Author Accepted Manuscript

Citation: Lee, H. (2025) "A unified conceptual model of immersive experience in extended reality," *Computers in Human Behavior Reports*, Volume 18, 100663.

https://doi.org/10.1016/j.chbr.2025.100663

A Conceptual Model of Immersive Experience in Extended Reality

Hyunkook Lee

(h.lee@hud.ac.uk)

Applied Psychoacoustics Laboratory (APL), University of Huddersfield, HD1 3DH, UK.

Abstract

The term "immersion" is frequently used to describe and evaluate technologies within the field of extended reality (XR), which encompasses virtual, augmented, and mixed reality. Over the past few decades, extensive research has been conducted on immersion. However, there remains a lack of consistency in how the term is defined and applied in the literature. Additionally, there is no clear and consistent conceptual hierarchy of related terms across different measurement models. To address these issues, this paper explores the multidimensionality of immersion, as well as associated concepts such as presence and involvement. From this, a unified conceptual model of immersive experience is proposed for future research in XR. The model defines physical presence, social presence, self-presence, and involvement as the core dimensions of an immersive experience, which arise from sensorimotor, narrative, and task/motor engagement. Plausibility, interactivity, and interestingness are identified as key properties of immersive systems and content that facilitate engagement, each influenced by subjective factors: internal reference, skills/knowledge, and personal preference, respectively. This model provides a comprehensive framework for researchers to measure immersive experiences more consistently and build a coherent body of research in XR.

Keywords: immersion, immersive experience, conceptual model, extended reality, presence, involvement.

1. Introduction

The last decade has seen remarkable advancements in technologies for virtual reality (VR), augmented reality (AR), and mixed reality (MR), collectively referred to as extended reality (XR). These immersive technologies are reshaping digital interaction by providing users with novel ways to engage with virtual environments and digital agents beyond traditional screen-based interfaces. In VR, the user is fully immersed in a technology mediated virtual environment, with the physical world visually and aurally occluded through a head-mounted display (HMD) and headphones. This creates a sense of presence, allowing users to feel as if they are inside and interacting with virtual environment and beings/objects.

In contrast, AR overlays virtual elements onto the physical world, allowing users to perceive them while remaining aware of their surroundings. This is achieved through AR glasses, mobile screens, or spatial audio systems that blend virtual sound sources with the real-world environment. In AR, interaction between users and virtual stimuli is possible, but that between virtual stimuli and real stimuli in the physical environment is not (Bekele and Campion, 2019).

MR represents a continuum between VR and AR, where virtual and real elements coexist and interact in real time. Unlike simple overlays in AR, MR enables users to manipulate and interact with virtual stimuli as if they were part of the physical environment, creating a more immersive and interactive experience compared to AR ((Bekele and Campion, 2019).

Today XR technologies are increasingly adopted across a wide range of industries. For instance, XR is widely used in gaming and entertainment, offering more immersive and interactive experiences. In education and training, XR enables more engaging learning environments, from virtual classes to medical simulations. Healthcare applications leverage XR for surgical planning, rehabilitation, and mental health intervention, while tourism and cultural heritage use XR to create interactive museum exhibits and virtual travel experiences.

Given this rapid adoption, academic research on XR has expanded significantly. Studies explore the psychological and cognitive effects of immersion in games (Carvalho et al., 2014; Slater & Sanchez-Vives, 2016), the impact of XR on learning outcomes in education (Makransky and Petersen, 2021; Freina & Ott, 2015), and healthcare intervention efficacy (Andrews et al., 2016; Harris et al., 2025; Lee et al., 2023), and methods to enhance user presence in virtual tourism experiences (Tussyadiah et al., 2018; McGookin et al., 2019). There is also an increasing interest in the measurement of immersive experience in XR, with researchers developing conceptual models and measurement instruments (Jung and Lindeman, 2021; Shin 2017; Tcha-Tokey et al., 2018; Nhan et al., 2022; Pianzola et al., 2021; Balcerak Jackson and Balcerak Jackson, 2024).

These studies are based on the assumption that XR offers a more immersive experience than traditional media, leveraging high-resolution 3D audiovisual display, motion tracking, tactile feedback, and other multisensory technologies. However, there are two main issues in current XR research. Firstly, the terminology used in the literature is inconsistent and ambiguous. Although there has been ongoing debates and confusion about the meaning of immersion, no universally accepted definition of immersion has been established. Different conceptual models use overlapping terminology or assign different meanings to the same term depending on context.

Secondly, there is no clear hierarchical structure among related concepts, such as presence, involvement, engagement and flow, which makes it challenging to establish a comprehensive framework for understanding and measuring immersion. For example, some studies consider immersion to be a determinant of presence (e.g., Berkman & Akan, 2019; Cummings & Bailenson, 2016), while others view presence as a predictor of immersion (e.g., Ermi & Mäyrä, 2005; Zhang, Perkis, & Arndt, 2017). In addition, some studies treat flow as a sub-concept of presence or immersion (e.g., Shin, 2019; Pianzola et al., 2021; Tcha-Tokey et al., 2018), while others separate flow from immersion (e.g., Jennett et al., 2008; Agrawal et al., 2020). The lack of consistency in terminology and conceptual hierarchy can lead to confusion and misinterpretation in comparing different studies (Kober & Nueper, 2013; Grassini and Laumann, 2020; Kukshinov et al., 2025).

To address these issues, the present paper aims to define various concepts related to immersion, explore their interrelationships and integrate them into a unified conceptual model of immersive experience, which enables more consistent measurement and comparison of immersive experiences across different XR applications. This model is expected to contribute to a more coherent body of research and facilitate more effective XR system and content development. The paper first discusses the source of confusion for the inconsistency of the use of the term immersion and propose a standard terminology: immersive system and immersive experience. The paper then discusses the multidimensional nature of immersive experience found in the literature and identify two underlying concepts: presence and involvement. Section 3 explicates the concepts of physical presence, social/self presence and involvement, which are considered as the main factors of immersive experience. Based on these, Section 4 proposes a unified conceptual model of immersive experience and discusses its implications for future XR research.

2. Defining Immersion

This section identifies the source of confusion around the term ‘immersion’ and proposes a clear terminology. It then reviews various concepts of immersion and categorise them.

2.1. Immersion as technology vs. Immersion as experience

The term ‘immersion’ in the literature is typically used in two different contexts: immersion as technology and immersion as experience. Slater (2003) asserts that immersion is simply “what the technology delivers” to provide the user with a sensation of being there. He equates the level of immersion to the level of the technology; the more advanced, the more immersive (Slater, 1999). This notion has been followed by many researchers studying presence in XR, e.g., Berkman & Akan, 2019; Cummings & Bailenson, 2016; Diemer, Alpers, Peperkorn, Shiban, & Mühlberger, 2015; Ragan, Sowndararajan, Regis, & Bowman, 2016; Jung and Lindeman, 2022).

However, the term immersion is also frequently used to describe a psychological and cognitive experience resulting from a technological process, as will be described in detail in the following sections (Ermi & Mäyrä, 2005; Arsenault, 2005; Adams & Rollings, 2007; Agrawal et al., 2020; Witmer & Singer, 1998; Balcerak Jackson and Balcerak Jackson, 2024). This inconsistency in using the same term causes confusion.

To avoid potential confusion about the meaning of immersion due to the aforementioned inconsistency in the definition and use of the term, it is proposed here to standardise the terminology, such that we explicitly say ‘immersive experience (IE)’ and ‘immersive system (IS)’ when referring to immersion as an experience and immersion as a technological process, respectively. This would clarify the cause-and-effect relationship between system (independent variable) and experience (dependent variable).

If one says “a higher level of immersion leads to a stronger sense of being there”, for example, it would be unclear what immersion exactly means here. If it meant a technological process, it would be clearer to say that “a more advanced *immersive system* provides a stronger sense of being there”. If the term was used to refer to an experience, it would be less confusing to say that “a higher level of *immersive experience* leads to a stronger sense of being there”. However, immersive experience in this statement is described as an independent variable for the sense of being there (i.e., physical presence), but the opposite is more commonly accepted in the literature as discussed in the following section – an immersive system provides the sense of physical presence, which is one of the factors that contribute to an immersive experience. It is argued here that immersive experience is a higher-level concept that necessitates mental or/and physical involvement in a task or an activity as well as presence. Hence, it is considered more correct to say that "a strong sense of physical presence leads to a high level of immersive experience".

2.2. Multidimensionality of immersive experience

Although there is no universally accepted definition of immersion, there is general consensus in the literature that immersive experience is a multidimensional construct. As summarised in Table 1, researchers have proposed different dimensions of immersion using various descriptive words, e.g., perceptual and psychological immersion (Lombard & Ditton, 1997), sensory, imaginative and challenge-based immersion (Ermi & Mäyrä, 2005), sensory, fictional and systemic immersion (Arsenault, 2005), narrative and ludic immersion (Ryan, 2003), narrative and strategic/tactical immersion (Adams & Rollings, 2007), and system, spatial, social/emphatic and narrative/sequential immersion (Han, Melissen and Haggis-Burridge, 2024).

However, some of these terms largely overlap in their meanings, and seem to connote the general ideas of either 'presence' or 'involvement', which are explicated in Sec. 3 later. For example, Biocca and Delaney (1995) defined perceptual immersion as "the degree to which a virtual environment submerges the perceptual system of the user". The same term is used by McMahan (2013) to describe the sensation of being surrounded by a virtual environment (VE), which is also implied in the definition of sensory immersion by Ermi and Mäyrä (2005). These terms commonly describe a passive experience of immersion, which is induced by the sensory simulation of a technology. They are also commonly related to the concept of 'presence'.

The other immersion terms above describe an active (cognitive) experience of immersion. For instance, imaginative immersion (Ermi & Mäyrä, 2005)and narrative immersion (Adams & Rollings, 2007; Ryan, 2003) commonly require involvement in the narrative of a content. Challenge-based immersion, ludic immersion, systemic immersion and strategy/tactical immersion are commonly to do with involvement in a challenging task or an activity.

Several researchers attempted to provide standalone definitions of immersion (e.g., (Agrawal, Simon, Bech, Bærentsen, & Forchhammer, 2020; Murray, 1997; Witmer & Singer, 1998). However, such definitions tend to be biased towards either passive or active dimension of immersion. For example, Witmer and Singer (1998) defines immersion as "a psychological state characterized by perceiving oneself to be enveloped by, included in, and interacting with an environment that provides a continuous stream of stimuli and experiences". Whilst this definition mainly describes the perceptual aspect of the experience provided by the system (i.e., Presence), the cognitive aspect of the experience is not clearly implied.

