Using Extended Reality to Study the Experience of Presence

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Abstract Extended reality (XR), encompassing various forms of virtual reality (VR) and augmented reality (AR), has become a powerful experimental tool in consciousness research due to its capability to create holistic and immersive experiences of oneself and surrounding environments through simulation. One hallmark of a successful XR experience is when it elicits a strong sense of presence, which can be thought of as a subjective sense of reality of the self and the world. Although XR research has shed light on many factors that may influence presence (or its absence) in XR environments, there remains much to be discovered about the detailed and diverse phenomenology of presence, and the neurocognitive mechanisms that underlie it. In this chapter, we analyse the concept of presence and relate it to the way in which humans may generate and maintain a stable sense of reality during both natural perception and virtual experiences. We start by reviewing the concept of presence as developed in XR research, covering both factors that may influence presence and potential ways of measuring presence. We then discuss the phenomenological characteristics of presence in human consciousness, drawing on clinical examples where presence is disturbed. Next, we describe two experiments using XR that investigated the effects of sensorimotor contingency and affordances on a specific form of presence related to the sense of objects as really existing in the world, referred to as 'objecthood'. We then go beyond perceptual presence to discuss the concept of 'conviction about reality', which corresponds to people's beliefs about the reality status of their perceptual experiences. We finish by exploring how the novel XR method of 'Substitutional Reality' can allow experimental investigation of these topics, opening new experimental directions for studying presence beyond the 'as-if' experience of fully simulated environments.

Keywords Experience of presence · Extended reality · Reality monitoring · Sense of presence · Substitutional reality · Virtual reality

1 Introduction

Extended reality (XR) has for many years offered substantial promise to the scientific study of consciousness. XR is a general term encompassing virtual reality (VR), augmented reality (AR), as well newer methods such as substitutional reality (SR), which is described later in this chapter. Recent advances in XR technologies related to Head-Mounted Displays (HMD) and motion capture systems have provided powerful new tools enabling experimenters to manipulate specific aspects of the experienced world, or self, within highly realistic virtual environments (Bohil et al. 2011; Foreman 2010; Wilson and Soranzo 2015). Experiments capitalising on XR in these ways have addressed topics including spatial navigation (Ekstrom et al. 2003; Hartley et al. 2003; Shelton and Hedley 2004; Voermans et al. 2004), multisensory bodily perception (Ehrsson 2007; Lenggenhager et al. 2007; Slater et al. 2010; Suzuki et al. 2019a), and social neuroscience (de Borst and de Gelder 2015; Parsons 2015; Parsons et al. 2017; Pertaub et al. 2002). In the context of consciousness research, XR appears to offer the unique advantage of creating holistic, immersive conscious experiences of oneself and the environment within a simulated reality, while still permitting the manipulation of sensory input in a highly controlled manner – and crucially, enabling embodied interactions to be studied and manipulated (Bohil et al. 2011; Parsons et al. 2020).

What does it mean to feel presence within a virtual environment? Imagine that you put on a HMD and find yourself suddenly immersed in a highly realistic virtual environment. You are standing on a ledge of a very tall skyscraper, and looking down, you see the streets far below. You remain aware that this experience is not actually real: you know that the visual and auditory information your senses are receiving arise from the technology you are wearing. However, you nevertheless find yourself responding to these sensory signals 'as if' they were real: you are reluctant to move closer to the edge, you feel a sense of vertigo, your heart rate increases, and so on. Cognitively, you know that you are not in any danger, but you still experience the danger in some sense as being real. This contrast, verging on a contradiction, is at the heart of the concept of presence within XR environments.

In general, the feeling of presence has been defined as the subjective sense of reality of the world and of the self within the world (Metzinger 2003a; Sanchez-Vives and Slater 2005). More specifically within the context of XR, presence has been operationalised as the sense of being present in a virtual environment, rather than the place where one's body is actually located (Sanchez-Vives and Slater 2005; Lombard and Ditton 1997; Felton and Jackson 2021). Thanks to the growing body of research using XR, we now have considerable knowledge regarding the technological and psychological factors that modulate the sense of presence within XR, which we will discuss below (Bailenson and Yee 2008; Bowman and McMahan 2007; Slater et al. 1995).

Beyond XR research, there has been a growing interest more broadly within psychology and neuroscience to understand how the subjective experience of presence arises – and, more generally how perceptions and beliefs regarding our sense of 'reality' about the self and the world arise (Metzinger 2003a; Sanchez-Vives and Slater 2005; Seth et al. 2012). The topic of presence has also attracted the attention of clinicians investigating and treating mental disorders such as depersonalisation/derealisation disorder (DPDR), in which patients report a loss of their sense of presence in the world. Further research into conditions such as these promises to shed light on the cognitive and neural mechanisms of presence more generally.

In this chapter, we will analyse the concept of presence in terms of the general question of how humans generate and maintain a stable sense of reality during both natural perception and virtual experience. We will distinguish several aspects of 'presence' as it is generally construed. First is the notion of presence as the subjective *impression of being present* within a virtual environment. Second, there is the characteristic of normal perceptual phenomenology that the contents of perception seem to 'really exist' – we call this the *perceptual presence*.[1] Finally, there are higher-level beliefs that the contents of perceptual experience not only *seem* real but actually *are* real. Normally these two aspects go together, but they can come apart – for example, in lucid dreams. Crucially, XR experiences and technological design have tended to emphasise the first aspect of presence while neglecting the latter two. Indeed, most participants in XR, though they have the subjective impression of being present within a virtual environment, neither experience their virtual environment as being fully real, nor believe it to be real. Broadening the analysis of presence to these additional dimensions will add value to XR development and may catalyse insightful interactions between XR and perceptual presence in normal perceptual experience, as well as in a number of relevant clinical conditions.

2 Presence

2.1 Presence in XR

In this section, we first expand the above analysis of presence, alongside various methods to measure it in XR, and its relationship to conscious experience. We will also address similar concepts that have been discussed within the fields of neuropsychology and psychiatry in the context of specific mental disorders, such as DPDR.

We begin by outlining some of the many different definitions of presence that have been proposed within the XR literature (Felton and Jackson 2021; Lee 2004; Lombard and Ditton 1997), all of which arguably share the central idea that presence refers to the feeling of being physically present within a virtual environment, irrespective of one's actual physical reality (Witmer and Singer 1998). Alternative or complementary definitions, again within the XR context, consider presence as a loss of awareness of the media through which perceived objects or environments are conveyed (e.g. losing awareness of a HMD as mediating an XR experience). This conception of presence is somewhat coextensive with the philosophical notion of 'transparency' (Lee 2004; Lombard and Ditton 1997; Metzinger 2003b, 2014). Perhaps the most precise general definition of presence emerging from this background comes from Felton and Jackson (2021), who define the feeling of presence as 'the extent to which something (environment, person, object, or any other stimulus) appears to exist in the same physical world as the observer'. Notably, this definition could apply equally to normal (non-XR-mediated) experiences, as well as to XR.

[1] Note that perceptual contents seem real does not mean that they are, in some objective sense, real. Colours, for example, often seem to really exist in the world, even though they do not exist in any mind-independent way.

