and Paes et al. (2021), to refer to a particular perceptual process within visual perception that governs the interpretation of visual cues about the three-dimensional configuration of a space, that is, its three-dimensionality (horizontal, vertical, and depth dimensions).

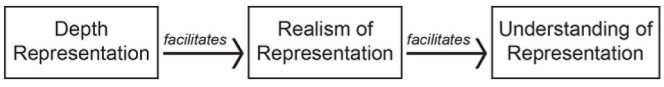

Fig. 1. Relationship between depth representation and understanding of representation.

3.2. Presence

Another major factor in delivering lifelike experiences is the sense of presence: the subjective human experience of inhabiting an environment also derived from perceptual processes. Witmer and Singer (1998) define presence as "the subjective experience of being in one place or environment, even when one is physically situated in another" and argue that it is based on "the interaction between sensory stimulation, environmental factors, and internal tendencies." Presence is a defining factor of VR experiences, resulting from perceiving oneself in the digital space (Wann and Mon-Williams, 1996) and an essential component for the complete perceptual experience in the virtual world (Bertol, 1997). It positively correlates with information acquisition, learning, and task performance (Oren et al., 2012; Faas et al., 2014). Users should be better able to perform visual search – find, locate, and recognize visual information, as defined by Gibson (1979) and Gifford (2002) – and, therefore, better perceive space in virtual environments thanks to greater presence levels (Henry and Furness, 1993; Kalisperis et al., 2006; Heydarian et al., 2015).

Witmer and Singer (1998) argue that the sense of presence in virtual environments is a function of two essential factors, namely, involvement and immersion, which in turn are subject to individual factors (including immersive tendencies) and a virtual environment's characteristics – such as the properties of the visual stimulus (resolution, color, sharpness, brightness, contrast, etc.). However, in Witmer and Singer's (1998) studies, there is a significant degree of ambiguity in describing these factors thought to underlie presence. These comprise control, sensory, distraction and realism factors and are expected to interact with one another and influence presence by affecting involvement, immersion, or both. Most of these factors, however, have never been verified empirically. Furthermore, it should be noted that while Witmer and Singer (1998) consider immersion and involvement as components of the presence construct, as per Caroux (2022), immersion and presence are still often used interchangeably despite efforts made to differentiate between them. While immersion would be typically related to sensory feedback (resulting in the *sense of being surrounded by* the virtual environment), presence would be more related to a cognitive psychological response (the *feeling of being in* the virtual environment) (Caroux, 2022).

Regarding human factors, studies have consistently found that some can significantly affect presence (Nowak et al., 2008); level of experience and age are known examples (Stanney et al., 1998). Besides visual input, the information presented via other sensory channels, such as haptic feedback via intuitive interaction controls (Kim and Rhiu, 2021), may also contribute to the sense of presence, but perhaps to a lesser degree (Witmer and Singer, 1998). Other studies have identified technological factors such as stereopsis, wide field of view, and high interactivity as critical to promoting great levels of presence (Castronovo et al., 2013; Dunston et al., 2011; Paes et al., 2021). Caroux (2022) stated that the display mode can significantly influence presence levels and that HMDs promote greater levels than conventional monitors. Alshaer et al. (2017) found that, among other system characteristics, the display type (between monitor and HMD) can affect presence and perception measures. In turn, and contrary to Witmer and Singer's (1998) expectations, Khashe et al. (2018) found no relationship between

certain technological factors and presence levels.

In summary, despite extensive research in the field, there is still much controversy about which factors affect presence in virtual environments (Renner et al., 2013). Studies suggest that these are both human and technological factors (Witmer and Singer, 1998; Khashe et al., 2018). Identifying and characterizing them has been acknowledged as a critical step toward enhancing VR experiences (Slater, 1999).

3.3. Relationship between three-dimensional representation and presence

Given the above, an association that appears quite straightforward is between 3D representation (a VR system's factor) and presence (a human factor) in virtual environments, mediated by 3D perception. The assumption is that people would experience greater presence levels in simulations that improve the perception of the virtual environment's three-dimensional configuration. Thus, the perception of three-dimensionality through depth representation would influence presence in virtual environments (Fig. 2) in the same way it influences their realism level (Bertol, 1997). The expectation about such association dates back to the early Renaissance when perspective paintings on walls at natural scale (a depth representation technique) promoted a strong psychological response where the viewer would feel transported into (or *present in*) the virtual space created by the painting (Bertol, 1997; Brooks, 2017). One must perceive the three-dimensional space portrayed in that representation to perceive oneself in the place depicted. In short, depth representation would enable depth perception, promoting the sense of presence (Fig. 2).

Contemporary theorists reinforce the expectation of a direct association between 3D perception and presence. Bertol (1997) suggests that immersive environments (which promote greater levels of presence) can improve perception (*presence* > *perception*); Henry and Furness (1993) make a deliberate assumption that presence enhances people's ability to perceive space (*presence* > *perception*). Steuer (1992) states that immersive environments enhance the level of presence due to, among other factors, stereoscopic visualization (*representation* > *perception* > *presence*); Witmer and Singer (1998) state that presence derives from perceptual processes, which in turn are subject to the realism of a simulation (*representation* > *perception* > *presence*). Schwind et al. (2019) found that the variance of presence responses significantly depends on the realism of the virtual scene (*representation* > *perception* > *presence*). Chowdhury et al. (2021) argue that greater presence levels could be induced by stronger depth cues, suggesting that presence could be associated with how accurately participants can form a mental model of depth information (*representation* > *perception* > *presence*). Combined, these arguments corroborate the expectation of a positive association between 3D perception and presence in virtual environments.

To reinforce, theorethically, depth perception seems to influence both the perceived realism and presence in virtual environments. Thus, in Fig. 2, presence occupies the same position as realism of representation in a reasonable assumption supported by literature that, in virtual environments, presence and realism are products of the same process, as discussed above. Assuming that presence and realism arise from the same process (depth representation and perception), one can expect to observe greater presence levels in more three-dimensionally realistic environments.