Agrawal et al. (2020), on the other hand, define immersion as "a phenomenon experienced by an individual when they are in a state of deep mental involvement in which their cognitive processes (with or without sensory stimulation) cause a shift in their attentional state such that one may experience disassociation from the awareness of the physical world". Although this definition could be applied in a wide scope including when there is no sensory input is involved (e.g., immersion in daydreaming or reading a novel), it primarily focuses on the cognitive facets of immersion. The disassociation from the physical world mentioned in their definition is based on the concept of narrative-induced transportation ("immersion or absorption into a narrative world" (Green & Brock, 2000)) rather than that of a technology-induced transportation (i.e., telepresence (Minsky, 1980) or physical presence (Biocca, 1997).

Murray (1997, pp. 98-99) describes immersion in VR as follows: "The experience of being transported to an elaborately simulated place is pleasurable in itself, regardless of the fantasy content. We refer to this experience as immersion. Immersion is a metaphorical term derived from the physical experience of being submerged in water. We seek the same feeling from a psychologically immersive experience that we do from a plunge in the ocean or swimming pool: the sensation of being surrounded by a completely other reality, as different as water is from air, that takes over all of our attention, our whole perceptual apparatus". This definition connotes the concept of physical presence (Biocca, 1997) (i.e., being transported into and surrounded by a VE), but also suggests a "pleasurable" experience as a cognitive outcome of immersion. As will be discussed more in Sec. 3.3 later, however, immersive experience is not necessarily pleasurable. The element of pleasure seems to be more related to the concept of flow (Mirvis, 1991).

Han, Mellisen & Haggis-Burridge (2024) define immersive experiences as "the acceptance of one's involvement in the moment that is conceived through multiple senses, creating fluent and uninterrupted physical, mental, and/or emotional engagements with a present experience, with the ability to attain a lasting mental and emotional effect on the user post-experience." This definition encompasses both the sensory and cognitive aspects of immersion. However, it does not explicitly incorporate the concept of presence or the sense of being transported into a virtual environment, which is fundamental to XR applications. Instead, it emphasizes the mental and emotional impact of immersive experience. Moreover, it could be argued that the sustained psychological and emotional effects should be considered as outcomes of an immersive experience rather than a core requirement of it.

Based on the above discussions, it is clear that defining a single, universal concept of immersive experience across all applications is challenging. From a research design and content creation perspective, it is more critical to clearly define the underlying components of immersive experience and understand their interrelationships, which are explored in the following sections.

Table 1. Summary of different immersion terms from the literature.

Immersion terms	Descriptions	Connoted concept
Perceptual (Biocca & Delaney, 1995; McMahan, 2013)	"the degree to which a virtual environment submerges the perceptual system of the user" (Biocca & Delaney, 1995); The sensation of being surrounded by a virtual environment (McMahan, 2013)	Presence (physical, social and self) Presence (social/self)
Sensory (Ermi & Mäyrä, 2005)	The state of being surrounded by audio-visual stimuli that can "overpower the sensory information coming from the real world"	
Spatial (Han, Mellisen & Haggis-Burridge, 2024)	"Transportation into a different environment creating a sense of presence in the new environment"	
Social/Empathic (Han, Mellisen & Haggis-Burridge, 2024)	"Emotional connection with characters and relatedness to own social context"	
Imaginative (Ermi & Mäyrä, 2005)	The state of being heavily involved (cognitively absorbed) in the story world and by its characters.	Involvement in a narrative of a content
Fictional (Arsenault, 2005)		
Narrative (Adams & Rollings, 2007; Ryan, 2003)		
Ludic (Ryan, 2003)	The stage of being heavily involved in a challenging task or an activity that requires mental or/and motor skills.	Involvement in a task or an activity
Challenge-based (Ermi & Mäyrä, 2005)		
Systemic (Arsenault, 2005)		
Strategic and Tactical (Adams & Rollings, 2007)		
Sequential (Han, Mellisen & Haggis-Burridge, 2024)		

3. Underlying Concepts of Immersive Experience

The discussions in Section 2 highlight that defining and measuring an immersive experience is a complex task. A clearly structured conceptual model is essential for designing studies that effectively measure immersive experience. As identified in Table 1, most definitions of immersion incorporate elements of presence and involvement. Additionally, the concept of flow is often linked to both presence and immersive experience. To establish a robust conceptual model, this section explicates these terms and examine their relationships.

3.1. Presence

Presence is a complex construct to standardise. In the literature, the terms presence and immersion are often used as synonyms (e.g., (Lombard & Ditton, 1997; McMahan, 2013; Murray, 1997, pp. 98-99)), whereas some researchers distinguish them as separate concepts (e.g., (Agrawal et al., 2020; Diemer et al., 2015; Jennett et al., 2008; Nilsson, Nordahl, & Serafin, 2016)). On the other hand, researchers in the field of the so-called "presence research" often consider immersion as a lower-level concept or a determinant of presence (e.g., (Berkman & Akan, 2019; Cummings & Bailenson, 2016; Diemer et al., 2015; Ragan et al., 2016; Witmer & Singer, 1998)), whereas some others tend to regard immersion as a higher-level concept (e.g., (Brown & Cairns, 2004; Ermi & Mäyrä, 2005; Zhang, Perkis, & Arndt, 2017)). Furthermore, many existing presence questionnaires differ in terms of items and factors and do not align with one another as they were developed for different contexts (Bareišytė et al., 2024).

To conceptualise the relationships between presence and immersive experience in this study, the typology of presence is first discussed. Arguably, the most widely cited typology of presence is Biocca (1997)'s three types of presence: physical, social and self presence. This typology encompasses many immersion-related terms that convey the sense of being present in virtual environments, with or without virtual beings and agency.

3.1.1. Physical presence

Biocca (1997) defines physical presence as the sense of being physically situated in a virtual environment through sensory simulation. Terms with a similar meaning include telepresence (Minsky, 1980), spatial presence (Caroux, 2023; Hartmann et al., 2016; Schubert, Friedmann, & Regenbrecht, 2001) and place illusion (Slater, 2009). Biocca (1997) argues that physical presence is crucial in designing applications that depend on spatial cognition, the translation of spatial models between virtual and physical environments, or the sensory overload needed for escaping the real world, e.g., architectural walkthroughs, battle simulations and entertainment rides. This type of presence is often understood simply as a consequence of sensory simulation provided by an immersive system; the more advanced the system is, the higher the level of presence is ((Biocca, 1997; Ermi & Mäyrä, 2005; Slater, 2003; Slater & Wilbur, 1997; Steuer, 1995; Witmer & Singer, 1998)). In this sense, physical presence can be considered to be equivalent to sensory immersion (Ermi & Mäyrä, 2005) or perceptual immersion (Biocca & Delaney, 1995).

However, as Schubert et al. (2001) argue, physical presence is not just a hard-wired perceptual phenomenon that occur immediately from sensory information, but also involves a cognitive process to make sense the VE as a physical reality. Brown and Cairns (2004) suggest that presence is a state of total immersion (as an experience), which is achieved through engagement and engrossment in a task or activity. From a questionnaire survey on presence, Witmer and Singer (Witmer & Singer, 1998) identified that selective attention as well as sensory fidelity determined the level of presence. This is supported by Schubert et al. (2001)'s finding that the two primary factors of presence were spatial constructive and attention. Literature also suggests that physical presence can occur without any sensory stimulation. For example, it would be possible to experience a sensation of presence through the narrative of the content (i.e., narrative engagement (Busselle & Bilandzic, 2009), narrative transportation (Green & Brock, 2000)).

In addition, Lee (2004) claims that Biocca's definition of physical presence does not apply to the sense of presence in low-tech media (e.g., television), as it assumes the existence of a para-authentic self that is perceived within a virtual environment. To broaden the domain of presence research, Lee (2004) defines physical presence as "a psychological state in which virtual (para-authentic or artificial) physical objects are experienced as actual physical objects in either sensory or nonsensory ways", suggesting that physical presence occurs when technology users fail to recognise the mediated nature of virtual objects or environments.

Whilst it is acknowledged that the role of cognition and the potential for feeling presence without technology or through low-tech media must be considered when explaining presence, it is argued that in the context of technology-mediated immersive experiences in XR applications, more advanced immersive systems are likely to reduce the cognitive effort require to achieve physical presence. In the real world, a mental model of the surrounding environment is automatically and instantly generated from a sensory pattern recognition mechanism (Biocca, 1997). Therefore, a high-level sensory simulation in XR is expected to enhance the sense of physical presence. Furthermore, Sheridan (1992) asserts that the ability to physically and realistically interact with the VE (e.g., switching on and off a fan in a virtual room) is an important factor for physical presence. Heeter (1992) refers to this type of presence 'environmental presence'.

3.1.2. Social presence

Social presence, usually defined as the sense of being together and interacting with another intelligence (Biocca, 1997; Heeter, 1992), is considered to be both perceptual and cognitive experiences. Biocca (1997) states that the level of social presence is determined by "the degree to which the user feels access to the intelligence, intentions, and sensory impressions of another"; social presence is minimum when the technology user can simply sense the presence of another intelligence, which is similar to the original concept of co-presence (Goffman, 1963). The perceptual stage of social presence can be understood as a type of sensory immersion (e.g., the sensation of being surrounded by other intelligences within the same virtual environment in VR or the same physical environment in AR).

If the technology can facilitate the user with the ability to physically interact with the virtual environment or/and beings, then the social presence could be understood as a challenge-based immersion (Ermi & Mäyrä, 2005). From a systematic review, Oh, Bailenson, & Welch (2018) found that interactivity as well as the audio-visual qualities of the system were important predictors for social presence in AR. Interactivity is also considered to be a property of an immersive system that could induce involvement.

For instance, consider an AR application where the user can see and listen to virtual orchestral musicians in their physical space. Being surrounded by static, animated musicians and listening to the performance in conventional stereo can be considered a low-level social presence experience in AR since there is no interactivity. The level of social presence would likely increase if the musicians' facial expressions and movements were rendered in high-resolution 3D, accompanied by realistic sound and accurately simulated spatial acoustics over headphones.