Although, as we will discover, many factors affecting presence are related to the perceptual domain (e.g. visual immersion, field of view, or synchronisation of multisensory information), many have argued that the experience of presence should not be viewed simply as an attribute of some other, more specific, perceptual content. There is an ongoing discussion about the nature of presence in conscious experience, i.e. 'what the experience of presence is like'. For example, Seth (2009) proposed that presence is a 'structural property' of consciousness – one that can apply to perceptual experiences in general – rather than to a specific instantiation of perceptual contents (e.g. a coffee cup on a table). Others have gone further, suggesting that presence within XR should be viewed as a distinct state of consciousness (Felton and Jackson 2021), based on similarities in the shifts of presence that may occur within XR to other distinct states of consciousness such as dream states (Biocca 2003), psychotic hallucinations (Bentall 1990), or during drug-induced mental states (Klüver 1942). These views emphasise presence as having its own distinctive signature in perceptual awareness, that is, presence cannot be reduced to other perceptual attributes, and has its own distinctive perceptual phenomenology. An alternative view suggests that the concept of presence refers to a type of 'metacognitive feeling' (Dokic and Martin 2017). This perspective proposes that the sense of presence is a cognitive rather than a perceptual experience, which is constructed based on judgements about reality. However, proponents of this view also emphasise that presence has an affective component, which they describe as a 'feeling', which again contrasts with the idea of presence as a primarily world-related perceptual attribute of some specific content (such as, for example, the experienced spatial dimensionality of a perceived object; Dokic and Martin 2017).

XR research has largely focused on uncovering the factors that are necessary for presence (as defined above) to emerge, and designing reliable measures that assess the degree to which presence is experienced. This line of research has been motivated, at least in part, by a need to assess the effectiveness of XR technologies for virtual training, entertainment, and applications in psychotherapy. Overall, the factors that have been shown to affect the feeling of presence within XR can be grouped into three categories: sensory factors; coupling of sensation and action (sensorimotor coupling); and embodiment.

Many of the *sensory factors* that affect the sense of presence in XR relate to basic properties of the media technologies used to create virtual environments. For example, the degree to which a HMD occludes a person's vision from the physical world, providing a field of view within the HMD that is roughly equivalent to the human visual field (e.g. 180°), and using a minimum graphics frame-rate of $\sim$15 Hz have all been shown to increase the feeling of presence within XR (Axelsson et al. 2001; Duh et al. 2002; Lin et al. 2002; Slater et al. 1996; Witmer and Singer 1998). These types of differences in the properties of the media hardware are also tightly related to the concept of immersiveness (i.e. the degree to which sensory information appears to originate in an external world rather than from the technological device itself; Weech et al. 2019).

The addition of multisensory feedback, for example, haptic or auditory feedback, within virtual environments has also been shown to increase reported feelings of presence (Bailenson and Yee 2008; Cooper et al. 2015; Freeman and Lessiter 2001). While general haptic feedback has yet to be fully achieved due to the non-trivial technical challenges associated with this form of sensory feedback (although see here https://haptx.com/), it can be cheaply simulated with the so-called static haptics or tactile feedback. A static haptic is a simple version of a physical object located in the real world that corresponds to a virtual counterpart, such as a plank of wood on the floor corresponding to the edge of a simulated building. There are many methods of producing tactile feedback in XR. For example, in a previous experiment from our lab that investigated the sense of agency induced by virtual hand movements within XR (Suzuki et al. 2019b), we simulated the tactile sensation associated with a virtual button press by attaching a vibrating pad to the participant's fingertips, which vibrated whenever the participant pressed a virtual button – here, the tactile feedback from the pad created a sense of touching a physical object. The experience of presence can also be enhanced by combining multiple multisensory cues (Cooper et al. 2015; Dinh et al. 1999), possibly due to multiple sources of sensory information confirming a particular perceptual interpretation of a virtual environment. Altogether, these parameters provide a repertoire of presence-affecting factors which researchers can use to increase or otherwise modulate the felt presence of a virtual environment within XR experiments.

As well as considering the fidelity, transparency, and multimodality of sensory data, presence may also depend in substantial ways on the incorporation of action – in the form of *sensorimotor couplings* or contingencies within XR environments (Flach and Holden 1998; Grabarczyk and Pokropski 2016; Zahorik and Jenison 1998). The central idea here is that presence is shaped by the range of actions it is possible to perform within a virtual environment – and by their sensory consequences (Sanchez-Vives and Slater 2005). This view inherits from the concept of affordances (Dalgarno and Lee 2010; Gibson 1979), which we will discuss in more depth in the next section. Within this view, the degree of interactivity and sensorimotor coupling that XR technology can provide is critical in creating a sense of presence (Lallart et al. 2009; Slater and Usoh 1993; Steuer 1995). One key aspect of this view is that sensorimotor coupling is fundamental in eliciting a sense of *agency*, which can be thought of as the experience of controlling one's own actions, more generally, of being the cause of things that happen, and which is considered to be a key part of the experience of the 'self' (Gallagher 2000; Haggard 2017).

A further dimension that has been shown to affect presence within XR can broadly be termed *embodiment*. Using virtual avatars within immersive VR environments allows users to experience the sensation of ownership over a virtual body, which in turn leads to the feeling of being 'embodied' in such a virtual avatar (Grabarczyk and Pokropski 2016; Schultze 2010; Slater et al. 2009a). For instance, people report an increased sense of presence when their avatar is a complete virtual body, compared to a more simple representation such as a 3D cursor (Slater and Usoh 1993). Embodying a virtual avatar has been shown to produce particularly interesting effects within social contexts: research has found that participants experienced a greater sense of interactivity and immersion when the appearance of the avatar reflected their ideal self rather than their actual appearance (Jin 2009; Kafai et al. 2010). Finally, the experience of 'embodying' a virtual avatar within XR in a broader context has been used to investigate the experience of the bodily self (Blanke and Metzinger 2009; Lenggenhager et al. 2007; Slater et al. 2010). These studies have extended the rubber hand illusion (RHI), a cornerstone of the scientific literature of embodiment, in which people (to varying degrees) report experiencing illusionary ownership of a rubber hand when synchronous visuo-tactile stimulation is applied to the visible rubber hand and to the participant's own occluded hand (Botvinick and Cohen 1998; Roseboom and Lush 2022).

Although research into how these factors contribute to the feeling of presence within XR has been considerable, one underappreciated factor, particularly relevant to embodiment, is the potential role for demand characteristics (Orne 1962) and – more generally – participant expectations in shaping aspects of any XR experience, including reported presence. Demand characteristics refer to the long-standing concern in psychology that characteristics of experimental design may lead people to 'know the correct answer' that the experimenter is 'looking for' – and that this knowledge, or expectation, whether implicit or explicit, may influence or explain their responses. It is difficult to think of a situation more prone to embedding demand characteristics and participant expectations than XR environments, which are usually designed explicitly to bring about immersive and highly specific experiences. Importantly, demand characteristics may exert their effects not only through participants merely making responses according to what they think the experimenter wants ('behavioural compliance'), but also by shaping or generating subjective experiences to fit experimental demands (Kirsch and Council 1989; Olson et al. 2020).

For example, a recent study found that people who are more capable of producing experiences consistent with task demands in a hypnotic context, may also be able to respond to demand characteristics in general, outside of that context, by changing their actual experience (Dienes et al. 2020). In a series of follow-up studies this group investigated the effects of individual differences in suggestibility (trait phenomenological control) on the RHI (Lush et al. 2020; Lush and Seth 2022; Roseboom and Lush 2022; see also Ehrsson et al. 2022). Together, these studies revealed that individual differences in suggestibility confounded the subjective measurements of ownership in the RHI. The authors concluded that it is not possible to exclude the possibility that the experience of embodiment in the RHI is due to implicit imaginative suggestion effects – to phenomenological control. These findings are not a concern only for the RHI, but likely extend to any experimental setting involving measuring subjective experiences that does not adequately control for the effects of demand characteristics. Future studies investigating the sense of presence in XR should carefully consider the implicit demand characteristics inbuilt into the design of their experiments and develop suitable conditions to control for these factors. Such an approach will allow the field to develop a better understanding of the mechanisms and processes underlying empirical, phenomenological, behavioural, and physiological observations in XR, while also broadening our understanding of the role top-down expectations play in the construction of perceptual experiences in both real and virtual worlds.