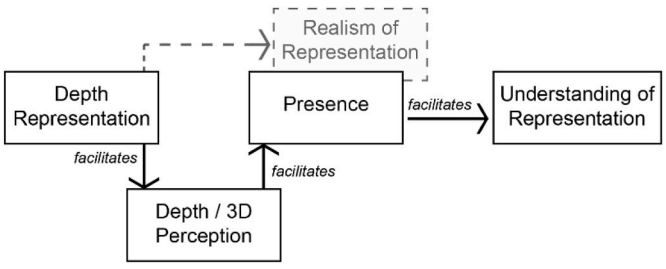

Fig. 2. Relationship between depth representation and presence.

3.4. Past experiments

The relationship between visual perception and presence in virtual environments is a challenging research topic. Data collection methods are difficult to develop since variables of interest often result from complex and unclear cognitive phenomena. Faas et al. (2014) thoroughly reviewed past attempts, most of which looked into the relationship between presence *or* perception (separately) and possible underlying factors. It should be noted that the relationship between perception and presence has not been thoroughly examined to date. Identifying and characterizing the technological and human factors that affect presence in virtual environments has been acknowledged as a critical step toward enhancing VR experiences (Slater and Wilbur, 1997; Slater, 1999; Zikic, 2007; Interrante et al., 2008).

3.4.1. Measuring presence

Assuming that presence was a function of a person's response to a system's properties, Witmer and Singer's (1998) presence questionnaire aimed at providing presence measurements based on users' opinions on the extent to which certain VR system characteristics led them to experience presence. Most questions were derived from involvement and immersion factors assumed to underlie presence. However, their scale is frequently criticized for measuring a person's subjective opinions about various VR system characteristics rather than the psychological state of presence (a cognitive response) (e.g., Slater, 1999; Usoh et al., 2000; Faas et al., 2014). Nevertheless, several studies have adapted and used their questionnaire to investigate presence in virtual environments. Other presence questionnaires (either adapted versions or completely new ones) have also been used in the VR research community, such as the Slater-Usoh-Steed (SUS) scale (Usoh et al., 2000) and the Igroup Presence Questionnaire (IPQ) (Schubert et al., 2001). Caroux (2022) provides a list of the various instruments found in the literature.

Using the SUS scale (Usoh et al., 2000), Higuera-Trujillo et al. (2017) found a correlation between presence levels and physiological and psychological responses. Chowdhury et al. (2021) investigated the relationship between presence, visual stimuli, and visually-induced postural activity in an immersive VR system and found that postural sway could predict presence responses. In some investigations, presence levels were compared among different VR systems. Khashe et al. (2018) found no relationship between presence and VR systems (immersive and non-immersive ones). In contrast, Castronovo et al. (2017) found greater presence levels in a semi-immersive VR system than in a non-immersive one. Alshaer et al. (2017) found that, among other system characteristics, the display type (monitor and HMD) can significantly affect presence measures.

3.4.2. Measuring three-dimensional perception

While there are many methods to assess a person's visual perception in virtual environments (Interrante et al., 2006), performing such experiments correctly is difficult, and care should be taken to understand and consider the factors involved (Gooch and Willemsen, 2002).

A commonly used measure of depth or 3D perception in physical and virtual environments is distance estimation, which can be performed through various techniques (e.g., Henry and Furness, 1993; Witmer and Sadowski, 1998; Sinai et al., 1999; Gooch and Willemsen, 2002; Thompson et al., 2004; Interrante et al., 2006; Ziemer et al., 2009; Renner et al., 2013). These include different walking, pointing, or reaching tasks. In the latter, participants use a mouse (Chiuhsiang and Widyaningrum, 2018) or sticks (Chiuhsiang and Woldegiorgis, 2017; Chiuhsiang et al., 2019) to point to virtual targets. In an interesting study, Alshaer et al. (2017) base their method on Gibson's affordance theory (Gibson, 1979) to measure perceived spatial size and distance, asking participants to judge whether wall openings were wide enough to

afford the passage of a power wheelchair.

Chiuhsiang and Woldegiorgis (2017) provide an extensive list of past studies on the accuracy of "space perception" in both virtual and real worlds and conclude that "*unlike the relatively accurate space perception in the physical world … compression has been reported in the majority of studies of stereoscopic environments.*" In general, findings suggest that people are very good at estimating distances in the real world (Henry and Furness, 1993). While egocentric distance estimation within action space (up to 30 m radius) is quite accurate (Ziemer et al., 2009), people tend to underestimate values over greater distances. In general, egocentric judgments are approximately 8% underestimated (Witmer and Sadowski, 1998), that is, they do not correspond to the absolute distances or the actual measures (Gooch and Willemsen, 2002). Interobject distance judgments are also underestimated. However, when walkthrough exploration is allowed, distance perception is near veridical (Cutting and Vishton, 1995; Sinai et al., 1999; Gooch and Willemsen, 2002). When exploration is allowed in interobject distance estimation, a participant might simply position oneself near one of the objects and look at the other, approximating interobject estimation to egocentric estimation. In virtual environments, egocentric distance estimation is even less accurate than those 8% of underestimation in the real world: virtual dimensions appear approximately 15% shorter (compressed) than the actual/absolute dimensions (Thompson et al., 2004). While walkthrough exploration may benefit egocentric distance estimation to virtual targets (Thompson et al., 2004), in general, distances appear more compressed in virtual environments than in the real world (Ziemer et al., 2009). Also, although stereoscopic widescreen displays enable slightly higher egocentric distance estimation accuracy compared to HMDs, underestimations and overestimations are often found in both setups (Chiuhsiang et al., 2019). Chiuhsiang and Woldegiorgis (2017) also found inaccurate egocentric distance estimations in a stereoscopic widescreen system but accurate ones in the real world.

Therefore, while virtual environments may evoke similar physiological and psychological responses to those observed in physical environments (Higuera-Trujillo et al., 2017), this is not entirely true for distance perception. As discussed above, past studies that have compared distance judgments in the real world to judgments in a virtual environment have almost consistently shown that egocentric distances are underestimated in virtual environments in relation to egocentric estimates in the real world (Interrante et al., 2006; Renner et al., 2013). Henry and Furness (1993) found that architects consistently underestimated the dimensions of a gallery space in all three computer simulation conditions compared to touring the real environment. Particularly large differences were observed between distance judgments in the real and virtual conditions by Witmer and Sadowski (1998).

In summary, people tend to underestimate egocentric distances in physical and virtual environments, but the underestimation seems larger in the virtual setting. The factors that account for these systematic and large egocentric underestimations in virtual settings remain unknown. If egocentric distance judgments in the virtual world are not as good as in the real world, according to Cutting and Vishton (1995) one could assume that there are not enough depth cues available in virtual environments to enable a veridical depth perception (close to perception in the physical world).