3.1.3. Self presence

Self presence (Biocca, 1997), also referred to as personal presence by Heeter (1992), represents a user's mental model of himself or herself inside the VE and the physiological and emotional states (i.e., virtual self is experienced as the actual self in either sensory or nonsensory ways (Lee, 2004)). As with social presence, self presence is a phenomenon occurring in both perceptual and cognitive domains at distinct levels. Based on Damasio

(1999)'s self-map framework, Ratan (2012) divides self presence into three levels: proto-self (body-level), core-self (emotion-level), and extended-self (identity-level). Proto-self leads to core-self, which allows for extended-self (Ratan, 2012). Proto-self presence is about how realistic the representation of the virtual self is, which is related to the technological level of immersive system. Again, the original definition of sensory immersion could be further expanded to incorporate proto-self presence, e.g., the sensation of the full or part of the virtual self's body being surrounded by virtual intelligences and environment. Core-self is induced through social interactions with mediated objects, which leads to a social identity of the self (extended-self) (Ratan, 2012).

Recalling the AR virtual orchestra example above, extended-self presence as well as social presence are likely to be maximised when the user can interact with the musicians at an intelligent level, such as by virtually conducting them, with their musical intentions expressed through motion (e.g., tempo and dynamic) reflected in the musician's performance. This can be also linked with challenge-based immersion. Hence, it is suggested that social presence and self presence are closely inter-related, both requiring interactivity and plausibility. From this, both concepts are included as key components in the immersive experience model proposed in Section 4. The concepts of social and self presence are particularly relevant in XR applications, where the interactivity of the system and content is paramount.

3.2. Involvement

The term involvement is often described as a necessary condition for cognition-based immersion (Ermi & Mäyrä, 2005; Lombard & Ditton, 1997; Ryan, 2003) or presence (Lombard & Ditton, 1997; Witmer & Singer, 1998). Witmer and Singer (1998) defines involvement as "a psychological state experienced as a consequence of focusing one's energy and attention on a coherent set of stimuli or meaningfully related activities and events". According to Wirth (2007), involvement is a "motivation-related meta-concept that includes various forms of intense interactions with a mediated stimulus", including cognitive, affective, conative and/or behavioural aspects.

Calleja (2007) specifies six dimensions of involvement in the context of digital games: *tactical, performative, affective, shared, narrative and spatial*. Tactical involvement is related to all kinds of decision making and interaction with the rules of the games as well as with other players. Performative involvement is about execution of the decision made from tactical involvement. Affective involvement represents the mood and emotional states resulting from the design and aesthetics of games. Shared involvement is to do with the ability to locate and interact with other intelligences. Narrative involvement is the extent to which the user is engaged with the designed and personal narratives of the game. Finally, spatial involvement is related to localising oneself and other players in the game area beyond the visible screen using a mental map.

Brown and Cairns (2004) established a ground theory, in the context of digital games, suggesting that total immersion occurs through two steps of involvement: engagement and engrossment. Engagement is the minimum level of involvement with a game, which occurs when the gamer decides to spend time and energy to play it. This depends on the gamer's personal preference as well as game controls. The next level of involvement is that the gamer become engrossed in the gameplay to a point where he or she pays a full attention and becomes emotionally attached to the game. The final stage is total immersion, where the gamer is completely dissociated from the physical reality and absorbed in the game world. Brown and Cairns equates total immersion to presence. However, in contrast to the concept of sensory or perceptual immersion (Biocca, 1997), the conceptualisation of immersion by Brown and Cairns (2004) and Calleja (2007) have a heavier focus on involvement rather than the sensation of being surrounded by the VE. This seems to be because their study was conducted specifically in the context of games, where the content has an active nature requiring the user's mental and physical efforts in interactive gameplay.

3.3. Flow

Csikszentmihalyi (1990) developed a concept of 'flow' to describe an optimal experience for happiness. To experience a flow state, there are eight conditions to meet: tasks with a reasonable chance of completion, clear goals, immediate feedback, deep involvement, sense of control, loss of self-consciousness and time transformation. These seem to have some conceptual overlap with psychological immersion (Lombard & Ditton, 1997), challenge-based immersion (Ermi & Mäyrä, 2005) and narrative immersion (Ermi & Mäyrä, 2005; Ryan, 2003). They all necessitate involvement and result in a sensation of being dissociated from the physical world. Michailidis, Balaguer-ballester, He, & Balaguer-ballester (2018) argue that total immersion by Brown and Cairns (2004) is essentially an experience of a deep flow state.

Some researchers have also linked flow to presence. Redaelli & Riva (2011) considers presence as a higher-level concept than flow in their 'flow for presence' questionnaire, i.e., flow is one of the determinants of presence. Pianzola et al. (2021) suggest that flow facilitates the development of physical presence and social presence as well as narrative absorption (i.e., involvement). On the other hand, Thissen et al. (2018) puts flow and presence at the same level in the conceptual hierarchy in the measurement of optimal reading experiences.

However, it is important to note that the key elements of the optimal experience in the flow concept are ‘control’ and ‘enjoyment’, based on which flow is often distinguished from immersive experience (Frochot, Elliot, & Kreziak, 2017; Jennett et al., 2008; Sanders & Cairns, 2010). Jennett et al. (2008) point out that immersion is not necessarily an enjoyable experience; as an outcome of immersive experience, one can develop negative emotions such as anxiety and frustration, whereas a flow experience will always positively influence the mindset. For instance, consider playing a boxing game in VR. The player might be highly present and involved in the game, but it would likely be an unpleasant and frustrating experience if he or she lost it after having been brutally beaten. This is why tasks with a reasonable chance of completion and sense of control are necessary conditions to experience a flow state, whereas they are not always necessary for feeling immersed.

Overall, there appears to be a lack of consensus among researchers regarding the relationship between immersive experience (IE) and flow. It remains unclear whether flow and IE should be treated as distinct constructs or if flow is a determinant of IE. However, based on the argument put forth by Jennett et al. (2008), it is evident that an immersive experience does not always lead to an optimal experience. Based on this, flow is not incorporated into the immersive experience model presented in the next section.

4. Proposed Model of Immersive Experience in XR

As discussed above, immersive experience (IE) has multidimensional nature. Although previous models of immersion use several different adjectives to describe different types of IE, the literature review identified that they all share common connotations of the underlying concepts of physical presence, social presence, self presence or involvement. This section proposes a unified conceptual model of IE in XR based on the literature reviewed above and other technical and contextual factors considered important for XR applications.

4.1. Model overview

The model aims to provide the hierarchical structure of the high-level and low-level factors of IE and their relationships with the properties of immersive system and content as well as potential bias factors. This section overviews the proposed model, and the following sections detail each component of the model, and discuss the applications of the model for XR studies.

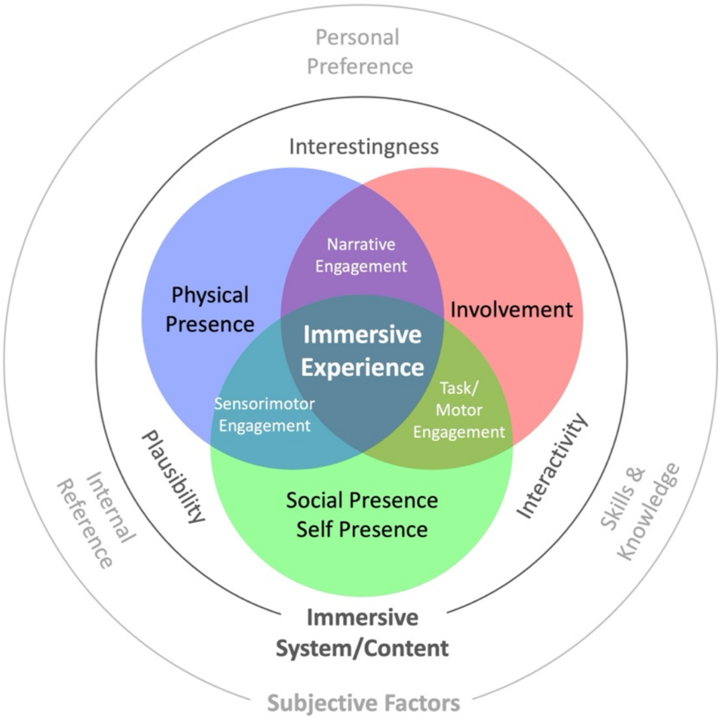

Fig. 1. Proposed conceptual model of immersive experience in extended reality.

Fig. 1 illustrates the proposed model, and Table 2 describes the components of the model and their relationships. As discussed in Sec. 2.3, the term ‘immersive experience (IE)’ is used to avoid a potential confusion with ‘immersion’ that is often used to mean a technological process. In the conceptual hierarchy, IE is the highest-level dependent variable, whilst the ‘immersive system (IS)’ and Content are the independent variables. There are four main determinants of IE: physical presence (PP), social presence (SP), self presence (SP) and involvement (INV). Social and self presence are both referred to as SP not only due to their shared initials but also because they are closely interrelated concepts that require interactivity and plausibility, as discussed in Sec. 3.1.3.

Each of the three attributes has overlapping sub-components: sensorimotor engagement between PP and SP, narrative engagement between PP and INV, and task/ engagement between INV and SP. These attributes are selectively related to the three main properties of IS and Content: plausibility for PP and SP, interestingness for PP and INV, and interactivity for INV and SP. Plausibility, interestingness and interactivity are influenced by subjective factors: internal reference, personal preference, and skills/knowledge, respectively. These are considered as confounding variables.

Note that in the scope of the proposed model, IE does not necessarily require all of PP, SP and INV to occur together. Each of the dimensions can independently create IE, but the overall level of IE would become stronger if more of these dimensions contributed collectively. This is further discussed using example scenarios later.

Table 2. Descriptions of the components in the proposed conceptual model of immersive experience.