2.2 Measuring Presence

Adding complexity to the presence research landscape is the lack of consensus about how best to measure it, either within XR contexts or more generally. Questionnaires are the most commonly used method, due to their controlled and structured nature and simplicity of administration (Van Baren 2004). The use of questionnaires does not require special equipment and can be performed easily before or after the experimental sessions (Witmer and Singer 1998). However, questionnaire-based methods for assessing presence have been shown to be unstable, in that prior information can change the results (Freeman et al. 1999), and as mentioned above, they are also susceptible to the effects of demand characteristics (Van Baren 2004). A more subtle worry is that reports of presence may only arise in XR when participants are probed to provide them (Slater 2004), suggesting that researchers need to move away from the current heavy reliance on questionnaires in order to make progress in this area.

Besides questionnaires, researchers have sought to identify behavioural signatures of presence in XR. Such behavioural signatures revolve around the intuition that if participants within a XR experience behave as if they are in an equivalent real environment, then they are likely to be experiencing presence within that virtual environment. For example, if a participant ducks in response to a looming stimulus or shows postural sway in response to moving visual field, then this may be used as a sign of presence (Freeman et al. 2000; Held and Durlach 1992; Sanchez-Vives and Slater 2005). An extension of this approach is to use physiological measures, based on a similar assumption that if a participant's normal physiological response to a particular situation is replicated in a virtual environment, then this is a sign that they are experiencing a high degree of presence. So far, expected alterations in heart rate (Meehan et al. 2002), skin conductance (Slater et al. 2009b), and electroencephalography (Terkildsen and Makransky 2019) have all been demonstrated in response to fear inducing situations within virtual environments.

Although physiological measures like these may be less subject to explicit bias than direct subjective reports, it is important to note that they are not immune from the effects of demand characteristics or implicit imaginative suggestion. For example, imaginative suggestion has been repeatedly demonstrated for more than half a century to affect skin conductance responses including responses to the RHI (Barber and Coules 1959; Kekecs et al. 2016; Lush et al. 2020). Furthermore, there are concerns about the degree to which behavioural and physiological measures actually reflect the subjective sense of presence, as objective and subjective measures of presence have been shown to diverge in some cases (Bailey et al. 2009; Freeman et al. 2000; IJsselsteijn et al. 2002; Riva et al. 2003; Wiederhold et al. 1998).

Given the current state of art regarding measuring presence, there is a need to continue to develop new behavioural measures that correlate with presence, while carefully avoiding the demand characteristics mentioned above. For example, behavioural measures such as proprioceptive drift (Botvinick and Cohen 1998) or intentional binding (Haggard et al. 2002) have been considered as behavioural signatures of (respectively) body ownership and agency, which could relate to presence in the context of embodiment and sensorimotor coupling. However, great care needs to be taken to measure participant expectancies for such measures in order to avoid confounds due to demand characteristics (Lush et al. 2021). Outside the context of embodiment, there is a need to develop behavioural measures that correlate with presence in simple perceptual tasks. In Sect. 3, we introduce one possibility along these lines, using a version of continuous flash suppression.

Another possible avenue towards developing measures that remain unconfounded by demand characteristics is to use a version of XR called substitutional reality (SR), which we will describe in detail in Sect. 3. For now, it suffices to say that the defining feature of an SR experience is that participants are unable to distinguish it from the corresponding real-world situation. In such cases, one primary demand characteristic confound is removed since participants should not be able to strategically behave in a particular way in the virtual situation. However other, more general demand characteristics related to expected performance in the experiment as a whole may remain.

Studies attempting to identify the neural correlates of presence remain rare, in part due to the difficulties of bringing a virtual reality environment into an fMRI scanner (Clemente et al. 2014; Jäncke et al. 2009; Sjölie et al. 2014). Among the few studies that have been conducted, the dorsolateral prefrontal cortex (DLPFC) has emerged as one of the relevant brain areas in shaping the reported degree of presence and immersiveness (Baumgartner et al. 2008; Jäncke et al. 2009). It is interesting to relate these findings to neuroimaging studies of DPDR, which have shown both reduced activation in neural regions typically implicated in the generation of affective responses towards salient stimuli (e.g. insula and amygdala) along with increased activation (e.g. hyperactivation) of prefrontal regions (Jay et al. 2014; Phillips and Sierra 2003; Sierra and Berrios 1998). Furthermore, Dresler et al. (2012) using fMRI found increased activation in right DLPFC and in frontopolar areas in lucid dreams compared to REM sleep, while Filevich et al. (2015) showed greater grey matter volume in the frontopolar cortex for people reporting higher dream lucidity compared to the low lucidity group. Together, these neuroimaging results – while sparse and largely indirect – nonetheless offer some support for metacognitive accounts of presence (e.g. Dokic and Martin 2017), while also highlighting the delicate balance between monitoring mechanisms, interoceptive and emotional processes in orchestrating the experience of presence (see also Sects. 2.3 and 4.1).

2.3 Disorders of Presence in Clinical Conditions

In our everyday lives our sense of reality is so pervasive that it tends to be taken for granted. Only when it is disturbed pathologically do we even appreciate that it existed in the first place (Jaspers 1973, 1997). For example, in DPDR people report feeling that their sense of reality is attenuated or diminished. DPDR is a type of dissociative disorder in which the patient reports persistent or recurrent feelings of being detached (dissociated) from their body or mental processes, usually accompanied by a feeling of being an ‘outside observer’ of their life (depersonalisation), or of being detached from their surroundings (derealisation), both of which are related to the experience of presence (Phillips et al. 2001; Shorvon 1946; Sierra et al. 2005; Sierra and David 2011) Interestingly, people with DPDR usually have normal or near-normal cognitive and perceptual capabilities, suggesting that DPDR may occur due to a separation between the experience of specific perceptual content and a more general (structural) experience of presence.

Another commonly reported clinical feature of DPDR in conjunction with a loss of presence is emotional numbness, characterised by attenuated emotional colouring of subjective experiences (Sierra and David 2011). The observation that patients with DPDR display attenuated emotional responses supports theories of presence that suggest that it is a (possibly metacognitive) affective experience, or a *feeling,* that rejects the idea of presence as being a purely world-directed perceptual experience (Dokic and Martin 2017).

Although the neurological causes of DPDR are not fully understood, it has been suggested that aberrant integration of autonomic signals from the body, which are thought to be crucial in generating normative emotional responses, may underlie some features of DPDR (Lemche et al. 2008; Sierra et al. 2002). Supportive of this theory are findings that show that DPDR seems to be associated with a reduction in autonomic responses to aversive stimuli (Sierra et al. 2002). In a related line of work, we developed a computational model of DPDR, in which we proposed that the lack of presence in DPDR was due to abnormal inference of (the causes of) interoceptive signals (Seth et al. 2012). Within this interoceptive inference framework, a sense of presence arises when interoceptive signals are successfully explained by top-down predictions supported by hierarchical generative models in the brain. According to our model, the loss of presence associated with DPDR is associated with imprecise predictions relating to interoceptive signals, which cannot explain away the prediction errors. Experimentally, we found that visual feedback of an individual’s own cardiac signals can induce illusory experiences of body ownership (Suzuki et al. 2013), which supports the notion that interoceptive signals may have a role in the generation of the bodily sense of presence (Suzuki et al. 2013; see also Aspell et al. 2013). Although, as discussed earlier, the results of these studies may have been confounded by demand characteristics, as this experiment did not control for expectations or individual differences in suggestibility (Lush et al. 2020).