As per Kimura et al. (2017), visual-spatial cues can be broadly categorized into geometric (e.g., distance or direction) and featural cues (e.g., color or texture). The latter may not significantly impact distance perception in virtual environments. Evidence shows that the quality of graphics of the virtual simulation (rendering effects associated with featural cues) has little to no effect on distance judgments. A thorough study conducted by Thompson et al. (2004) found that egocentric distance judgments based on wireframe renderings (with floor tiling grid) are just as good as judgments from 360° photographs of the actual environment (veridical featural cues) presented with the same display system. The floor tiling grid pattern in the low-fidelity model seems to have provided critical cues for depth perception, facilitating distance estimation (Sinai et al., 1999). However, when it comes to geometric binocular depth cues, parallax has been shown to influence distance judgments (Chiuhsiang and Woldegiorgis, 2017), and users perform better when targets are projected on the screen plane (zero parallax) than when projected in front of it (negative parallax) in projection-based systems (Chiuhsiang and Widyaningrum, 2018). Alternatively, other studies suggest that stereopsis, geometrical floor pattern, and high-fidelity graphics are all possibly critical cues for distance perception (Renner et al., 2013).

4. Research method

The research method is based on previous studies from different fields on visual perception and sense of presence in virtual environments that adopted presence or visual perception questionnaires to assess user experience (e.g., Witmer and Singer, 1998; Usoh et al., 2000; Ruschel et al., 2005; Kalisperis et al., 2006; Zikic, 2007; Castronovo et al., 2013; Faas et al., 2014; Heydarian et al., 2015b; Paes et al., 2017; Paes and Irizarry, 2018; Paes et al., 2021). The method is formally defined as a controlled experiment utilizing survey questionnaires to collect user experiences and comprises the steps shown in Fig. 3 below.

4.1. Experimental design

This study adopts a within-group experimental design, also called within-subject design, where all participants are exposed to both VR systems. Data analysis consists of testing the association between 3D perception and presence responses of each participant in each condition. A within-subject design ensures that when collecting participants' responses and testing the association between them in each virtual environment separately, results are clear from possible effects of individual characteristics (that would otherwise vary if participants were different across systems). For instance, a participant's age equally impacts their 3D perception and presence responses in both virtual environments. In summary, results are expected to be impacted by the individual characteristics of participants – as the response variables relate to cognitive functions – and this can be minimized or controlled more efficiently through a within-subject design (Lazar et al., 2017).

The participants' 3D perception and presence responses are collected in each VR condition (steps 1 and 2, Fig. 4). As recommended by Higuera-Trujillo et al. (2017) and conducted by Chiuhsiang and Woldegiorgis (2017), the participants' 3D perception responses in the VR conditions are standardized against their responses in the physical environment (PhE in step 1, Fig. 4). A detailed description of experiment sessions is provided in section 4.5. The physical environment is the physical lobby space, whereas VR conditions are the virtual environments, as described next.

4.2. VR systems

A simulation of the Caddell Building's lobby space on the Georgia Tech campus was used for the experiment in both VR systems. The decision between using a high- or low-fidelity simulation in the VR modes is guided by the research context. As pointed out by Berg and Vance (2016) and Paes and Irizarry (2019), the degree of pictorial realism and vividness needed in virtual environments is strictly a function of their purposes. High-fidelity simulations are valuable but not always required for decision-making in architectural design. For designers who concentrate on the fit, form, and function of a space, a model's geometry must be accurate and representative of the design solutions with respect to scale, size, orientation, and position. In this scenario, decision-makers are less interested in the pictorial realism of the simulation and more interested in whether the design fulfils the technical specifications. Thus, using high-fidelity renderings may not be a priority in this case. Indeed, low-fidelity BIM (Building Information Modelling) models are the most used in the architectural design practice and across the

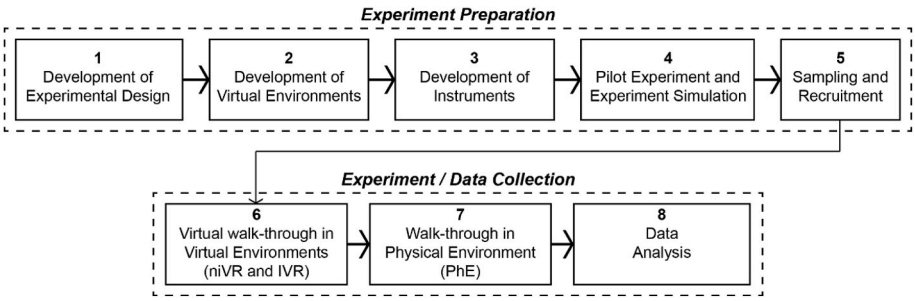

Fig. 3. Research method framework.

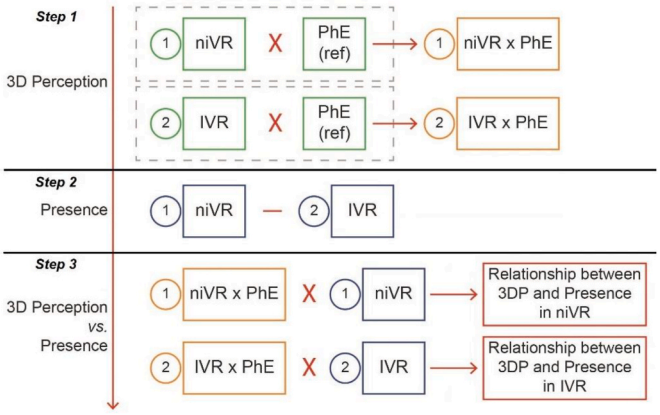

Fig. 4. Experimental design structure.

construction industry (Eastman et al., 2008). Alshaer et al. (2017) adopted a similar approach and used a low-fidelity Trimble SketchUp model with basic rendering effects to develop and test their simulator.