Category	Component	Descriptions
Core dimensions of immersive experience	Physical Presence	The sense of being physically situated in a virtual environment and/or experiencing virtual objects as if they exist in the real environment.
	Social Presence	The sense of perceiving virtual intelligences in a virtual or real environment as perceptually and/or socially real.
	Self Presence	The sense of being embodied into a virtual self in sensory and/or cognitive manners.
	Involvement	The sense of deep cognitive and behavioural engagement with a narrative and/or task.
Preconditions for physical, social and self presence, and involvement	Sensorimotor Engagement	Engagement with physical action and sensory feedback. Initial stage of physical presence and social/self presence.
	Task/Motor Engagement	Engagement with task and physical action. Initial stage of social/self presence and involvement.
	Narrative Engagement	Engagement with the narrative of content. Initial stage of involvement and physical presence.
Properties of immersive system and content	Plausibility	The degree to which a virtual environment, object or being is perceived as realistic or believable. Supports sensorimotor engagement.
	Interactivity	The extent to which a user can actively influence or interact with virtual environments, objects or beings, physically and/or intelligently. Supports task/motor engagement.
	Interestingness	The quality of an immersive system or content that captures a user's attention, curiosity or motivation. Supports narrative engagement.
Subjective factors	Internal Reference	Cognitive cues drawn from a user's prior experiences, expectation or knowledge. Influences plausibility.
	Skills and Knowledge	Prerequisite to perform a task or activity with an immersive system. Influences interactivity.
	Personal preference	Individual interest at disposition. Influences interestingness.

4.2. Presence and Involvement as the main attributes of immersive experience

The proposed model considers PP, SP and INV to be the high-level determinants of IE. The rationale for the conceptual hierarchy and the relationship among the attributes are discussed in this section.

4.2.1. Definitions and justification for the typology

The proposed model follows Biocca (1997)'s typology of presence (physical, social and self presence), since, as discussed in Section 3.1, it encompasses the definitions of various immersion terms proposed in different models. The perceptual aspect of PP is connoted in the definitions of perceptual immersion (Biocca & Delaney, 1995; McMahan, 2013), sensory immersion (Ermi & Mäyrä, 2005) and spatial immersion (Zhang et al., 2017), whilst the cognitive aspect is incorporated in the definitions of imaginative immersion (Ermi & Mäyrä, 2005) and narrative immersion (Ryan, 2003). They all are to do with an experience of being physically transported from the PE into a VE, and the highest level of such experiences is that the user is completely dissociated from the PE (e.g., "the perceptual illusion of nonmediation" (Lombard & Ditton, 1997)).

Although Biocca (1997)'s definition of physical presence focuses only on the concept of the sense of being there in VR, the proposed model defines PP as "the sense of being physically situated in a virtual environment and/or experiencing virtual objects as if they exist in the real environment". This is based on Lee (2004)'s definition of physical presence, which considers both virtual environments and objects. The proposed definition broadens the applicability of physical presence to VR, AR and MR. It is important to clarify the meanings of virtual environments and virtual objects here. A virtual object refers to a specific digital item, whereas a virtual environment encompasses the overall digital space, which consists of multiple virtual objects. Virtual environments are primarily relevant in VR, whereas virtual objects play a key role in AR and MR.

Based on the discussions in Sections 3.1.2 and 3.1.3, the proposed model defines social presence as "the sense of perceiving virtual intelligences in a virtual or real environment as perceptually and/or socially real", and self presence as "the sense of being embodied into a virtual self in sensory and/or cognitive manners". Higher levels of both experiences are achieved not only through plausible sensory simulation (Biocca, 1997) but also through social interactions in tasks or activities that engage the user intellectually (Biocca, 1997; Ratan, 2012). Therefore, social presence and self presence are considered distinct yet interrelated concepts in the context of interactive XR applications. SP (social and self presence) can be considered as a possible scenario of challenge-based immersion (Ermi & Mäyrä, 2005) and ludic immersion (Ryan, 2003), where a virtual self is engaged in a certain activity or task with or without other virtual intelligences. Ratan (2012)'s model of self presence (Section 3.1.3) suggests that although proto self presence does not require other people or objects in the VE, core and extended self presence is closely associated with social presence. Therefore, it is hypothesised that, whilst self presence does not necessarily induce social presence, a higher level of social presence (through interactions) fosters a higher level of self presence.

As with presence, INV is an underlying concept for various immersion terms that were previously defined. In particular, some of Calleja's concepts of INV introduced in Section 3.2 are connoted in the definitions of narrative immersion (Ryan, 2003) (narrative involvement), challenge-based immersion (Ermi & Mäyrä, 2005) (tactical and performative involvement), imaginative immersion (Ermi & Mäyrä, 2005) (spatial involvement), and cognitive absorption (Agarwal & Karahanna, 2000). Therefore, the proposed model defines INV as "The sense of deep cognitive and behavioural engagement with a narrative and/or task". This is a similar concept to 'engrossment' in game play by Brown and Cairns (2004).

4.2.2. Relationship between Presence and Involvement

The proposed IE model considers that PP, SP and INV are at the same level of the conceptual hierarchy. Slater (2003) claims that PP and INV are orthogonal concepts, with the former being facilitated by Immersive System and the latter being related to Content. However, it is argued here that they influence each other and collectively contribute to IE. This is supported by the findings of several studies discussed in Sec. 2. INV is an important factor that determines the level of presence (Brown & Cairns, 2004.; Calleja, 2007; Heeter, 1992; Witmer & Singer, 1998; Wirth, 2007). However, presence can also foster INV. Ryan (2003) claims that in VR a strong physical presence could develop an intimate relation to the narrative of the content as well as a sense of being there. Furthermore, Slater (2009) argues that the sensation of being in a plausible VE leads to the user's realistic responses to sensory stimulation within the environment. It is possible that this can also foster more natural interactions with virtual objects and eventually lead to a deep state of INV in the activity, e.g., consider the virtual orchestra conducting example introduced in Sec. 3.1.3.

Some researchers exclusively distinguish presence from INV and IE (Agrawal et al., 2020; Jennett et al., 2008; Nilsson et al., 2016). For instance, Jennett et al. (2008) use double dissociation examples to distinguish presence from IE; playing a game such as Tetris would not induce presence due to the low-level graphics, but can still provide a high level of IE, whilst VR can produce a high level of presence even if the task is not immersive due to the content being not interesting. However, the implicit assumption of these examples seems to be that IE is only to do with INV, and PP is purely a sensory phenomenon. It is important to consider both perceptual (sensory) and cognitive (narrative) aspects in the conceptualisation and evaluation of IE as pointed out in previous studies (Berkman & Akan, 2019; Calleja, 2007; Ermi & Mäyrä, 2005).

Based on the proposed model, the Tetris example by Jennett et al. (2008) is a case of an IE with a high level of INV and a low level of PP. Even with the simple graphics used in the game, PP could still occur through the narrative of the content and an imagination (Ermi & Mäyrä, 2005; Ryan, 2003). The overall level of the IE might become higher if the game was produced in VR or AR using high-level graphics, where the sensory simulation helps the users feel as if they are in a world of falling blocks. Furthermore, the increased level of PP could also enhance INV (Ryan, 2003). For example, a documentary film about animals or nature shown on TV may not be interesting to everyone. However, if the content is provided in a high-resolution VR where the surrounding environment and sounds are presented three dimensionally, the user may become more intrigued and involved in the content. This is supported by Makransky and Petersen (2021)'s claim that virtual environment can foster the technology user's situational interest, which is discussed further in Sec. 4.4.3.

4.3. Engagement as the initial step towards PP, SP and INV

The term engagement is often interchangeably used with involvement. In the proposed model, however, the term is defined to be the mediators of PP, SP and INV, i.e., users must first be effectively engaged with the IS and content before they can experience a deep sense of presence and involvement. This is based on previous research. For example, Biocca (1997) uses the terms 'sensory engagement' and 'motor engagement' to describe a process towards presence in VR. Brown and Cairns (2004) describe engagement as the first step towards engrossment (i.e., INV) and total immersion (i.e., IE) in digital games. Han et al. (2023) defines engagement as the state in which a game player becomes acquainted with the game's setup, environment, interactions, and mechanics. In addition, Agarwal and Karahanna (2000) consider engagement as a factor of cognitive absorption, which is essentially the same concept as INV. In line with these, the current model considers engagement as a lower-level concept to

PP, SP and INV, thus being the initial step towards IE; Engagement per se does not directly induce IE, but it allows for PP, SP and INV, which eventually lead to IE.

4.3.1. Sensorimotor engagement

The proposed model posits that 'sensorimotor engagement' occurs at the intersection of PP and SP. The sense of being in a VE with or without other intelligences initially requires the user's sensory channels (e.g., visual, auditory and tactile) to be engaged by the VE (Biocca, 1997). Biocca (1997) highlights that "the degree to which the senses are engaged or connected to the interface" plays a crucial role in determining PP. For instance, a high-quality XR display with detailed visuals, combined with realistic 3D audio and acoustic simulation, enhances the engagement of both the auditory and visual channels. This, in turn, strengthens the feeling of being physically present in the virtual space (PP) and fosters a sense of social presence (SP) when interacting with virtual beings.

However, sensory perception of the physical environment (PE) is also influenced by bodily movement, a concept known as sensorimotor contingencies (SMCs) (O'Regan & Noë, 2001). Therefore, the user's motor engagement must also be considered when evaluating the plausibility of sensory simulation in extended reality (XR). Slater (2009) suggests that greater interactivity and bodily engagement enhance the place and plausibility illusion (i.e., PP). This is particularly relevant in applications where the user can move freely within a virtual or real environment using six degrees of freedom (6DoF). In these cases, the user expects sensory inputs to change dynamically in response to their full range of movement, ensuring a natural and coherent interaction with the virtual environment and beings/objects.

Sensorimotor engagement is also a precondition for SP. When social agents (real or virtual) are present in an environment, people tend to engage more actively (Bailenson & Yee, 2007). Furthermore, the predictive coding theory suggests that humans anticipate how others will respond in an interaction, and this process that relies on sensorimotor models of shared action possibilities (Kilner et al., 2007). Therefore, Social Presence in XR requires a sensorimotor engagement to be facilitated by the immersive system, which is further discussed in the next section.

Sensorimontor engagement is also crucial for Self Presence. The embodiment theory by Kliteni et al. (2012) suggests that the sense of owning and controlling a virtual body arises from sensorimotor congruence. Botvinick & Cohen (1998) demonstrated the 'rubber hand illusion' – when a person's hidden real hand and a visible rubber hand placed in a believable position in front of them are simultaneously stimulated with touch, it gave rise to the illusion that the rubber hand is part of their own body. This suggests the need for accurate sensorimotor engagement to enhance Self Presence in XR. The accuracy of the sensorimotor engagement is related to the proto-self level of Ratan (2012)'s Self Presence model: how realistic the representation of the virtual self is.