In this section, we introduced the concept of presence as the subjective sense of reality of the world and of the self. We have seen how XR technologies can enhance experienced presence through combinations of sensory factors, sensorimotor coupling, and embodiment. We also emphasised the issue of demand characteristics when measuring any type of subjective experience, an issue that we suggest potentially confounds existing measures of presence. Shifting focus to the phenomenology of presence, we have seen how the experience of presence is pervasive in our everyday experience and how it can be disturbed in certain clinical conditions, notably in DPDR. Clinical cases such as this raise the question: What causes us to experience certain specific perceptual contents as veridical and realistic rather than fake or unreal? In the next section, we discuss the specific sense that external objects seem to really 'exist' out there in the world, a concept we refer to as *perceptual presence*.

3 Perceptual Presence

In this section, we describe XR experiments that connect presence to the sensorimotor theory of consciousness through manipulations of the perception of real and virtual objects.

3.1 Perceptual Presence and 'Mastery' of Sensorimotor Contingencies

In addition to our sense of presence in the world and within the context of VR, we also experience a distinct sense of presence associated with objects in the real world. For example, when we see a coffee cup on a table, we perceive this object as an existing real entity embedded in the world. This perceptual experience that there is a really-existing object out there in the world can be called *perceptual objecthood* – or, for simplicity here, just objecthood. To flesh out this notion, consider again the coffee cup. When we observe a coffee cup in real life, we experience it as having a back (and sides) even though the back (and perhaps sides) are not immediately available within our vision. We experience the cup as having a three-dimensional volumetric extension in the world. The same feeling does not arise from a coffee cup as represented in a photograph or a painting. This notion of objecthood is one way of bringing specificity to the more general notion of 'perceptual presence'.

The property of perceptual presence has motivated the sensorimotor theory of consciousness (Noë 2004; O'regan and Noë 2001), which understands perceptual phenomenology to be shaped by 'mastery' of the sensorimotor contingencies governing how sensory signals respond to actions. This theory views perceptual experience as being instantiated through a closed loop between action and perception, a proposal which inherits from James J. Gibson's concept of *affordance*, which refers to the opportunities an object presents for action (Gibson 1979). According to Noë, the perceptual presence of a real object is given by the learnt 'know-how' or 'mastery' of the sensorimotor contingency that governs how the sensory information is altered by a particular action (Noë 2004; O'regan and Noë 2001). To continue the coffee cup metaphor, I see a coffee cup as really existing in the world because my brain 'knows about' the sensory consequences of moving my eyes or rotating the cup. In this sense, I perceive that the cup has a back even though I cannot directly see it[2] (Noë 2004; O'regan and Noë 2001).

While influential, the sensorimotor theory of consciousness expressed by O'Regan and Noë (2001) has been criticised for lacking a clear implementation in neural circuitry. More recently there have been attempts to incorporate sensorimotor contingencies into a *predictive processing* account of perception (Seth 2014). In the predictive processing framework, perception is viewed as probabilistic inference of the 'hidden causes' of sensory information, by neuronally encoding a generative model that makes predictions about the likely causes of sensory information (Clark 2013; Friston 2010; Rao and Ballard 1999). The Predictive Processing Theory of SensoriMotor Contingencies (PPSMC) proposes that perceptual presence arises when the brain encodes a rich repertoire of predictions using a generative model that can make predictions about how sensory signals would change given specific actions (Seth 2014, 2015).

These theoretical developments have been accompanied by a growing body of empirical work investigating the effects of action, or the opportunity an object presents for action, on visual perception (Bekkering and Neggers 2002; Chan et al. 2013; Lindemann and Bekkering 2009). One of the most promising avenues of research for investigating how actions may affect perceptual presence focuses on how the brain responds to real objects versus images of objects (Gomez et al. 2018; Marini et al. 2019; Snow et al. 2014; Snow and Culham 2021). One such study investigated how a person's attention changes when viewing either real objects or images of the same objects (Gomez et al. 2018). In this experiment, participants were asked to identify the orientation of a target object (a spoon) within a field of distractor objects as quickly as possible. The results revealed that compared with both 2-D and 3-D images, real objects yielded slower response times overall and elicited greater flanker interference effects. Interestingly, when the real spoon was placed outside of the participant's reach, or when a transparent screen was placed between the spoon and the participant the differences in reaction time and interference effects were comparable with that of 2-D images. These results demonstrate that real objects exert a more powerful influence on attention and motor responses compared to representations of objects and suggest that this effect may be due to the affordances that real objects provide for physical interaction. However, returning to the core predictions of the sensorimotor theory of consciousness, few empirical studies have directly addressed if 'mastery' of sensorimotor contingencies contributes to perceptual presence. Fortunately, XR technologies offer new opportunities to

[2] One might argue that it is possible to experience objecthood even for a cup in a painting or a video. Consider, for example, that in the painting or video, there is a person trying to grasp the cup. In this example, we might have some sense that the cup is indeed a three-dimensional object. Critically, though, this is with respect to the person in the painting, not with respect to us as external observers. Arguably, the notion of objecthood that pertains in this case is more indirect, and cognitive, rather than the direct and immediate objecthood that is part of our real-world everyday perceptual experience.

investigate this question using naturalistic sensorimotor interactions with virtual objects.

3.2 Using Binocular Suppression to Measure Perceptual Presence

An early study investigating the link between action and perception used a binocular rivalry paradigm, in which two dynamic visual stimuli compete for perceptual awareness (Maruya et al. 2007). This study found that when the motion of one stimulus (but not the other) was contingent on a participant's voluntary actions, dominance durations for that stimulus were longer, and suppression times were shorter, compared to stimuli that moved independently from the participant's actions. This finding suggests that disruption of veridical sensorimotor contingencies can affect the formation of a visual percept even outside of awareness. However, the simple visual stimuli used (random dot stereogram), and the trained stereotypical movements used in this study did not address how naturalistic sensorimotor interactions with real-world objects shape subjective visual experience.

To address these issues, we developed a novel experimental setup combining AR and VR technologies that allowed real-time naturalistic sensorimotor interactions with novel virtual 3D objects. Our setup allowed us to investigate the dependence of visual experience on the dynamic causal coupling between actions and their sensory consequences within a real-world setting (Suzuki et al. 2019b). We manipulated the specific sensorimotor contingencies associated with virtual objects within a well-studied visual paradigm called continuous flash suppression (CFS; Jiang et al. 2007; Stein et al. 2011; Tsuchiya and Koch 2005). CFS is a more controllable version of binocular rivalry in which perceptual awareness of a target stimulus presented to one eye is suppressed by a series of rapidly changing, high contrast, Mondrian patterns (see Fig. 1b) presented to the other eye, and the time it takes the target to 'break-through' into awareness is measured. Often (as in our paradigm) the relative contrasts ramp up (for the target) and down (for the Mondrian) to ensure break-through occurs within a reasonable time frame. Differences in the time it takes a stimulus feature to breakthrough into conscious awareness in CFS have been interpreted by some authors as indicating the amount of unconscious processing associated with a specific stimulus feature (Salomon et al. 2013; Stein and Sterzer 2014). Although earlier studies focused on examining the effects of low-level visual features, such as image contrast, on breakthrough times, later studies found that even high-level visual features can modulate unconscious visual processing within the CFS paradigm. For example, upright faces have been shown to breakthrough into conscious awareness faster than inverted faces (Jiang et al. 2007). In addition, the CFS paradigm has been used to study how multisensory information affects visual awareness by manipulating the congruency between somatosensory and visual information (Salomon et al. 2013, 2015).