Therefore, using a BIM model of low-fidelity graphics in both VR modes was set as a first requirement. Regardless of the controversy about the extent to which the quality of graphics affects perception and presence in virtual environments, featural spatial cues (e.g., color, texture, etc.) were kept the same across VR systems to allow for isolated observation of display effects (stereopsis, field of view, and interactivity effects) on 3D perception and presence. Keeping graphics quality the same across VR conditions eliminates eventual effects due to graphics differences and automatically leaves the effects due to the visualization mode "at their will." As recommended by Alshaer et al. (2017), furnishings and decorations were excluded to remove size and distance cues provided by familiar objects. IrisVR Prospect Plus was the converter application chosen to run an Autodesk Revit BIM model in both conditions, ensuring identical graphics and interfaces. Thus, both VR conditions include: a) first-person view walkthrough navigation mode, where users can navigate freely through the virtual environment, b) identical low-fidelity graphics/rendering effects, and c) identical user interfaces. Naturally, the VR modes employ different displays (monitor and HMD) and interaction devices (keyboard and mouse and wireless controllers).

In the non-immersive mode (niVR), hardware consisted of a mobile workstation comprising a high-performance laptop, keyboard and mouse (as interaction devices). The laptop is a Dell Alienware 15, comprising an Intel Core i7-7700HQ processor, an NVIDIA GeForce GTX 1070 graphics processing unit, 32 GB DDR4 at 2400 MHz of RAM, a 256 GB PCIe SSD and a 1 TB 7200RPM SATA, and a built-in 15.6″ FHD (1920 × 1080) 60 Hz IPS Anti-Glare 300-nits display. It was placed on a conventional office desk so users could navigate the virtual environment while seated, using the interaction devices. In the immersive mode (IVR), hardware consisted of the same mobile workstation comprising a high-performance laptop, a head-mounted display HTC Vive, and two wireless controllers (as interaction devices). The HMD comprises a dual AMOLED 3.6" diagonal screen with a resolution of 1080 × 1200 pixels per eye, 90 Hz refresh rate, 110° field of view, and interpupillary and lens distance adjustment. It was set up in room-scale mode so users could navigate the model while standing, with limited space for moving around the experiment room (approximately one step in each direction). Fig. 5 shows a set of screenshots of the virtual environment in both VR systems.

4.3. Data collection instruments

Data collection instruments included the Demographic Questionnaire (DQ), the 3D Perception Questionnaire (3DPQ), and the Presence Questionnaire (PQ). Table 1 provides a summary of variables and instruments used in the VR conditions and physical environment.

The Demographic Questionnaire (DQ) is used to collect participants' characteristics, including age, gender, computer usage, educational level, experience in design review, experience with 3D virtual environments, familiarity with the experiment environment, and spatial ability. An adapted version of the Spatial Ability Test (Revised PSVT:R) was used to collect this individual trait (Yoon, 2011). This information is

Fig. 5. Screenshots of the virtual environment.

Table 1
Variables and instruments per visualization and reference modes.

	niVR	IVR	PhE (reference mode)
Variables	3D Perception Presence	3D Perception Presence	3D Perception
Instruments	3DPQ-niVR PQ	3DPQ-IVR PQ	3DPQ-PhE

used to test the influence of individual factors on the association between 3D perception and presence. Basic demographic data also gives the representativeness of nonprobability-based samples and the validity of survey responses (Lazar et al., 2017).

4.3.1. 3D perception questionnaire (3DPQ)

3D perception is operationalized in this study as one's understanding of the dimensions, proportions, and scale of a space (Zikic, 2007), provided by estimates of egocentric distances to and between objects in space. Thus, a 3D Perception Questionnaire (3DPQ) was developed and used to collect participants' 3D perception (horizontal, vertical, and depth judgments combined) of a virtual indoor space in each VR system (immersive and non-immersive) as well as in the physical environment (PhE) for standardization. In line with previous research (e.g., Henry and Furness, 1993; Kalisperis et al., 2006; Zikic, 2007; Paes et al., 2017; Paes et al., 2021), the 3DPQ comprises twelve multiple-choice items for egocentric and interobject distance estimation (Table 2), with answer options consisting of distance intervals such as "up to 10 m", "up to 12 m", and so on. To minimize learning effects, the items were randomly ordered to create three versions of the scale (same questions, but ordered in different sequences). Participants completed the 3DPQ during the visits to the virtual and physical environments.

4.3.2. Presence questionnaire (PQ)

Immediately after completion of the virtual walkthrough, participants were given a Presence Questionnaire (PQ) to collect their perceived level of presence during the 3D perception tasks in the virtual environments (niVR and IVR). Key elements that must be covered by presence instruments include the participants' feeling of being in the simulation, how much they recall it as a real location, and how predominant it felt against the physical environment (Slater, 1999). The PQ was mainly based on the SUS instrument developed by Usoh et al. (2000) (5 items), with selected questions from the instruments of Witmer and Singer (1998) (2 items), Zikic (2007) (2 items), and Lessiter et al. (2001) (1 item), as well as one new question (question 7), for a total of eleven items (Table 3). It used a 7-point Likert scale to maintain consistency with the 'Witmer and Singer' and SUS surveys.

Adapting and combining questions from existing presence instruments creates a custom-designed survey that matches the needs of the experiment. This practice is not uncommon in the VR research community. For example, Slater uses a modified version of the SUS survey in a psychophysical experiment on the plausibility illusion (Skarbez et al., 2017), removing one of the questions. Similarly, Peck et al. (2009), Park et al. (2022), and others (Paris et al., 2017; Riches et al., 2019) all report using modified SUS surveys in their work. Usoh et al. (2000) themselves modify the SUS survey to take into account their experimental conditions. Previous researchers have also taken selected questions from the Witmer and Singer survey and other instruments to create custom assessments. For example, Zikic (2007) utilized a 13-item questionnaire adapted and modified from three different sources, including the IPQ by Schubert et al. (2001) and the Witmer and Singer survey. Alshaer et al. (2017) also used the IPQ scale to derive an adapted version with fewer items and some simulator sickness questions. Fröhner et al. (2019) report on using selected questions from the Witmer and

Table 2
3DPQ's questions.