4.3.2. Task/motor engagement

The model considers that 'task/motor engagement' is the initial stage of SP and INV. Social and self presence can be enhanced by mental or physical interactions between virtual self and other intelligences in an activity (Biocca, 1997). Task/motor engagement in this context refers to the degree of attentional and cognitive investment in a task, which requires the user's mind and motor channels to be engaged with the virtual stimuli (Witmer & Singer, 1998). Research suggests that effective motor engagement improves user motivation and focus on a task in VR (Slater, 2009). Task/motor engagement can also be seen as an element of a task/activity-based INV (e.g., tactical/performative involvement (Calleja, 2007)). Consider playing a sport game in VR or AR. The levels of SP and INV that the player experiences may depend on how well they understand with the rule of the game and the required body movement tasks. Furthermore, the user is likely to be motivated to engage more with these tasks when they are interesting and rewarding, as this encourages sustained attention and intrinsic motivation (Krapp, 1999).

In addition, the levels of INV would be enhanced when effective motor engagement is supported by the immersive system. As Wirth et al. (2007) points out, involved users of VR technology have "various forms of intense interactions with a mediated stimulus" – as a result, they may want wish to act in the virtual environment (e.g., opening doors and exploring the rooms of the building), and the greater interactive capabilities the technology offers, the wider range of opportunities for exploratory activities will be (Wirth et al., 2007).

4.3.3. Narrative engagement

As discussed in Sec 3.1, engagement with the narrative of content not only is a crucial prerequisite for INV, as it facilitates deeper cognitive absorption in the content, but also plays a significant role in enhancing PP (Calleja, 2007; Gorini et al., 2011; Murray, 1997; Ryan, 2003). It is important to distinguish the concept of narrative engagement within the proposed model from the definition by Busselle and Bilandzic (2009). They define narrative engagement as a high-level construct, with narrative involvement and presence considered as factors of narrative engagement. In contrast, within the proposed model, narrative engagement is conceptualised as the initial step toward INV and PP aligning with the perspectives of Brown and Cairns (2004), Calleja (2007) and Biocca (1997).

Another distinguishing point is that Busselle and Bilandzic (2009) consider flow an outcome of narrative engagement, as an engaging narrative fosters complete focus and enjoyment. However, as discussed in Sec. 3.3, the proposed model separates flow from immersive experience; while flow requires enjoyment, immersive experience is not necessarily pleasurable (e.g., the boxing game example).

Attentional focus, one of the key factors in Busselle and Bilandzic's (2009) narrative engagement model, is also a crucial element for both INV and PP. When the narrative is interesting and engaging, it sustains the user's attention, fostering deeper involvement. Calleja (2007) argues that attentional focus is foundational for INV, while Schubert (2001) and Witmer & Singer (1998) highlight its importance for PP.

4.4. Properties of immersive system and content, and subjective factors

Plausibility, interactivity and interestingness are proposed as three main properties of Immersive System (IS) and Content. These are influenced by subjective factors, such as internal reference, skills and knowledge, and personal preference.

4.4.1. Plausibility and internal reference

Plausibility is closely associated with PP and SP in XR. A high level of presence does not necessarily require the VE stimuli to be a perfectly replica of the PE (Lee, 2004). Instead, presence is more dependent on the plausibility of the experience, i.e., how convincingly the VE stimuli are represented and how they respond to the user's expectations. Slater (2009) defines plausibility as "the overall credibility of the scenario being depicted in comparison with expectations", and considers plausibility illusion as an important condition for presence. Another good definition is found in the context of 3D audio: "a simulation in agreement with the listener's expectation towards an equivalent real event" (Lindau & Weinzierl, 2012). Both definitions suggest that the plausibility of the stimuli is not solely determined by the technological advancement of the IS but is also influenced by the user's subjective internal reference of what is realistic. This perception is shaped by previous experiences. For example, if a user had not previously encountered the virtual environment or the objects being simulated, they may initially perceive the stimuli as implausible, even if the sensory simulation is highly advanced. In such cases, greater cognitive processing may be required to interpret the unfamiliar environment and integrate it into the narrative of the content.

Therefore, for a natural and plausible simulation of a PE in an XR application, system-mediated sensory inputs should react to a user's actions and movements in the same manner as they would within the PE through which that user moves. This would allow the virtual objects and environment to be experienced as if they were real. Therefore, if the immersive XR system were able to support SMCs that are necessary for a plausible simulation of the PE, a mental model of the VE would likely be created more quickly and effectively than when using a lower-level system.

To maximise plausibility, the system's ability to dynamically render the virtual auditory-visual scene (e.g., location, size and loudness of the virtual stimuli) according to the user's head-orientation, position and distance from the virtual objects would be of paramount importance for understanding the environment (Martens & Cohen, 2020; Slater, 2009). The predictability of the movement-coupled changes in the sensory simulation creates a conscious experience of a simulated environment that obeys rules in ways that would be expected in an actual physical environment (Martens & Cohen, 2020). In addition, the SMCs afforded by the VR system can also influence how realistically the user behaves in the virtual environment (Slater, 2009).

Consider an AR sing-along app that projects virtual singers at different spatial locations in the physical environment, adjusting their perceived positions based on the user's head rotation and movement in 6DoF. However, if the app only supports static, monophonic and dry audio over headphones, an incongruency between auditory and visual perceptions would arise. This could not only reduce the plausibility of the virtual singers but also impair the user's ability to quickly and intuitively respond to them.

In addition, plausibility can also be understood as two different sub-concepts: social realism and perceptual realism, which are termed by Lombard and Ditton (1997). Social realism is about how likely the VE stimuli would occur in real life, whereas perceptual realism is about how close the implementation of the stimuli is to one's expectation if they existed in real life. For example, a science fiction video game in VR may have a low level of social realism but a high level of perceptual realism because objects and people in the film are unlikely to exist in real life but the visual representations are perceptually realistic, e.g., using an advanced computer graphics technology. Conversely, objects and people in an animation may be high in social realism but low in perceptual realism. Based on this view, the proposed model considers that plausibility is a property of not only IS but also Content.

4.4.2. Interactivity and skills/knowledge

Interactivity is a fundamental aspect of XR applications, fostering task/motor engagement and ultimately influencing the level of presence and involvement. Interaction plays a crucial role in inducing SP in XR environments, as it enables users to feel connected to virtual beings and other users within the virtual space (in VR) or the real space (in AR). According to Biocca, Harms, and Burgoon (2003), social presence emerges when users perceive virtual beings as real social actors with whom they can engage meaningfully. Higher levels of interaction, particularly those involving real-time responsiveness and shared activities, enhance the sense of SP and INV (Ratan, 2012; Oh, Bailenson, & Welch, 2018).

In XR applications, real-time physical interactivity can be facilitated through mechanisms such as head tracking, motion tracking, gesture-based control, gaze tracking and haptic feedback, all of which enable users to engage naturally with both the virtual environment and virtual beings, contributing to a stronger sense of being together in a shared space. The interactive features in XR systems allow for dynamic responses to users' movements and actions, mimicking real-life interactions. Head tracking and motion tracking allows the perceived spatial positions and intensities of audiovisual stimuli to adjust based on the user's real-time position and orientation in the virtual space. An effective 3D auditory display is particularly crucial for spatial localisation of virtual stimuli, as the field of view (FOV) of the viewport in a head-mounted display (HMD) is significantly narrower (90° to 110° horizontally) than the natural human FOV (approximately 200° horizontally). Consequently, auditory cues play a vital role in guiding the user's attention to virtual stimuli located outside the visible FOV, enhancing situational awareness.

Gesture-based controls and haptic feedback can simulate physical interaction with virtual beings or objects, enhancing the user's sense of agency and self presence (Kilteni et al., 2012). For instance, consider an AR social meeting platform where users can freely navigate and interact with other users or/and intelligent virtual beings represented as avatars. To facilitate a meaningful interaction and effective communication with the virtual beings, the system should support at least full-body motion tracking and head tracking to ensure realistic auditory-visual spatial perception. However, SP and INV would be maximised if the system could also facilitate social behaviours such as handshakes and eye contact by integrating gaze and gesture tracking features, along with haptic feedback. Moreover, intelligent virtual agents that can communicate with the user using artificial intelligence (AI) and speech recognition/generation technologies could further enhance the realism of social interactions.

However, user skills and knowledge can act as barriers to interactivity in XR applications. Firstly, if users lack familiarity with the technology or user interface, they may struggle to interact meaningfully with the system, potentially leading to frustration and disengagement. Furthermore, the cognitive load associated with learning new interaction skills can impair users' ability to focus on the content, especially when the system's interactions are complex or unintuitive. Moreover, individual differences in technical proficiency and experience may result in suboptimal immersive experience.

For instance, when two players engage in a tennis doubles match within a VR game, the more experienced player, with a greater understanding of the game rules and proficiency, is likely to experience higher levels of SP and INV, as their expertise allows for more effective interaction and a deeper connection with the game. On the other hand, beginners who lacks basic skills and struggle to concentrate on the mechanics of the game may experience lower levels of SP and INV, despite a high level of PP resulting from a realistic sensory simulation. Hence, the proposed model suggests that INV and presence can be influenced by both IS and Content. This contrasts Slater (2003)'s notion that INV is only to do with Content.

4.4.3. Interestingness and personal preference

Interestingness is a property of IS and Content that influences narrative engagement. The conceptualisation of interestingness is based on the psychological construct of interest proposed by Krapp, Hidi & Renninger (1992), which comprises three components: *individual interest as a disposition, interestingness and interest as a psychological state*. Individual interest as a disposition is the characteristics of the person. It develops over time and is often self-sustained, forming a stable personal preference (Krapp, Hidi & Renninger, 1992). Interestingness is a property of stimuli that can capture attention; a high level of interestingness leads to a high degree of attention and a readiness of the person to get involved with the task (Krapp, 1999). It is situational and may not lead to sustained engagement unless it aligns with the person's individual interest. Interest as a psychological state is a temporary cognitive and affective engagement with the stimuli (e.g., narrative engagement), resulting from both individual interest as a disposition (personal preference) and situational interest initiated by the interestingness of the stimuli (Krapp, Hidi & Renninger, 1992).