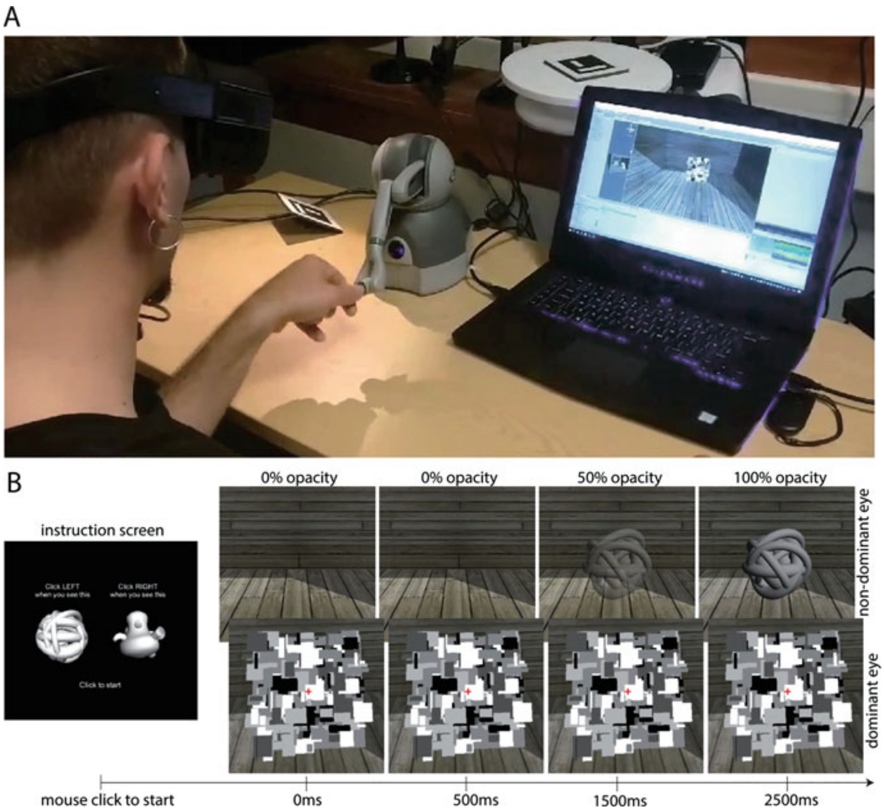

Fig. 1 An illustration of the continuous flash suppression (CFS) experiment used to investigate the effects of sensorimotor contingencies of virtual 3D objects on breakthrough times (adapted from Suzuki et al. 2019a, Crown Copyright © 2019 Published by Elsevier B.V. All rights reserved.). (**a**) Experimental setup, participants viewed a virtual 3D object and dynamic Mondrian through a HMD. They manipulated a virtual object using a motion-tracking stylus with their left hand. (**b**) Single trial structure of the experiment. The object's opacity gradually increased over time and was presented to the non-dominant eye (top) and the Mondrian mask was presented to the dominant eye (bottom)

We used this setup to test the influence of sensorimotor coupling on visual awareness of a virtual object whose visibility was suppressed by a CFS mask (Fig. 1). To exclude the influence of inter-subject differences in sensorimotor knowledge for familiar objects, we used a series of novel 3D virtual objects. For each trial, participants were asked to rotate a motion-tracking device held in one hand, which was reflected by the movements of the 3D object rendered to the non-dominant eye, whilst a CFS mask was presented to the dominant eye inside a head-mounted display. We found that participants' responses were faster when the virtual object was directly coupled to their ongoing actions, compared to when the object's movements were replayed from previous trials, or when the object did not move at all in response to their actions.[3]

While this study did not measure perceptual presence directly, the results support the idea that object perception is enhanced when naturalistic, ecologically valid sensorimotor contingencies are followed. More specifically, the acquisition of the sensorimotor contingencies associated with the virtual object during the live condition led to faster breakthrough times, compared to the replay or static conditions. Breakthrough time under CFS, in this paradigm, could therefore be considered as a potential behavioural proxy for perceptual presence.

Extending and complementary to the results of this study, Korisky and colleagues developed an experimental setup that enabled CFS with real objects (Korisky et al. 2019). Their setup consisted of AR glasses that displayed a CFS suppression mask to one eye, while the other eye viewed an object located in the physical world. Using this setup, they were able to use real objects and two-dimensional pictures of the same objects and measure the time taken for these two classes of stimuli to breakthrough into conscious awareness. It should be noted that, unlike in our experiments, the sensorimotor contingencies of the objects were not manipulated as the objects remained stationary. However, another difference was that the objects used were all familiar, permitting the assumption that the participants had already acquired mastery of the relevant sensorimotor contingencies. Interestingly, they found that real objects took less time to breakthrough into conscious awareness than two-dimensional images of the same objects. Since the object was only presented to one eye, there was no binocular disparity between the 3D real object and the 2D photograph, so the difference in reaction times could not be explained by stereoscopy. What then could account for the difference in breakthrough time between the real object and the two-dimensional photograph?

Korisky and Mudrik examined this question using an elaborate follow-up experiment (Korisky and Mudrik 2021) in which they created 3D replicas of the original familiar objects using a 3D printer. They then cut the 3D replica into pieces, and randomly combined them to create a 3D scrambled object. They then took photographs of the 3D object and of the scrambled counterpart. In vision science, scrambling techniques like these are often used to change the content of visual stimuli, while keeping the low-level statistical properties the same. Their 3D scrambled object provided a neat control condition, which shared the low-level visual features of the object, but removed the high-level features that define the object as a member of a certain category (Fig. 2). Using these four conditions (Intact 3D, Intact 2D, Scrambled 3D, and Scrambled 2D) they compared the time taken for each to reach conscious awareness in the same CFS paradigm as they previously used. They found that familiar 3D objects broke through into conscious awareness faster than their 2D pictorial representations. Critically, they found that the faster processing

[3]Note that we controlled for the speed of the participants' rotational movements of the virtual objects between live and replay conditions, meaning that any differences in breakthrough times were most likely due to the presence or absence of normal sensorimotor contingencies.

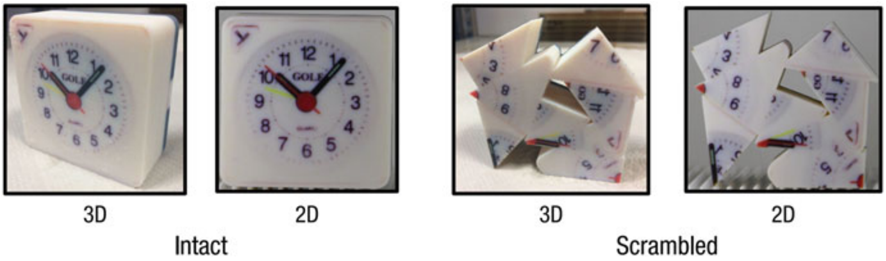

Fig. 2 Example stimuli used in the experiment used in real-world CFS experiments. 3D-printed familiar object and its 2D photograph (Left) and scrambled 3D object and its 2D photograph (Right) (adapted from Korisky and Mudrik 2021, Copyright 2020 Mudrik, Liad; Korisky, Uri)

times of 3D objects than the 2D pictures were not found for scrambled, unfamiliar objects. These results are also consistent with the idea that valid sensorimotor contingencies enhance object perception, with breakthrough times providing a potential behavioural proxy for perceptual presence. The key difference from Suzuki et al., was that, here, these contingencies were already present (since familiar objects were used) rather than learned during the experiment.