Category	Group	Dimension	Exploration	Question
Egocentric distance estimation	1	Depth	Not allowed (fixed position)	1. Please stand at the main entrance door. The distance between you and the flex space door is: 2. Standing at the main entrance door, the distance between you and the drinking fountain to your left is: 3. Please stand at the staircase end, facing the steps. The distance between you and the wall in front of you is:
Interobject distance estimation	2	Depth	Not allowed (fixed position)	4. Standing at the staircase end, facing the glass curtain. There are two panels in front of you – the glass curtain and another wall to the right with a vertical window. How distant is the glass curtain from the wall? 5. Please stand at the flex space door, facing the main entrance door. There are two panels in front of you – the entrance door, and a wall to the right with a TV display. How distant is the wall from the entrance door? 6. Standing at the flex space door, facing the center of the lobby. The maximum number of people standing that the space could accommodate (overcrowded) is:
	3	Horizontal	Allowed	7. The distance between the glass curtain wall and the opposite internal wall (adjacent to the staircase) is: 8. The distance between the opposite TV displays is: 9. How wider is the glass curtain compared to the wall with a vertical window?
	4	Vertical	Allowed	10. The maximum distance between the floor and the gypsum board ceilings is: 11. The maximum distance between the staircase landing and the top edge of the second floor railing is: 12. How taller is the flex space door compared to the elevator door?

Table 3
PQ's questions.

Question	Likert scale anchor terms
1. To what extent did you feel present in the lobby considering your presence experiences in the real world?	*Not at all* [1] to [7] *A great deal*
2. When you think back about your experience, to what extent do you think of the lobby as a place in a way similar to when you remember other places that you have been to today?	*Not at all* [1] to [7] *A great deal*
3. When you think back about your experience, to what extent do you think of the lobby as somewhere you were at?	*Not at all* [1] to [7] *A great deal*
4. During the experience, how strong was your sense of being in the lobby rather than being in the experiment room?	*Not at all* [1] to [7] *Very strong*
5. To what extent did your visual experiences in the lobby seem consistent with your visual experiences in the real world?	*Not at all* [1] to [7] *A great deal*
6. To what extent did you feel you could grasp an object in the lobby?	*Not at all* [1] to [7] *A great deal*
7. If the lobby ceiling had started to collapse, what would have been the probability of you dodging in an attempt to not getting hit by falling parts?	*Not at all* [1] to [7] *Very likely*
8. To what extent did you feel like exploring the rest of the environment (second floor, corridors, etc.)?	*Not at all* [1] to [7] *A great deal*
9. Were there times during the experience when the lobby was the reality for you?	*Not at all* [1] to [7] *Almost all times*
10. Were you involved in the experience to the extent that you lost track of time?	*Not at all* [1] to [7] *A great deal*
11. To what extent have you experienced motion sickness (nausea, dizziness)?	*Not at all* [1] to [7] *A great deal*

Singer survey that correspond to the control and sensory factors, Perez et al. (2019) created a custom survey combining questions from the Witmer and Singer survey with other questions, and Kraus et al. (2019) developed an 18-question survey of immersion using questions from four different instruments, including Witmer and Singer's one.

4.4. Participants

The nonprobabilistic sample comprises 38 participants and complies with the following qualification/inclusion criteria: experience in architectural design review (including classroom and industry experience), within 18–69 years of age, and a minimum educational level equal to or over completed high school. An *a priori* power analysis was conducted to determine the sample size of 38 participants (Paes et al., 2021). As per Lazar et al. (2017), 30 respondents would be considered a baseline minimum number of participants in Human-Computer Interaction (HCI) research. As a basis of comparison, the sample size in the study conducted by Faas et al. (2014) was 30 participants; Interrante et al. (2006) conducted two experiments for which they recruited 7 and 10 participants; Witmer and Singer (1998) performed a set of experiments to validate their instruments, having recruited 38 participants on average in each study; Chowdhury et al. (2021) adopted a sample size of 15 participants. Recent within-subject studies with three conditions have recruited 10 (Chiuhsiang and Widyaningrum, 2018), 21 (Kim and Rhiu, 2021), and 34 (Soret et al., 2021) participants, and another two-condition study by Chiuhsiang et al. (2019) recruited 18 participants.

4.5. Experiment session

Following the development of the experimental design and IRB approval, a pilot experiment session and an experiment simulation with the participation of 17 people were conducted to check for the adequacy of the experimental design, data collection instruments, experiment procedure, and equipment. As Kuliga et al. (2015) pointed out, the order of exposure to different virtual environments (e.g., immersive and non-immersive) could influence their effects on participants. Therefore, to control for order effects and address the problem of systematic similarities across successive virtual environments, which is the cause of practice/learning effects (Lazar et al., 2017), the 38 participants were randomly assigned to the two possible sequences of conditions (randomization). Half of the sample experienced the niVR first, while the other half experienced the IVR first (counterbalancing).

The actual experiment sessions took approximately 70 min each, totalling 44 h of data collection. Each experiment session starts with virtual walkthroughs in each VR condition (niVR and IVR, observing randomization and counterbalancing procedures), followed by the completion of applicable questionnaires (3DPQ and PQ). These two initial steps take approximately 20 min each. Next, participants go to the physical environment to perform the perception task and complete the 3DPQ (approximately 30 min). Fig. 6 shows participants performing perception tasks during experiment sessions.

5. Results

5.1. Sample demographics

Nearly half the participants have between 26 and 33 years of age. Gender distribution is relatively balanced across the sample. All of the participants reported regular computer usage. Most have (or are studying towards) postgraduate degrees. Around half the participants have less than 5 years of experience in design review, whereas the other half have over 5 years. Slightly over half the participants reported having either beginner or intermediate-level experience with 3D virtual environments (3D modelling software, video games, etc.). Most participants said they either regularly or occasionally visited the experiment environment (Caddell Building's lobby space on the Georgia Tech campus). Out of 10 questions on the Revised PSVT:R, all participants scored between 6 and 10. Table 4 provides a breakdown of the sample characteristics.

Table 4
Sample demographics.