Based on this, the proposed model of IE considers interestingness as a prerequisite for narrative engagement, which is influenced by personal preference. Interestingness is usually considered as a property of Content, e.g., learning material (Krapp, Hidi and Renninger, 1992; Makransky and Petersen) and story (Bae et al., 2021). It can be assumed that content that contradicts user's personal preference is unlikely to result in narrative engagement. However, the proposed model also considers that interestingness to be a property of IS in XR applications; depending on the type of content and its personal relevance, technological features such as high-resolution, multisensory simulation and interactivity supported by IS (i.e., 'wow' factors) can lead to short-term, situational interest in exploring the content. This can drive the user to engage in an activity for the inherent enjoyment and satisfaction derived from the activity itself, i.e., intrinsic motivation (Deci and Ryan, 2000). Furthermore, the situational interest and intrinsic motivation may also develop into a long-term, individual interest (Hidi, 1990).

For instance, consider the animal documentary example in Sec. 4.3. If a viewer has little individual interest in wildlife and their habitats, a traditional documentary film shown on TV may fail to spark situational interest, resulting in minimal presence and involvement. However, if the film is presented in VR with a highly realistic 360° environment and lifelike 3D audiovisual representations of animals that the viewer can interact with, they are more likely to become intrigued and develop an interest in exploring the content. This heightened engagement may eventually lead to a deeper sense of involvement in the film's events and an increased feeling of presence. This immersive experience could even foster a newfound individual interest in wildlife and their habitats.

Another example is presented in the context of AR learning. Students may not be naturally interested in learning about historical figures from a textbook. However, their intrinsic motivation for learning could be significantly enhanced if these figures were represented as highly realistic, AI-powered 3D characters in AR, allowing the students to engage in both intellectual and physical interactions while acquiring knowledge.

However, it is important to note that the impact of IS's interestingness on narrative engagement may be limited by the type of content and the user's physical and cognitive or limitations. For example, a person with acrophobia is unlikely to engage with a virtual roller coaster experience in VR for enjoyment, even though such scenarios can be used effectively in VR exposure therapy. Furthermore, the content's interestingness depends on the contextual relationship between the user and cultural context (McGookin et al., 2019). It is evident from research that cross-cultural factors can influence user preference (Kim et al., 2015) and the adoption of XR (Monteiro, et al., 2024).

4.5. *Implications of the model for future research*

The proposed model is expected to provide researchers and technology developers with a unified conceptual framework for future XR studies. It serves as a foundation for assessing the immersive potential of immersive systems (IS) and content, as well as for formulating research questions and developing self-reported questionnaires to study IE and other dependent variables.

4.5.1. Development of IE measurement scales

As discussed in Section 2, inconsistent terminology and conceptual hierarchies in different measurement models make it difficult to compare and interpret different studies, hindering the development of a coherent knowledge base (Bareišytė et al., 2024; Grassini & Laumann, 2020). The proposed model addresses this issue by providing a unified conceptual understanding of the four dimensions of IE (physical, social, self presence and involvement), which collectively encompass the diverse descriptors used in different immersion and presence models. Using this consistent structure for measuring IE will allow comparisons between future studies.

However, it is important to note that the proposed model is not intended to establish a single questionnaire for IE, but rather to serve as a theoretical dimensional structure that guides researchers in formulating hypothesis and developing questionnaire items questionnaire items tailored to their research context. It is often assumed researchers that a validated questionnaire can be used for other studies measuring the same construct. However, it is argued that complex constructs such as presence or immersive experience cannot be measured using a standardised questionnaire due to its strong dependency on content and contextual factors (Biocca et al., 2003; Lombard et al. 2015; Rattray and Jones, 2007; Laarni et al., 2015; Bareišytė et al., 2024).). Section 4.4.3 also discussed the importance of considering cross-cultural influence on interestingness and adoption of XR.

Therefore, researchers aiming to measure immersive experience (IE) in XR applications are encouraged to use the proposed model to design novel questionnaires that maintain the consistent high-level dimensional structure of physical presence, social presence, self presence and involvement, while tailoring questionnaire items within each dimension to the specific content type, application, and target group. For instance, in a VR orchestra conducting scenario, self presence items could focus on controlling the performance of the orchestra and the sense of musical and emotional connection, while in an AR learning application, self presence could emphasise the manipulation of virtual objects and the ability to exchange information.

4.5.2. Validation of the immersive potential of IS and content

The model also defines clear criteria for assessing the immersive potential of IS and content: plausibility, interactivity and interestingness. While research focusing on XR technology development typically discuss low-level technical features in detail, studies that considers IE as a mediator for dependent variables such as therapeutic effects, learning outcomes and purchase decisions, often overlook the validation of immersive potential of the IS and content used. Typically, only one type of content is used in such studies, and detailed technical descriptions of the systems used are not provided (Harris, 2025). Although this is understandable given the large sample sizes in survey-based research and the potential lack of technical expertise among researchers, failing to assess immersive potential introduces the potential risk of misleading conclusions. For instance, consider a study investigating the effect of audiovisual VR on stress reduction. If the VR content used was created with low-resolution, suboptimal audiovisual technology, and the study found no significant effect, it would be premature to conclude that VR has no impact on stress reduction, since certain quality issues with the technology could have biased the results.

Therefore, it is proposed that future research should validate the immersive potential of IS and content in terms of plausibility, interactivity and interestingness before measuring immersive experience or other dependent variables. For this, researchers may need to develop set of scales relevant to the technical or narrative aspects of the IS and content. For example, plausibility can be assessed through the spatial congruency of audio and visual information, perceptual and social realism of audiovisual simulation, etc. Interactivity can be measured through physical aspects (e.g., system response time, motion tracking accuracy, naturalness of haptic feedback) and intellectual aspects (e.g., naturalness of a virtual agent's reactions, relevance of AI-generated responses). Interestingness can be evaluated based on whether situational interest is developed by the content.

4.5.3 Consideration of subjective factors

Section 4.4 discussed the subjective factors of the model (internal reference, skills/knowledge and personal preference) and their relationships with the properties of IS and content. Future research should investigate how PP, SP and INV in XR depend on the subjective factors in different XR contexts. As pointed out in Section 4.2.2, some research tends to simply assume that content with plain narrative is not able to produce INV despite a high level of PP (Jennett et al., 2008; Agrawal et al., 2020). For example, viewing a high-resolution 360° VR landscape of grand nature might be assumed to induce a high level of PP but a low level of INV, resulting in a lower overall IE. However, for mountain climbers with a deep interest in nature and landscapes, INV could also be high, leading to a high level of IE for the specific group. Integrating intelligent social agents, such as a virtual tour guide or other virtual tourists, could further enhance the IE by enabling social interaction. Additionally, as briefly mentioned in Section 4.4.3, situational interest triggered by an IS in XR could develop into a long-term individual interest. Therefore, individuals without a prior interest in landscapes may find intrinsic motivation to explore further. This topic warrants further investigation in future research.

Cross-cultural differences in XR experience are an important area of research that deserves further attention. Studies suggest that cultural differences influence various aspects of VR, such as system preference (Kim, 2015), system adoption (Monteiro et al., 2024), visual attention patterns (Šašinková, 2023), and presence (Burcolo, 2004; Triberti, 2025). More research is needed to understand how cross-cultural differences affect PP, SP, and INV across various content types in AR and MR, as well as VR. Utilising the unified conceptual model will not only enable researchers from different countries to collaborate in building a coherent body of research but also guide content creators in designing more effective IEs for diverse target audiences.

4.5.4 Overall level of immersive experience

Overall, the discussions in this paper suggest that a maximally immersive experience is achieved when all components of the model are fully utilised. To illustrate this, consider a scenario where a boy is transported into a virtual Disney story world via a 6DoF VR system. He finds himself surrounded by buildings while a theme song from a Disney animation he previously watched plays in the background – an example of internal references. The audio-visual representation of the virtual environment (VE) feels highly realistic and plausible. As a Disney fan, he is immediately drawn to the VE, resulting in a high level of physical presence (PP) due to strong sensory and narrative engagement. However, the overall level of IE remains moderate, as there is no social interaction or significant cognitive or physical involvement.

As he explores the VE, teleporting to different areas, his sense of presence is further enhanced through sensorimotor contingencies such as motion and head tracking. When he hears singing from a nearby building, he accurately localises the sound, aided by motion- and head-tracked 3D audio. Upon entering, he encounters Mickey Mouse, Donald Duck, and other beloved Disney characters, who are singing and dancing with children. Their perceptual and social realism (Lombard & Ditton, 1997; see Sec. 4.4) is so convincing that he feels physically present with them, marking the initial stage of social presence (SP).

The Disney characters greet him, ask his name, and invite him to join the party. As he engages with them both mentally and physically, his level of social presence deepens significantly. Over time, he begins to feel as though he is a member of the story world, experiencing self-presence (SP) as he becomes fully embodied and forgets the real self. At this stage, all dimensions – PP, SP, and INV reach their peak, resulting in an ultimate immersive experience. By comparison, watching a Disney animation on television may still provide an immersive experience through its compelling narrative, but it lacks the intensity of the fully immersive VR experience. The absence of interactive social elements and the limited sense of presence prevent full dissociation from the physical world, making the experience less immersive overall.

5. Conclusions

This paper first discussed the diverse definitions and multidimensionality of immersive experience and explicated the concepts of presence and involvement. Based on this, a unified conceptual model of immersive experience (IE) for XR was proposed. The summary of the model is as follows. IE has four high-level dimensions: physical presence (PP), social and self presence (SP) and involvement (INV). PP and SP necessitate sensorimotor engagement as an initial step and require the plausibility of the sensory information provided by the system and content. This can be influenced by the system user's internal reference about what is realistic. SP and INV commonly require task or/and motor engagement, served by the interactivity of the system and content. Related subjective factors and barriers for this are the user's skills and knowledge. INV and PP both require a certain level of narrative engagement, which is related to the interestingness of the stimuli produced by the content and system. Ultimately, the overall level of IE is determined collectively by the sum of PP, SP and INV.

The proposed model serves as an overarching conceptual framework, based on which researchers can develop new context-specific IE measurement scales and validate the immersive potential of immersive system and content for their studies. This will facilitate more effective collaboration among XR researchers as well as comparisons across different studies.

Furthermore, the model provides high-level evaluation criteria for XR content creation and system development.

References

Adams, E., & Rollings, A. (2007). *Game design and development: Fundamentals of game design*. New Jersey: Pearse Prentice Hall.