Taken together, the results of these CFS experiments provide convergent evidence that objects with learned or familiar sensorimotor contingencies are associated with shorter breakthrough times. What justifies the notion that breakthrough time in this paradigm could be a behavioural surrogate for perceptual presence? A common interpretation of breakthrough time in CFS studies is that it reflects differential unconscious processing (Gayet et al. 2014). Thus, one might interpret the results of these studies as reflecting unconscious processing of sensorimotor contingencies and affordances, both of which have been proposed as factors that influence perceptual presence (Flach and Holden 1998; Grabarczyk and Pokropski 2016; Zahorik and Jenison 1998). In the case of affordances, such an interpretation is in line with findings of enhanced attentional capture by 3D object flankers compared with photographs of flankers (Gomez et al. 2018), as well as with the shorter suppression times reported for useful tools compared with useless tools (Weller et al. 2019). However, while the perceived ability to act on an object (affordance) is clearly closely related to the perceptual impression that the object really exists in the world (perceptual presence), these perceptual properties may not be equivalent to each other, and we again note that neither study explicitly investigated perceptual presence.

In this section, we have discussed the characteristic of normal perceptual phenomenology that the contents of perception seem to 'really exist' – a quality which for objects we call 'perceptual presence' or, equivalently, 'objecthood'. We examined how this aspect of perception may be constructed from the sensorimotor contingencies and affordances associated with perceptual content. Describing the results of two empirical studies that leveraged combinations of XR technologies with a binocular suppression paradigm, we have shown how the validity of sensorimotor contingencies affects object perception. The use of such perceptual tasks combined with modern XR immersive technologies allows for the manipulation of sensory input in a highly controlled manner, providing many advantages compared to classical experimental settings, which can be exploited in future studies to investigate not only presence, but many aspects of conscious experience.

4 When Presence Is Not Enough: Beyond Virtual Reality

While previous sections highlight the capacity of VR and AR to manipulate different aspects of presence, there are certain features of human sense of reality that this method cannot directly address.

4.1 Layers of Veridicality

Whenever a person behaves within a virtual environment, they may sometimes be in a state of suspension of disbelief, in which their judgments about the artificiality of the virtual world are temporarily suspended, in order for them to properly engage with it. Such situations may be characterised by their behaviour and subjective reports being 'as if' the world that the HMD presents to them corresponds to, or is, the 'real' world. People may *feel* that they are immersed and present in the virtual world, but it is highly unlikely that they would ever *believe* that what they are experiencing was actually real. This dissociation between feeling and believing highlights that the concept of 'sense of reality' cannot be reduced to, or described along a single dimension, but necessarily spans domains and layers.

Recently, in the context of his predictive processing model of sensorimotor contingencies (PPSMC), Seth (2014) proposed to differentiate perceptual contents by means of four different dimensions of reality/veridicality, as reproduced in Table 1.

In this formulation, perceptual reality refers to the vividness of the content, whereas veridicality is divided into three subtypes: (1) *subjective*, namely the property of being phenomenologically experienced as part of the real world (here equivalent to objecthood/perceptual presence); (2) *doxastic*, the property of being cognitively considered as part of the real world (e.g. 'I believe that this coffee cup I am perceiving really exists'); and (3) *objective*, which obtains when the contents of perception lawfully correspond to an aspect of the real world (e.g. I perceive this coffee cup as being real, and indeed it is real).

This classification system can help orient us to alterations in experienced reality, whether in VR or otherwise. For instance, the experience of derealised patients can be considered as a deficit at the level of subjective veridicality (and possibly at the vividness level of perceptual reality too), while the doxastic component is retained. Patients typically feel alienated from their bodies and experience the world 'as if' it is flat and unreal (Radovic and Radovic 2002), while their ability to distinguish

Table 1 A schematic subdivision of different kinds of perceptual content and their corresponding veridicality status (adapted from Seth 2014 under CC BY 4.0 licence)

	Perceptual reality	Subjective veridicality	Doxastic veridicality	Objective veridicality
Normal perception	✔	✔	✔	✔
Dreaming (non-lucid)	✔	✔	✔	✗
Hallucinations (with delusions)	✔	✔	✔	✗
Dreaming (lucid)	✔	✔	✗	✗
Hallucinations (without delusions)	✔	✔/✗	✗	✗
Synesthesia (projector)	✔	✗	✗	✗
Afterimages (e.g. retinal)	✔	✗	✗	✗
Synesthesia (associator)	✔/✗	✗	✗	✗
Imagery/associative recall	✗	✗	✗	✗

between what is real and what is not remains intact (Guralnik et al. 2000). More precisely, since people that suffer from derealisation tend to be also depersonalised, it is necessary to characterise their condition by considering the loss of a global sense of presence which – as already mentioned in previous sections – has been hypothesised to be related to aberrant interoceptive prediction errors (Seth et al. 2012).

Similarly, the experience of VR can be conceptualised at the opposite side of the spectrum: people tend to react as if virtual contents are real, while at the same time being fully aware that they are not. Thus, VR allows us to create and maintain both the perceptual reality and (perhaps) subjective veridicality component via sensorimotor coupling, but fails to reach the doxastic level (see Fortier 2018, who criticises the idea that VR and DPDR correspond to completely symmetric experiences).

At first glance, the outlined classification might appear superfluous and unnecessary for pragmatic applications, but it is important to highlight that its usefulness goes beyond VR (and DPDR). As illustrated in Table 1, further examples of dissociation between 'levels of veridicality' can be found in typical forms of dreaming and lucid dreaming. While normal dreams are characterised by a total state of immersion for the dreamer, lucid dreams are distinguished by the presence and maintenance of a level of insight over the experience: a form of metacognitive monitoring that allows the dreamer to recognise that they are dreaming, retaining doxastic insight.

Other clinical examples in which we observe alterations in experienced reality include phenomena such as hallucinations and delusions. Hallucinations are defined as percepts that occur in the absence of a (typically) corresponding external stimulus (Tracy and Shergill 2013) and they constitute one of the most common symptoms of conditions such as schizophrenia and Parkinson's disease. Hallucinations tend to occur in all sensory modalities with a clear prevalence for audition (70% of schizophrenia patients; Hugdahl et al. 2008) and vision (27% of schizophrenia patients;

Waters et al. 2014) and similar experiences have been reported in 'neurotypical' populations as well as being a consequence of certain pharmacological manipulations (e.g. psychedelics like LSD or psilocybin; Müller et al. 2017; Schmid et al. 2015). Delusions are defined by the Diagnostic and Statistical Manual of Mental Disorders (DSM-5 – American Psychiatric Association, 2013) as false beliefs – not accounted by the person's intelligence, cultural or religious background – that are firmly maintained in the face of overwhelming contrary evidence (Bortolotti et al. 2012; Kiran and Chaudhury 2009).