Parameter	Sample (n = 38)	
	#	%
Age		
18–25	10	26.3%
26–33	16	42.1%
34–41	7	18.4%
50–69	5	13.2%
Gender		
Female	17	44.7%
Male	21	55.3%
Computer usage		
Regular	38	100%
Educational level		
Bachelor's degree	2	5.3%
Master's degree	25	65.8%
Doctoral degree	11	28.9%
Experience in design review		
Up to 1 year	8	21.1%
1–5 years	10	26.3%
5–10 years	9	23.7%
10–15 years	5	13.2%
15–20 years	2	5.3%
20 + years	4	10.5%
Experience with 3D virtual environments		
None	3	7.9%
Beginner	11	28.9%
Intermediate	9	23.7%
Expert	15	39.5%
Familiarity with the experiment environment		
None	5	13.2%
Rare visits	1	2.6%
Occasional visits	10	26.3%
Regular visits	22	57.9%
Spatial ability score (out of 10)		
6 score	2	5.3%
7 score	6	15.8%
8 score	8	21.1%
9 score	7	18.4%
10 score	15	39.5%

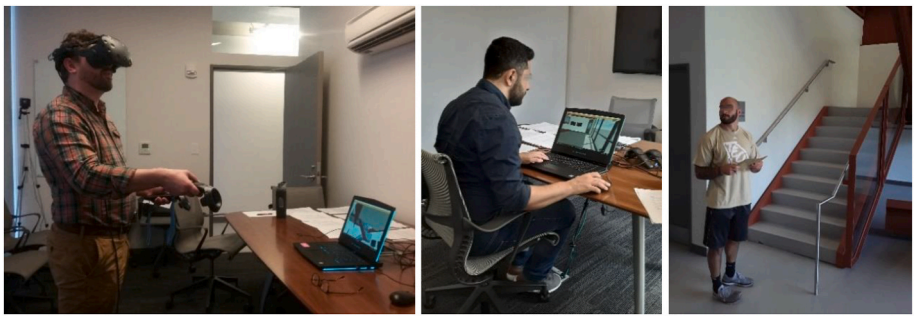

Fig. 6. Participants performing perception tasks: in IVR mode (left), in niVR mode (center), and in the physical environment (right).

5.2. Analyses of the association between 3D perception and presence in each virtual environment

The preprocessing of data for statistical analyses involved cleaning up, coding, and organizing it for specific statistical software (PAST software application – Hammer et al., 2001). The analyses examine whether dependent variables of 3D perception and presence are associated in each virtual environment. In statistical terms, two variables are associated if there is a significant relationship between them. The expected association tested is unidirectional, that is, 3D perception affecting presence. It should be noted that a significant association does not necessarily imply that changes in one variable cause changes in the other. In some cases, a hidden variable can act as the underlying cause of those changes (Lazar et al., 2017). Both presence and 3D perception scores are treated as quantitative continuous variables, assuming normal/Gaussian probability distributions. Therefore, the analyses utilize several regression models to test the statistical hypothesis. *P* values provide the significance of the relationships observed ($\alpha = 0.05$).

In the first analysis, virtual environments (conditions) and 3D perception scores (accuracy scores) were included in the model as predictor variables of presence scores (multiple regression model with two predictor variables). Fig. 7 shows the linear relationship between 3D perception scores and presence scores in each virtual environment (IVR and niVR). The assumptions of normality, homoscedasticity and independence were tested, and no violations were observed.

No significant association between 3D perception and presence was found in the conditions (IVR slope: $r = 0.00495$, $p = 1.0$; niVR slope: $r = -0.175$, $p = 0.3$). Therefore, we fail to refute the null hypothesis of no relationship between 3D perception and presence in the VR modes. It is clear from Fig. 7 that there is no pattern in any VR condition. For instance, while in the IVR most participants reported great levels of presence, some achieved poor 3D perception (low accuracy scores) while others achieved the opposite.

The second analysis looks into the expected association between 3D perception and presence per group of 3D perception questions. The set of twelve 3D perception questions was divided into four groups according to their type (see Table 2), as follows: Group 1) questions 1/2/3 of egocentric, depth, fixed estimation; Group 2) questions 4/5/6 of interobject, depth, fixed estimation; Group 3) questions 7/8/9 of interobject, horizontal, exploration estimation; Group 4) questions 10/11/12 of interobject, vertical, exploration estimation. Virtual environments (conditions), 3D perception scores (accuracy scores), and groups of questions were included in the model as predictor variables of presence scores (multiple regression model with three predictor variables). Fig. 8 shows the linear relationship between 3D perception scores and presence scores in each virtual environment (IVR and niVR) per group of questions. The assumptions of normality, homoscedasticity and independence were tested, and no violations were observed.

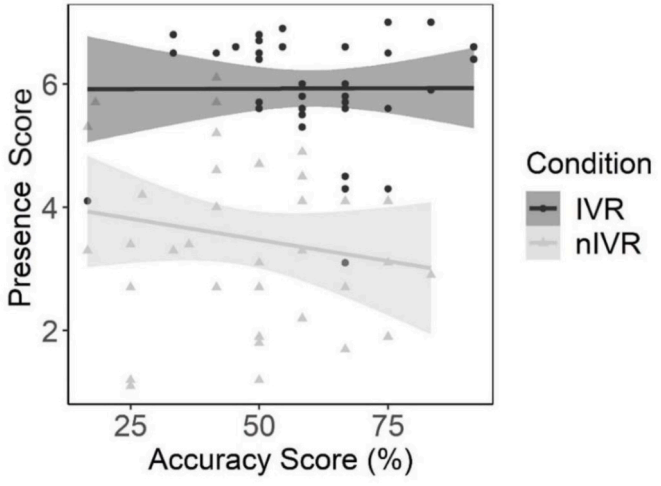

Fig. 7. Linear relationship between 3D perception and presence in the virtual environments.

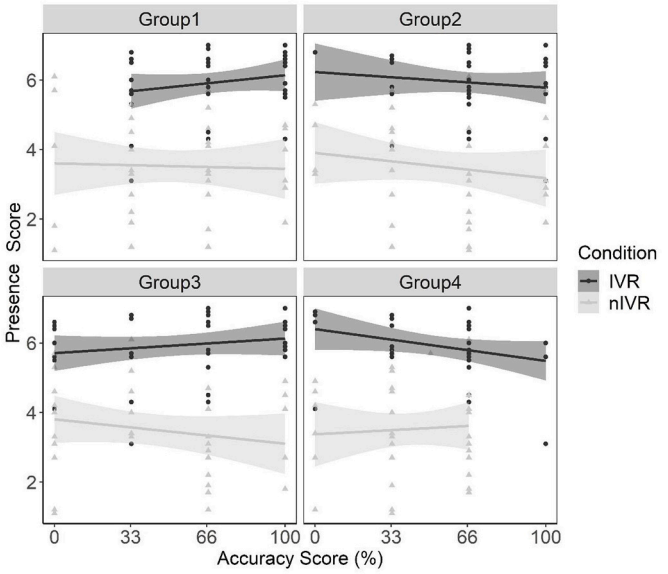

Fig. 8. Linear relationship between 3D perception and presence in the virtual environments, per group of questions.