Agarwal, R., & Karahanna, E. (2000). Time flies when you're having fun: Cognitive absorption and beliefs about information technology usage. *MIS Quarterly: Management Information Systems*, *24*(4), 665–694. doi:10.2307/3250951

Agrawal, S., Simon, A., Bech, S., Bærentsen, K., & Forchhammer, S. (2020). Defining immersion: Literature review and implications for research on immersive audiovisual experiences. *Journal of the Audio Engineering Society*, *68*(6), 404–417. doi:10.17743/jaes.2020.0039

Andrews, C., Southworth, M. K., Silva, J. N. A., & Silva, J. R. (2016). Extended reality in medical practice. *Physiology & Behavior*, *176*, 139–148. doi:10.1016/j.physbeh.2017.03.040

Arsenault, D. (2005). Dark Waters: Spotlight on Immersion Dominic. *In Game-On North America 2005 Conference Proceedings*, (March), 50–52.

Bae, BC., Jang, S., Kim, Y., Park, S. (2021). A Preliminary Survey on Story Interestingness: Focusing on Cognitive and Emotional Interest. In: Mitchell, A., Vosmeer, M. (eds) Interactive Storytelling. ICIDS 2021. Lecture Notes in Computer Science(), vol 13138. Springer, Cham. https://doi.org/10.1007/978-3-030-92300-6_45

Bailenson, J. N., & Yee, N. (2007). Virtual interpersonal touch: Haptic interaction and co-presence in collaborative virtual environments. International Journal of Human-Computer Studies, 65(4), 295–304.

Balcerak J.M. & Balcerak J.B. (2024). Immersive Experience and Virtual Reality. Philosophy and Technology 37 (1):1-24.

Lina Bareišytė, Syl Slatman, Judith Austin, Martin Rosema, Iris van Sintemaartensdijk, Steven Watson, Christina Bode, Questionnaires for evaluating virtual reality: A systematic scoping review, Computers in Human Behavior Reports, Volume 16, 2024, https://doi.org/10.1016/j.chbr.2024.100505.

Bekele, M. K. and Champion E (2019) A Comparison of Immersive Realities and Interaction Methods: Cultural Learning in Virtual Heritage. Front. Robot. AI 6:91. doi: 10.3389/frobt.2019.00091

Berkman, M. I., & Akan, E. (2019). Presence and Immersion in Virtual Reality. *Encyclopedia of Computer Graphics and Games*, 1–10. doi:10.1007/978-3-319-08234-9_162-1

Biocca, F, & Delaney, B. (1995). *Immersive virtual reality technology*.

Biocca, F. (1997). The Cyborg's Dilemma: Progressive Embodiment in Virtual Environments. *Journal of Computer-Mediated Communication*, *3*(2), 0–0. doi:10.1111/j.1083-6101.1997.tb00070.x

Biocca, F., Harms, C., & Burgoon, J. K. (2003). Toward a More Robust Theory and Measure of Social Presence: Review and Suggested Criteria. Presence: Teleoperators and Virtual Environments, 12(5), 456-480. https://doi.org/10.1162/105474603322761270

Botvinick, M., Cohen, J. Rubber hands 'feel' touch that eyes see. Nature 391, 756 (1998). https://doi.org/10.1038/35784

Brown, E., & Cairns, P. (2004). A Grounded Investigation of Game Immersion. *CHI '04 Extended Abstracts on Human Factors in Computing Systems*, 1297–1300. doi:10.1145/985921.986048

Busselle, R., & Bilandzic, H. (2009). Measuring narrative engagement. *Media Psychology*, *12*(4), 321–347. doi:10.1080/15213260903287259

Calleja, G. (2007). Revising immersion: A conceptual model for the analysis of digital game involvement. *3rd Digital Games Research Association International Conference: "Situated Play", DiGRA 2007*, 83–90.

Caroux, L. (2023). Presence in video games: A systematic review and meta-analysis of the effects of game design choices. *Applied Ergonomics*, 107, 103936.Carvalho, B., Soares, M., Neves, A., Soares, G., & Lins, A. (2014). The State of the art in virtual reality applied to digital games : A Literature Review. *5th International Conference on Applied Human Factors and Ergonomics AHFE* doi:10.13140/2.1.2439.8722

Csikszentmihalyi, M. (1990). *Flow: The Psychology of Optimal Experience*. New York: Harper and Row.

Cummings, J. J., & Bailenson, J. N. (2016). How Immersive Is Enough? A Meta-Analysis of the Effect of Immersive Technology on User Presence. *Media Psychology*, *19*(2), 272–309. doi:10.1080/15213269.2015.1015740

Damasio, A. R. (1999). *The feeling of what happens: Body and emotion in the making of consciousness*. New York, NY: Harcourt Brace.

Diemer, J., Alpers, G. W., Peperkorn, H. M., Shiban, Y., & Mühlberger, A. (2015). The impact of perception and presence on emotional reactions: A review of research in virtual reality. *Frontiers in Psychology*, *6*(Jan), 1–9. doi:10.3389/fpsyg.2015.00026

Eaton, C., & Lee, H. (2019). Quantifying factors of auditory immersion in virtual reality. *In Proceedings of the AES International Conference*.

Ermi, L., & Mäyrä, F. (2005). Fundamental components of the gameplay experience: Analysing immersion. *Proceedings of DiGRA 2005 Conference: Changing Views - Worlds in Play*.

Freina, L., & Ott, M. (2015). A literature review on immersive virtual reality in education: State of the art and perspectives. *Proceedings of ELearning and Software for Education*

(ELSE), 8. doi:10.12753/2066-026X-15-020

Frochot, I., Elliot, S., & Kreziak, D. (2017). Digging deep into the experience – flow and immersion patterns in a mountain holiday. *International Journal of Culture, Tourism, and Hospitality Research*, *11*(1), 81–91. doi:10.1108/IJCTHR-09-2015-0115

Goffman, E. (1963). *Behavior in public places*. New York: The Free Press.

Gorini, A., Capideville, C. S., De Leo, G., Mantovani, F., & Riva, G. (2011). The role of immersion and narrative in mediated presence: the virtual hospital experience. *Cyberpsychology, Behavior and Social Networking*, *14*(3), 99–105. doi:10.1089/cyber.2010.0100

Grassini S and Laumann K (2020) Questionnaire Measures and Physiological Correlates of Presence: A Systematic Review. Front. Psychol. 11:349. doi: 10.3389/fpsyg.2020.00349

Green, M. C., & Brock, T. C. (2000). The role of transportation in the persuasiveness of public narratives. Journal of Personality and Social Psychology, *79*(5), 701–721. doi:10.1037/0022-3514.79.5.701

Hakemulder, F Kuijpers, M. M., Tan, E. S., Bálint, K., & Doicaru, M. M. (Eds. . (2017). *Narrative Absorption*. John Benjamins.

Dai-In Danny Han, Frans Melissen & Mata Haggis-Burridge (2024) Immersive experience framework: a Delphi approach, Behaviour & Information Technology, 43:4, 623-639, DOI: 10.1080/0144929X.2023.2183054

Harms, C., & A.Biocca, F. (2004). Internal consistency and reliability of the networked minds social presence measure. In M. Alcaniz & B. Rey (Eds.), Seventh Annual International Workshop: Presence 2004. Valencia: Universidad Politecnica de Valencia.

Harris, E., Fenton, S., Stephenson, J., Ewart, F., Goharinezhad, S., Lee, H. and Astin, F. (2025), Do Extended Reality Interventions Benefit Patients Undergoing Elective Cardiac Surgical and Interventional Procedures? A Systematic Review and Meta-analysis. J Clin Nurs. https://doi.org/10.1111/jocn.17578

Hartmann, T., Wirth, W., Schramm, H., Klimmt, C., Vorderer, P., Gysbers, A., & Sacau, A. M. (2016). The spatial presence experience scale (SPES): A short self-report measure for diverse media settings. *Journal of Media Psychology*, *28*(1), 1–15. doi: 10.1027/1864-1105/a000137

Heeter, C. (1992). Being There: The Subjective Experience of Presence. *Presence: Teleoperators and Virtual Environments*, *1*(2), 262–271. doi:10.1162/pres.1992.1.2.262

Hidi, S. (1990). Interest and its contribution as a mental resource for learning. Review of Educational Research. 60, 549-571.

Jennett, C., Cox, A. L., Cairns, P., Dhoparee, S., Epps, A., Tijs, T., & Walton, A. (2008). Measuring and defining the experience of immersion in games. *International Journal of Human Computer Studies*, *66*(9), 641–661. doi:10.1016/j.ijhcs.2008.04.004

Jung, S. and Lindeman, R.W. (2021) Perspective: Does Realism Improve Presence in VR? Suggesting a Model and Metric for VR Experience Evaluation. Front. Virtual Real. 2:693327. doi: 10.3389/frvir.2021.693327

Kilner, J.M., Friston, K.J., Frith, C.D. Predictive coding: an account of the mirror neuron system. Cogn Process. 2007 Sep;8(3):159-66. doi: 10.1007/s10339-007-0170-2. Epub 2007 Apr 12. PMID: 17429704; PMCID: PMC2649419.

Kilteni, K., Groten, R. & Slater, M. (2012). Sense of embodiment in virtual reality. Presence: Teleoperators and Virtual Environments, 21(4), 373–387.

Kim, S., King, R. & Kamekawa, T. A cross-cultural comparison of salient perceptual characteristics of height channels for a virtual auditory environment. Virtual Reality 19, 149–160 (2015). https://doi.org/10.1007/s10055-015-0269-1

Kober, S. & Neuper, C. (2013) Personality and Presence in Virtual Reality: Does Their Relationship Depend on the Used Presence Measure?, International Journal of Human-

Computer Interaction, 29:1, 13-25, DOI: 10.1080/10447318.2012.668131

Krapp, A., Hidi, S., & Renninger, KA. (1992). Interest, learning and development. In K.A. Renninger, S. Hidi, & A. Krapp (Eds.), The role ofinterest in learning and development (pp. 3-25). Hillsdale, NJ: Erlbaum.

Eugene Kukshinov, Joseph Tu, Kata Szita, Kaushall Senthil Nathan, Lennart E Nacke, Widespread yet Unreliable: A Systematic Analysis of the Use of Presence Questionnaires, *Interacting with Computers*, 2025;, iwae064, https://doi.org/10.1093/iwc/iwae064

Laarni,J.,Ravaja,N.,Saari,T.,Böcking,S.,Hartmann,T.andSchramm,H.(2015)WaystoMeasureSpatialPresence:ReviewandFutureDirections.ImmersedInMedia:TelepresenceTheory,Measurement&Technology,139–185.https://doi.org/10.1007/978-3-319-10190-3_8.