In spite of their heterogeneous aetiology, hallucinations have often been described in a rather unitary way by assuming that whoever experiences them is unable to distinguish them from 'ordinary reality'. In this context, Martin Fortier (2018) argues that this might not always be the case. In the chapter: 'Sense of Reality, Metacognition and Culture in Schizophrenic and Drug-Induced Hallucinations', he points out that hallucinating patients show at least two differential patterns that the clinical literature has described as 'single bookkeeping' and 'double bookkeeping'. The former refers to the phenomenon by which the sense of reality of hallucinations is equated with ordinary perception and, when accompanied by delusions, patients act coherently with their beliefs. The latter refers to the observation that for some patients, their hallucinatory reality does not feel 'real' in the same way as normal perception and, when accompanied by delusions, these aberrant beliefs are not accompanied by coherent behaviour (Bleuler 1911, 1950; Bortolotti and Broome 2012), As Ratcliffe (2017) write:

> [. . .] this is consistent with the observation that delusions and hallucinations often involve a kind of double-bookkeeping, where the patient speaks and acts in ways that are in some respects consistent with believing or perceiving that p, but also speaks and acts in other ways that distinguish her attitude toward p from her ordinary perceptions and beliefs (Ratcliffe 2017)

In a similar manner, different drugs seem to produce hallucinations that are experienced with different levels of veridicality (see Table 1). While psychedelics can be related to the phenomenon of double-bookkeeping, the effects of anticholinergic drugs might exemplify single-bookkeeping. Psychedelic compounds like LSD, psilocybin, or N,N-Dimethyltryptamine (DMT) that typically act as agonists to serotonin receptors (mostly 5-HT2A receptors; González-Maeso et al. 2007; Rolland et al. 2014) appear to generate vivid and colourful visual hallucinations that nonetheless are not equated with the same level of reality as normal perception (e.g. psychonauts remain able to distinguish them from ordinary perception, while considering them real). Other hallucinogenic plants like toé (brugmansia), belladonna, or synthetic compounds such as Ditran are known for their powerful anticholinergic activity that causes delirium-like symptoms (Ashton 2002). People administered with these substances show a complete lack of insight and reduced reality monitoring skills such that they experience their hallucinations as being completely indistinguishable from ordinary perception and typically take everything they see at face value.

Fortier (2018) argues that this clinical and pharmacological evidence pose a threat for classical metacognitive monitoring models like the source monitoring model

(Johnson and Raye 1981; Simons et al. 2017) and the online reality monitoring model (ORM, Dokic and Martin 2017). By considering hallucinations simply as a unitary metacognitive tagging error (either offline or online) of an internal source that is mistakenly considered to be external, the two models might have difficulties in accommodating the different levels of reality reported for hallucinatory contents. Future work in this direction might usefully consider these phenomena in light of newer metacognitive monitoring models such as Lau's 'perceptual reality monitoring' model (Lau 2019; but see also Dijkstra et al. 2022, Gershman 2019).

Considering Fortier's argument in light of Table 1, it is possible to see that what Seth (2014) broadly defined years before as 'hallucinations without delusions' possesses the same features as serotonergic hallucinatory experiences (and double-bookkeeping): while the level of perceptual reality (vividness) and subjective veridicality makes the person feel that these constructs are real, the fact that they do not reach the doxastic level is reflected by preserved insight into the unreal nature of these experiences of patients and/or psychonauts (similarly with lucid dreams). Conversely, 'hallucinations with delusions' reflect anticholinergic hallucinations (and single-bookkeeping) since they maintain all the components listed above: the individual does not only experience them as real, but the lack of insight makes them fully convinced about their reality, thus leading to states of delirium (similarly to non-lucid dreaming).

This discussion makes clear that while most of the literature involved in the debate around sense of reality has focused on the concept of perceptual presence, of equal importance is the different (albeit related) concept of conviction about reality (CR), namely its higher order/metacognitive counterpart (or *doxastic veridicality* as in Table 1). To capture CR, technologies like VR appear to be still too limited at present. It is therefore necessary to examine methods which do not rely on digital environments per se, but rather leverage novel video production/recording capacities and/or *augment* them.

4.2 Substitutional Reality: A Promising Naturalistic XR Framework

The substitutional reality system (SR) is a novel experimental platform developed by Suzuki et al. (2012). The system is composed of an HMD coupled with a frontal (or detached) live camera. SR allows switching between the live feed of the camera and pre-recorded 360° videos (see Fig. 3, panel A). The goal of the system is to manipulate participants' CR by allowing them to believe that what they are experiencing is real and is happening live in that moment, even though it can be a pre-recorded, and perhaps manipulated video.

In the original description of SR (Suzuki et al. 2012), the authors reported that participants ($n = 21$) failed to recognise that what they were experiencing corresponded to a pre-recorded scene in a variety of different conditions other than

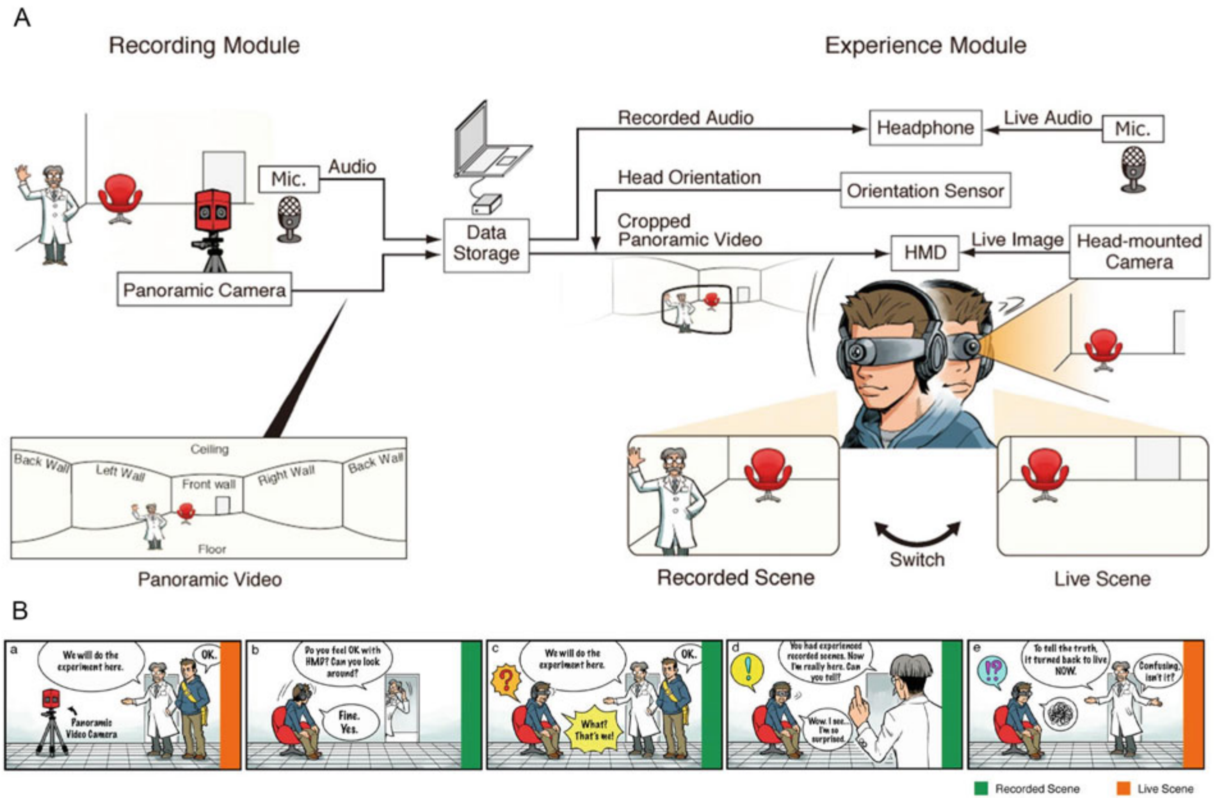

Fig. 3 (**a**) A schematic illustration of the substitutional reality system. (**b**) Potential experimental scenario using the SR system (adapted from Suzuki et al. 2012, under CC BY 4.0 licence)

one in which participants viewed the recording of themselves entering the room before the start of the experiment (the 'Doppelgänger' condition). Additional experiments confirmed that the major factor contributing to the maintenance of a stable CR within SR was the fidelity of the visuo-motor coupling that was modulated by motion parallax and head-position and rotation.