As shown in Fig. 8, no significant association between 3D perception and presence was found in the conditions for any group of questions. As in the previous analysis, there is no pattern in any VR condition. For instance, for Group 2 (interobject depth estimation at fixed position), while in the IVR most participants reported great levels of presence, some of them achieved poor 3D perception (low accuracy scores) while others achieved the opposite. A marginal significance in the IVR condition was found for Group 4 (interobject vertical distance estimation at allowed exploration); however, this relationship is negative, that is, the better the 3D perception, the lower the presence. Table 5 provides the *p* values of the relationships examined.

The third analysis looks into the effects of individual factors on the association between 3D perception and presence in each virtual environment. The individual factors examined are seven: age, gender, educational level, experience in design review, experience with 3D virtual environments, familiarity with the experiment environment, and spatial ability (computer usage is excluded as there was no variance across the sample). In order to test if the characteristics of the participants would influence the results, the correlation was calculated separately for each level of the demographic factors for both virtual environments (IVR and niVR). The assumptions of normality, homoscedasticity and independence were tested, and no violations were observed. The participants' characteristics were found to have no impact on the association between 3D perception and presence in either of the virtual environments, as shown by the correlation *p* values (Table 6).

Table 5
Significance of the linear relationship between 3D perception and presence in the virtual environments, per group of questions.

Virtual Environment	3D Perception Questions Group	*p* value
IVR	1	0.292
niVR		0.829
IVR	2	0.489
niVR		0.289
IVR	3	0.200
niVR		0.173
IVR	4	0.092
niVR		0.770

Table 6
Significance of the linear relationship between 3D perception and presence in the virtual environments, per individual factor.

Individual Factor	Factor Level	Virtual Environment	Correlation	*p* value
Age	18 to 25	IVR	−0.43	0.209
		niVR	−0.57	0.085
	26 to 33	IVR	0.33	0.219
		niVR	−0.03	0.910
	34 to 41	IVR	−0.04	0.930
		niVR	0.03	0.957
	50+	IVR	−0.31	0.616
		niVR	−0.53	0.363
Gender	Female	IVR	−0.07	0.803
		niVR	−0.01	0.974
	Male	IVR	0.08	0.715
		niVR	−0.30	0.190
Educational level	Doctoral degree	IVR	0.17	0.619
		niVR	0.13	0.713
	Master's degree	IVR	−0.15	0.463
		niVR	−0.22	0.294
Experience in design review	Up to 5	IVR	0.16	0.534
		niVR	0.12	0.639
	5 to 15	IVR	−0.28	0.331
		niVR	−0.46	0.102
	15+	IVR	0.27	0.601
		niVR	−0.62	0.186
Experience with 3D virtual environments	Beginner	IVR	−0.23	0.504
		niVR	−0.38	0.250
	Intermediate	IVR	0.13	0.738
		niVR	−0.55	0.124
	Expert	IVR	0.13	0.645
		niVR	−0.01	0.981
	None	IVR	−0.99	0.065
		niVR	0.21	0.868
Familiarity with the experiment environment	Occasionally	IVR	−0.46	0.184
		niVR	−0.26	0.473
	Regularly	IVR	0.15	0.501
		niVR	−0.10	0.662
	None	IVR	0.02	0.980
		niVR	−0.18	0.778
Spatial ability score	6 and 7	IVR	0.15	0.729
		niVR	−0.69	0.057
	8	IVR	0.04	0.918
		niVR	−0.14	0.737
	9	IVR	0.58	0.169
		niVR	−0.11	0.807
	10	IVR	−0.16	0.558
		niVR	−0.21	0.456

6. Discussions

This section lists and discusses this study's main contributions, findings, limitations and methodological advances over past research.

Understanding the factors that affect presence in virtual environments is essential to the development of more effective VR applications in the built environment domain. While 3D perception (or similar concepts) and presence have been investigated separately, their direct relationship has not been thoroughly examined to date (for instance, see Slater and Wilbur, 1997; Thompson et al., 2004; Kalisperis et al., 2006; Interrante et al., 2006; Interrante et al., 2008; Renner et al., 2013), although theoretically sound and assumed by many scholars in the field.

In this context, this study did not find significant evidence of a relationship between 3D perception and presence in virtual environments. Such a result allows for two possible interpretations. Either the tested relationship between these variables does not exist, or this study did not have enough statistical power to detect a significant relationship. Regarding the latter, it is important to point out that this study used a considerable sample size based on *a priori* power analysis. Therefore, if it still could not identify the relationship, at least it can be concluded that it is not a strong one.

Findings suggest that 3D perception may not be among the factors affecting presence, contrary to the expectations of Steuer (1992), Bertol (1997), and Witmer and Singer (1998). However, the fact that this study did not find significant evidence of a relationship between 3D perception and presence in virtual environments endorses Interrante's et al. (2008) argument that people might still perform well in estimating distances in virtual environments that do not offer the conditions for great levels of presence. The results also coincide with previous studies suggesting that accurate distance estimation may not be evidence of great presence levels (e.g., Thompson et al., 2004; Kalisperis et al., 2006; Interrante et al., 2006; Renner et al., 2013).

In other words, the quality of spatial cues in a VR simulation may not have any relationship with the level of presence experienced by the user while interacting with it. This study provides evidence that contradicts the assumption that more realistic virtual environments (in terms of 3D representation and user's 3D perception) – such as stereoscopic visualization-based VR systems – are inherently more immersive. Therefore, people may still feel strongly present in non-realistic virtual environments, whether these are places depicted in two-dimensional images on a movie theatre screen or a laptop monitor.

Naturally, the research results are restricted to the VR equipment utilized and spatial characteristics of the modelled environment. Different responses would likely have been observed if other VR systems and 3D models had been utilized. In addition, the VR systems (non-immersive and immersive) affected 3D perception and presence responses differently, and the reader can refer to our previous publication (Paes et al., 2021) for an in-depth analysis of such differences. In this study, the investigated association between 3D perception and presence was expected to exist in virtual environments, regardless of the levels of presence and 3D perception experienced by users in each of them.