Lee, K. M. (2004). Presence , Explicated. *Communication Theory*, 14(1), 27–50. doi:10.1111/j.1468-2885.2004.tb00302.x

Lee S, Yoon J, Cho Y, Chun J. Systematic Review of Extended Reality Digital Therapy for Enhancing Mental Health Among South Korean Adolescents and Young Adults. Soa Chongsonyon Chongsin Uihak. 2023 Oct 1;34(4):204-214. doi: 10.5765/jkacap.230046. PMID: 37841488; PMCID: PMC10568184.

Lindau, A., & Weinzierl, S. (2012). Assessing the plausibility of virtual acoustic environments, *Acta Acustica united with Acustica*, 98(5), 804–810. doi: 10.3813/AAA.918562

Lombard, M., & Ditton, T. (1997). At the heart of it all: the concept of presence. *Journal of Computer-Mediated Communication*, *3*(2). doi:10.1111/j.1083-6101.1997.tb00072.x

Lombard,M.,Biocca,F.,Freeman,J.,IJsselsteijn,W.&Schaevitz,R.Immersedinmedia:Telepresencetheory,measurement&technology.SpringerInternationalPublishing,2015,https://doi.org/http://link.springer.com/10.1007/978-3-319-10190-3

McGookin, D., Tahiroglu, K., Vaittinen, T., Kyt,ö, M., Monastero, B., and Vasquez, J. C. (2019). Investigating tangential access for location-based digital cultural heritage applications. Int. J. Hum. Comput. Stud. 122, 196–210. doi: 10.1016/j.ijhcs.2018.09.009

Makransky, G., Petersen, G.B. The Cognitive Affective Model of Immersive Learning (CAMIL): a Theoretical Research-Based Model of Learning in Immersive Virtual Reality. Educ Psychol Rev 33, 937–958 (2021). https://doi.org/10.1007/s10648-020-09586-2

Martens, W. L., & Cohen, M. (2020). Spatial soundscape superposition, part I: subject motion and scene sensibility. *Acoustical Science and Technology*, *41*(1), 288–296. doi:10.1250/ast.41.288

McMahan, A. (2013). Immersion, engagement, and presence: A method for analyzing 3-d video games. *The Video Game Theory Reader*, (May), 67–86. doi:10.4324/9780203700457-10

Michailidis, L., Balaguer-ballester, E., He, X., & Balaguer-ballester, E. (2018). Flow and Immersion in Video Games : The Aftermath of a Conceptual Challenge. *Frontiers in Psychology*, *9*, 1–8. doi:10.3389/fpsyg.2018.01682

Minsky, M. (1980). Telepresence. *Omni*, *2*, 45–51.

Mirvis, P. H. (1991). Flow: the psychology of optimal experience. *Academy of Management Review*, *16*(3), 636–640. doi:10.5465/amr.1991.4279513

Monteiro, D., Ma, T., Li, Y. et al. Cross-cultural factors influencing the adoption of virtual reality for practical learning. Univ Access Inf Soc 23, 1203–1216 (2024). https://doi.org/10.1007/s10209-022-00947-y

Murray, J. (1997). *Hamlet on the Holodeck: The Future of Narrative in Cyberspace*. Cambridge, MA: The MIT Press.

Nhan VK, Tam LT, Dung HT, Vu NT. A conceptual model for studying the immersive mobile augmented reality application-enhanced experience. Heliyon. 2022 Aug 12;8(8):e10141. doi: 10.1016/j.heliyon.2022.e10141. PMID: 36039131; PMCID: PMC9418222.

Nilsson, N. C., Nordahl, R., & Serafin, S. (2016). Immersion revisited: a review of existing definitions of immersion and their relation to different theories of presence. *Human Technology*, *12*(2), 108–134. doi:10.17011/ht/urn.201611174652

O'Regan, J. K., & Noë, A. (2001). What it is like to see: a sensorimotor theory of perceptual experience. *Synthese*, *129*(1), 79–103. doi:10.1023/A:1012699224677

Oh, C. S., Bailenson, J. N., & Welch, G. F. (2018). A systematic review of social presence: Definition, antecedents, and implications. *Frontiers Robotics AI*, *5*, 1–35. doi:10.3389/frobt.2018.00114

Pianzola F, Riva G, Kukkonen K and Mantovani F. (2021). Presence, flow, and narrative absorption: an interdisciplinary theoretical exploration with a new spatiotemporal integrated model based on predictive processing, Open Res Europe 2021, 1-28. (https://doi.org/10.12688/openreseurope.13193.2)

Qin, H., Patrick Rau, P. L., & Salvendy, G. (2009). Measuring player immersion in the computer game narrative. *International Journal of Human-Computer Interaction*, *25*(2), 107–133. doi:10.1080/10447310802546732

Ragan, E., Sowndararajan, A., Regis, K., & Bowman, D. A. (2016). The sense of embodiment in irtual reality. *Presence: Teleoperators & Virtual Environments*, *25*(2), 81–107. doi:10.1162/PRES

Ratan, R. (2012). Self-presence, explicated: Body, emotion, and identity extension into the virtual self. *Handbook of Research on Technoself: Identity in a Technological Society*, 321–335. doi:10.4018/978-1-4666-2211-1.ch018

Rattray J, Jones MC. Essential elements of questionnaire design and development. J Clin

Nurs. 2007 Feb;16(2):234-43. doi: 10.1111/j.1365-2702.2006.01573.x. PMID: 17239058.

Redaelli, C., Riva, G. (2011). Flow for Presence Questionnaire. In: Canetta, L., Redaelli, C., Flores, M. (eds) *Digital Factory for Human-oriented Production Systems*. Springer, London. https://doi.org/10.1007/978-1-84996-172-1_1Ryan, M. L. (2003). *Narrative as virtual reality: Immersion and interactivity in literature and electronic media*. Baltimore, MD, USA: The Johns Hopkins University Press.

Sanders, T., & Cairns, P. (2010). Time perception, immersion and music in videogames. *Proceedings of the 2010 British Computer Society Conference on Human-Computer Interaction, BCS-HCI 2010*, 160–167. doi:10.14236/ewic/hci2010.21

Šašinková, A., Čeněk, J., Ugwitz, P. et al. Exploring cross-cultural variations in visual attention patterns inside and outside national borders using immersive virtual reality. Sci Rep 13, 18852 (2023). https://doi.org/10.1038/s41598-023-46103-1

Schubert, T., Friedmann, F., & Regenbrecht, H. (2001). The experience of presence: Factor analytic insights. *Presence: Teleoperators and Virtual Environments*, *10*(3), 266–281. doi:10.1162/105474601300343603

Sheridan, T. B. (1992). Musings on Telepresence and Virtual Presence. *Presence: Teleoperators and Virtual Environments*, *1*(1), 120–126. doi:10.1162/pres.1992.1.1.120

Shin, D. (2017). How does immersion work in augmented reality games? A user-centric view of immersion and engagement. Information, Communication & Society, 22(9), 1212–1229. https://doi.org/10.1080/1369118X.2017.1411519

Slater, M. (1999). Measuring presence: a response to the Witmer and Singer presence questionnaire. *Presence: Teleoperators and Virtual Environments*, *8*(5), 560–565. doi:10.1162/105474699566477

Slater, M. (2003). A Note on Presence Terminology. *Presence Connect*, *3*, 1–5.

Slater, M. (2009). Place illusion and plausibility can lead to realistic behaviour in immersive virtual environments. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *364*(1535), 3549–3557. doi: 10.1098/rstb.2009.0138

Slater, M., & Sanchez-Vives, M. V. (2016). Enhancing our lives with immersive virtual reality. *Frontiers Robotics AI*, *3*, 1–47. doi:10.3389/frobt.2016.00074

Slater, M., & Usoh, M. (1993). Presence in immersive virtual environments. *1993 IEEE Annual Virtual Reality International Symposium*, 90–96. doi:10.1109/vrais.1993.380793

Slater, M., & Wilbur, S. (1997). A framework for immersive virtual environments (FIVE): Speculations on the role of presence in virtual environments. *Presence: Teleoperators and Virtual Environments*, *6*(6), 603–616. doi:10.1162/pres.1997.6.6.603

Steuer, J. (1995). Defining virtual reality: Dimensions determining telepresence. In F. Biocca & M. R. Levy (Eds.), *Communication in the age of virtual reality* (pp. 33–56). Hillsdale, NJ: Laurence Erlbaum Associates.

Tcha-Tokey, Katy, Christmann, Olivier, Loup-Escande, Emilie, Loup, Guillaume, Richir, Simon, Towards a Model of User Experience in Immersive Virtual Environments, Advances in Human-Computer Interaction, 2018, 7827286, 10 pages, 2018. https://doi.org/10.1155/2018/7827286

Thissen, B. A. K., Menninghaus, W., Schlotz, W. (2018). Measuring Optimal Reading Experiences: The Reading Flow Short Scale. *Frontiers in Psychology*, 9, doi:10.3389/fpsyg.2018.02542

Triberti, S., Sapone, C. & Riva, G. Being there but where? Sense of presence theory for virtual reality applications. Humanit Soc Sci Commun 12, 79 (2025). https://doi.org/10.1057/s41599-025-04380-3

Tussyadiah, I. P., Wang, D., Jung, T. H., & tom Dieck, M. C. (2018). Virtual reality, presence, and attitude change: Empirical evidence from tourism. *Tourism Management*, *66*, 140–154. doi:10.1016/j.tourman.2017.12.003

Usoh, M., Catena, E., Arman, S., & Slater, M. (2000). Using Presence Questionnaires in Reality. Presence: Teleoperators and Virtual Environments 9, 5, 497–503. https://doi.org/10.1162/ 105474600566989

Wirth, W., Hartmann, T., Böcking, S., Vorderer, P., Klimmt, C., Schramm, H., … Jäncke, P. (2007). A Process Model of the Formation of Spatial Presence Experiences. Media Psychology, 9(3), 493–525. https://doi.org/10.1080/15213260701283079

Witmer, B. G., & Singer, M. J. (1998). Measuring presence in virtual environments: A presence questionnaire. *Presence: Teleoperators and Virtual Environments*, *7*(3), 225–240. doi:10.1162/105474698565686

Zhang, C., Perkis, A., & Arndt, S. (2017). Spatial immersion versus emotional immersion, which is more immersive?, *9th International Conference on Quality of Multimedia Experience*. doi:10.1109/QoMEX.2017.7965655