Compared to other XR systems, the use of perceptually indistinguishable 360° videos offers a unique opportunity to directly investigate the impact of metacognitive belief states on perception (and vice versa). The core unique feature of SR is that it presents an intact perceptual and subjective veridicality and allows manipulation of the doxastic component of veridicality. The modulation of participants' (doxastic) belief state can be realised by either imposing it in a top-down manner (e.g. by labelling the kind of perceptual content that will be presented) or by introducing perceptual inconsistencies and observing modulations in their CR.

Froese et al. (2012) see SR as an example of an 'artificial embodiment' system aimed at investigating the enactive subject-environment loop by means of smooth sensorimotor coupling, thanks to its ability to overcome the limitation of suspension of disbelief required by orthodox VR. Fan et al. (2014) have proposed using SR to allow participants to re-experience past scenes or memories, opening up new avenues to investigate phenomena like deja vù and false memories, in ecologically plausible scenarios. Finally, Ito et al. (2019) augmented the SR system with eye-tracking ('EyeHacker') to dynamically introduce transitions between scenes (live vs pre-recorded) depending on participants' gaze position, head-movements, and scene dynamics (e.g. removing an object when participants' gaze exceed a distance threshold from that object).

In spite of these methodological studies, extensive experimental work involving SR is still lacking. This situation will hopefully soon change. In our laboratory, extending the work of Ito et al. (2019), we have incorporated eye-tracking within our SR system to run a series of change blindness and inattentional blindness experiments (Jensen et al. 2011). Change blindness refers to the phenomenon in which participants fail to notice large and sudden changes that happen right before their eyes in correspondence with a visual interruption (e.g. flicker, mask, eye-movement, Rensink 2000; Rensink et al. 1997; Ward 2018) while in inattentional blindness tasks, people fail to notice a salient event/change while their attention is occupied (typically with another task, Neisser and Becklen 1975; Simons and Chabris 1999).

In our SR tasks, participants freely visually explore a room full of objects by moving their head and eyes and are subsequently requested to localise any changes they noticed, and evaluate the confidence in their decisions. Critically, object changes are implemented using a gaze-contingent method (obviating the need for masking and/or mud-splash as in typical 2D settings, see Simons and Levin 1997) such that participants are never directly exposed to any transition. Crucially, participants' head and eye movements (including pupil size) are constantly monitored, making it possible to relate specific oculomotor patterns to both change detection performance and metacognitive assessments. More generally, such an experimental setting provides the opportunity to study the limits of awareness and attention in a more naturalistic and ecological manner – and critically one that involves the ability to manipulate doxastic veridicality.

Another fascinating potential application for SR is to investigate specific memory distortions. Indeed, Suzuki et al. (2012) noted that the switching between 'live' and pre-recorded scenes might resemble deja vù phenomena, and confabulations. Here, we explore the latter in a little more detail.

Confabulations are typically defined as false or erroneous memories that arise either spontaneously or in response to a memory challenge, demonstrating that the way in which people build up their sense of reality can also be impaired along the temporal dimension (Schnider 2003). While discussing different classification systems of confabulations is outside the scope of this chapter, Schnider (2008); Schnider et al. (2017) proposed four main categories: simple intrusions in memory tests; momentary confabulations provoked in response to questions; behaviourally spontaneous confabulations reflecting confusion of reality, and fully fantastical thoughts that can be found in advanced dementia and psychosis. According to Schnider et al. (2017), one of the crucial symptoms of patients with confabulations (e.g. with Korsakoff Syndrome and/or damages to the posterior orbitofrontal cortex) is the inability to properly locate memories and thoughts in the correct temporal context: the tendency of mistaking memories of the past as part of their current 'now' and erroneously acting according to them.

Directly eliciting confabulations using SR, whether in patients or in healthy controls, is an intriguing possibility, albeit one that is fraught with important ethical complications. Nevertheless, the ability of SR to introduce time shifts and unexpected changes in participants' perceptual experience within an immersive environment allows researchers to test scenarios that are completely impossible to investigate via classical 2D memory paradigms. For instance, we could imagine letting healthy participants explore an environment that they believe to be real and sequentially introducing a series of changes (obfuscating sharp transitions – see above). This would open up a series of questions: will participants notice these changes? If so, will they break their stable or sense of reality or will participants explain them away in order to maintain it? In the context of a continuous live-recorded loop, how would they react?

At present, using panoramic videos and live feed in SR, instead of carefully crafted virtual worlds, comes at the expense of limiting participants' interaction with the environment (currently, to head and eye movements), and the use of an HMD still provides a large degree of separation between reality frames as in VR. However, technological advances may alleviate some of these limitations. Regarding richness of interaction, the SR core principles might be exportable into an augmented reality context, in which the inclusion of virtual objects within the live feed could enhance participants' sense of presence and immersion within the environment. More ambitiously, recording footage using multiple light-field cameras might allow participants to move freely within an SR scene, which would dramatically increase the plausibility and richness of the substituted reality by improving the degree of interactivity and sensorimotor coupling that SR provides.

5 Conclusions

In this chapter, we have described some of the opportunities for consciousness science provided by XR technologies (especially VR). First we introduced the theoretical concept of presence, the factors that affect the sense of presence in XR, a selection of relevant neuroimaging studies, and outlined the need to develop better measures of presence that adequately control for the effects of demand characteristics. We then discussed clinical cases in which a normal sense of presence is disturbed, such as DPDR. We went on to describe a series of experiments that leveraged the unique advantages of XR that go beyond what is possible in classical experimental settings to investigate how sensorimotor coupling affects breakthrough times within a CFS paradigm.

Finally, we expanded on the notion of a 'sense of reality' by highlighting the existence of cases in which perceptual veridicality and subjective veridicality are not sufficient to capture the complexity of human experience, highlighting the need to also consider people's metacognitive state and beliefs – their conviction or reality, or state of doxastic belief. Examples that illustrate this position include the typical dissociation between experiences of XR and DPDR, different kinds of dream states (lucid vs non-lucid) and hallucination types (with and without insight).

We concluded by presenting an experimental paradigm (substitutional reality, SR) aimed specifically at manipulating doxastic veridicality (conviction about reality). Leveraging relatively simple technologies, such as panoramic recordings and concurrent live feed, SR allows researchers to study the relationship between doxastic states and the detection of perceptual inconsistencies, while potentially enabling the translation of classical attention and memory paradigms into a more ecological context.

The experience of 'what is real' is a complex and multifaceted phenomenon. Understanding how its various components are related and constructed requires (1) a multidisciplinary approach that combines different experimental paradigms, (2) solid theoretical and computational foundations, and (3) state-of-the-art XR technologies. Advances in XR technologies provide a suite of unique tools that can be used to answer these questions, complementing and extending other psychological and neuroscientific approaches. Perhaps above all, researchers should avoid resorting to XR simply because it is available and in some sense 'immersive', but should carefully consider which aspect of perceptual presence and the experience of 'what is real' that they wish to investigate.

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