In order to control for any eventual effects due to individual differences in 3D perception and presence responses across virtual environments, this study utilized a within-subject design, which ensures that when collecting participants' responses and then testing the association between them in each virtual environment separately, results are clear from possible effects of individual characteristics (that would otherwise vary if participants were different across conditions). For instance, a participant's age is equally impactful in her/his perception and presence responses in both virtual environments. In this study, individual factors were found to have no impact on the association between 3D perception and presence in either of the virtual environments.

As done by the studies discussed in sections 3.4.1 and 4.3.2, combining questions from multiple previous instruments is not unusual for presence studies in VR. In this study, the process for selecting questions from existing and validated presence questionnaires involved a qualitative assessment by the research team of the suitability of each of those questions to this study's particular VR experience and experimental design while ensuring that the final set of questions covered the three aspects of presence defined by Slater (1999). As pointed out, this is a common procedure in VR studies. However, although both the PQ and 3DPQ scales were derived from consolidated and well-accepted instruments, this strategy would be improved with a systematic validation of the final scales. This was not conducted in this study and should be addressed in the future through an in-depth look into three types of validity: construct, criterion, and content validity (Alexandre and Coluci, 2011).

In this study, some strategies were adopted to mitigate the subjectivity of questionnaire-based measurements of 3D perception, such as using objective answer options instead of Likert-scale level-of-agreement alternatives besides during-experience questionnaire completion. In turn, presence data were collected solely through post-experience self-report questionnaires. This traditional approach was deemed an adequate data collection method based on other studies that used post-experience instruments outside the VR. However, this method has significant limitations as it relies on memory recall and retrospective assessment of one's experience, which is inevitably prone to fabrication and distortion being an active reconstruction process. To avoid these and other undesirable effects such as the "break-in-presence", future

studies may consider administering presence questionnaires directly within a simulation (Schwind et al., 2019) hence conducting a virtual during-experience survey or using objective measures of presence such as physiological ones in addition to – and, eventually, instead of – self-reported data. For instance, changes in heart rate, skin conductance, and electroencephalogram (EEG) signals (brain activity) could be used as objective measures of presence and have been shown to correlate with subjective ones (Meehan et al., 2002; Higuera-Trujillo et al., 2017). Similarly, future studies may explore possible methods based on physiological measurements of 3D perception in virtual environments to replace questionnaire-based ones. This could involve, for instance, using saccadic eye movement data captured by eye-tracking sensors (Chiuhsiang and Widyaningrum, 2018). With sensors integrated into HMDs nowadays, using such physiological cues would allow for real-time and accurate data collection (Dey et al., 2019). Despite some promising evidence (Meehan et al., 2002; Higuera-Trujillo et al., 2017; Chiuhsiang and Widyaningrum, 2018), the validity and eventual advantage of physiological and imaging methods are yet to be demonstrated through vast data collection and possible triangulation of such measurements with self-reported and observational data.

Based on this study's results, the absence of depth cues will likely have no effect on the presence levels experienced by the users. They could still feel strongly present in the virtual environment, regardless of their 3D perception experience's accuracy. Therefore, developers may focus on enhancing presence through other means than depth realism. Other yet unexplored technological and human factors may play more significant roles in promoting the sense of presence in virtual environments. For instance, Kim and Rhiu (2021) showed that more natural navigation methods could impact, among other factors, users' sense of presence such that the more veridical they are, the higher the presence. Eventually, one may figure out an equation that allows the trade-off among those factors to enhance the user experience. The path towards such an equation starts by understanding the depictive information and interactivity needs in each application context, which is another topic for future research.

The level of pictorial realism and vividness of virtual environments is application-dependent. These may not incorporate certain visual cues (including depth cues, such as perspective) if the activity or task performed in/with the simulated environment does not require such information. In many cases, a low-fidelity simulation might be sufficient for reaching the desired perception and presence levels (e.g., conceptual design review, safety training, etc.) to successfully complete the task. Furthermore, realism requirements might not be restricted to visual stimuli only, as shown by Ebnali et al. (2021): a high level of interaction fidelity using more natural interfaces could improve the effectiveness of specific training applications. Chiuhsiang and Woldegiorgis (2017) also suggest that developers could focus on incorporating more direct and natural interaction methods for improved performance. As such, future research may look into the visual features, equipment specifications, and interaction methods to improve the efficiency of the different VR applications.

7. Conclusions

This study examined the fundamental relationship between 3D perception and presence responses in immersive and non-immersive systems. As discussed, 3D perception has been deemed the node connecting 3D representation to presence in virtual environments according to the following sequence: 3D representation > 3D perception > presence. This assumption is supported by the literature discussed. However, the expected connection between 3D perception and presence was yet to be observed, and very few studies have attempted to identify it to date.

In searching for the factors that affect presence in virtual environments, this study hypothesized a possible unidirectional association between 3D perception and presence. A study consisting of a controlled within-group experiment utilizing perception and presence questionnaires has been carried out, followed by data analysis to test the association in each virtual environment (regardless of the levels of presence and 3D perception experienced by users). Results indicate no association in either of the VR systems studied, contrary to the assumption of many scholars in the field but in line with recent studies on the topic. This finding suggests that 3D perception may not be a factor affecting the sense of presence. Therefore, depth representation incorporating, for instance, binocular depth cues of stereopsis, parallax, and binocular disparity, may not necessarily contribute to promoting presence in virtual environments.

This knowledge has many implications for VR applications in the AECO/FM sector. Its practical significance applies to VR users who would benefit from high levels of presence. In short, findings suggest that such applications may not need to incorporate advanced depth representation and visualization techniques to deliver highly immersive experiences. For instance, developers of VR-based construction safety training applications could design increasingly immersive experiences by addressing factors other than depth realism to promote trainees' engagement with the learning experience. Furthermore, as findings suggest that the levels of presence experienced by users are not subject to the display mode of a 3D model (whether immersive or non-immersive display), it may still be possible for professionals involved in the review of 3D models (e.g., designers, contractors, clients) to experience high levels of presence through non-stereoscopic VR systems provided that other presence-promoting factors (such as intuitive interaction methods) are included.

Data availability statement

All data and models generated or used during the study are confidential in nature and may only be provided with restrictions (e.g., anonymized data) by the corresponding author upon reasonable request.

Declaration of competing interest

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

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