OPINION

From presence to consciousness through virtual reality

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Abstract | Immersive virtual environments can break the deep, everyday connection between where our senses tell us we are and where we are actually located and whom we are with. The concept of 'presence' refers to the phenomenon of behaving and feeling as if we are in the virtual world created by computer displays. In this article, we argue that presence is worthy of study by neuroscientists, and that it might aid the study of perception and consciousness.

Suppose you are in a place that you know to be fictitious. It is not a 'place' in any physical sense, but an illusion created by a virtual reality system. You know that the events you see, hear and feel are not real events in the physical meaning of the word, yet you find yourself thinking, feeling and behaving as if the place were real, and as if the events were happening. You see a deep precipice in front of you, your heart races and you are frightened enough to be reluctant to move closer to the edge. From a cognitive point of view, you know that there is nothing there, but, both consciously and unconsciously, you respond as if there is. This paradox is at the root of the concept of presence.

Presence research was initiated by (and has largely remained within the ambit of) technologically orientated research departments, and has more recently attracted the interest of psychologists. The field has, however, remained quite separate from neuroscience: in fact, not a single reference to presence research appears in the neuroscience literature. In this article, we aim to rectify this situation, and highlight areas of overlap between the two fields, particularly with regard to the understanding of perception and consciousness.

Immersive virtual environments

In 1980, Minsky introduced the concept of telepresence to describe the feelings that a human operator might experience when interacting through a teleoperator system[1]. The operator sees through the eyes of the remote machine, and uses their own limbs to manipulate its effectors. A sense of being in a different place might develop, with the body of the machine 'becoming' the body of the human. This experience was thought to be conducive to effective task performance in the remote environment. The concept of telepresence has also been applied to experiences in virtual environments (VEs) (FIG. 1). In this case, a person is immersed in an environment that is realized through computer-controlled display systems, and might be able to effect changes in that environment. A feeling of being present could develop in the same way that Minsky noted for physical teleoperator systems.

Virtualization has been defined as "the process by which a human viewer interprets a patterned sensory impression to be an extended object in an environment other than that in which it physically exists"[2]. This definition comes from the domain of optics, in which there is, in fact, a real object corresponding to a virtual image. However, in a VE there is virtualization without the corresponding physical object (BOX 1). In addition, a VE should incorporate the participant as a part of the environment, so that head motions result in motion parallax from the participant's viewpoint, and vestibular and other physiological responses that are associated with focusing and object tracking are stimulated.

Typically, the visual fidelity of a VE display is low compared with physical reality. Even the most advanced computer graphics hardware cannot simulate the complexity of global light transport without a substantial sacrifice in real-time performance. In addition, the physical world is exceedingly complex, with infinite layers of detail: imagine rendering a human face, with full subtlety of expression — all the micro-muscle movements that go into the making of a facial expression — and the physical dynamics of hair and skin.

The generation of sound and haptics (touch and force feedback) is also problematic. The technology for producing highly convincing auditory output is advanced[3], but generating this in real time in a dynamically changing situation is not feasible. Haptics are possible within a restricted domain of application, and there are two main approaches. The first is to limit haptics to the end-effector

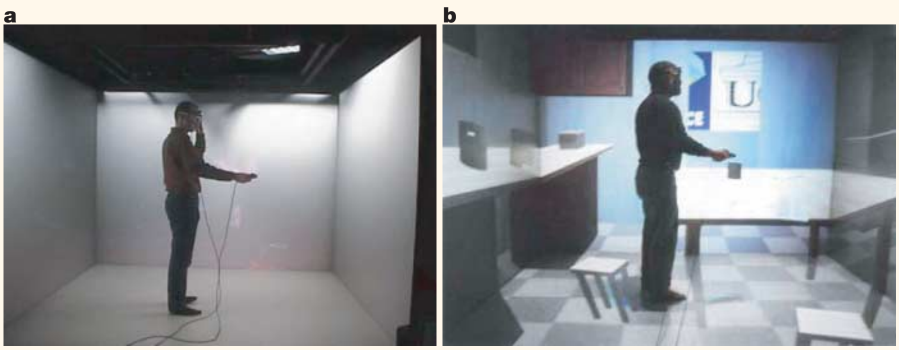


Figure 1 | **A Trimension ReaCTor system. a** | This particular type of CAVE like system[76] consists of four projection surfaces: the front, left and right walls are back-projected acrylic screens, whereas the floor is projected from above. The screens are seamlessly joined to provide a continuous projection surface. Only the top and the rear faces of the ReaCTor cube are not projection surfaces. This system is driven by an SGI Onyx 2 computer. **b** | A kitchen environment projected into the ReaCTor. The image is refreshed at 90 Hz. Left- and right-eye images are displayed to the participant, both at 45 Hz. The participant is wearing CrystalEyes stereo shutter glasses, which are controlled by infrared signals that are synchronized with the display refresh. The left-eye lens is open only during the left-eye image display, and the same applies to the right-eye lens and display. The participant is wearing an Intersense IS 900 tracking device that is attached to the top of the glasses. The head position and orientation is tracked at ~120 Hz and this information is relayed to the computer with a latency of ~4 ms. The computer graphics software uses this information to compute and display the left- and right-eye images. As the display is from the point of view of the tracked participant, the perspective of the projection does not seem to be correct when viewed from another angle. The participant is also holding a hand-tracking device, which similarly relays its position and orientation to the main computer. This device has buttons that can be programmed to initiate events, such as virtual locomotion, and can also be used for collision detection with virtual objects, thereby allowing the participant to interact with objects in the scene.

of an instrument, which is manipulated by the human user[4,5]. The instrument is represented within the VE and the user can feel when this virtual representation collides or creates friction with virtual objects. The second approach is to fit the user partially within the frame of an exoskeleton, which is mechanically controlled to impart forces on the user according to how that user interacts with objects in the VE[6]. The sensation of the weight of an object can be imparted in this way.

All of the above factors contribute to immersion, which refers to the technical capability of the system to deliver a surrounding and convincing environment with which the participant can interact. Important parameters of immersion include the extent of field of view, the number of sensory systems that the system simulates, the quality of rendering in each sensory modality, the extent of tracking, the realism of the displayed images (but see below), the frame-rate and the latency (the elapsed time between the participant initiating an event and the system responding). Of particular importance is the degree to which simulated sensory data matches proprioception — for example, as the participant's head turns, how fast and how accurately does the system portray the relevant visual and auditory effects. Moreover, in a system such as a head-mounted display (HMD) (FIG. 2), in which all real-world visual input is removed, it is important that the participants see, from an egocentric viewpoint, their virtual body, movement of which correlates with the proprioceptive model of the motor actions of that body. This also relates to the issue of control, which enables participants to effect changes in the VE through the impact of their motor actions on virtual objects. Therefore, control allows them to initiate and intervene in virtual events.

The degree of immersion is an objective property of a system that, in principle, can be measured independently of the human experience that it engenders. Presence is the human response to the system, and the meaning of presence has been formulated in many ways.

Box 1 | Basic functions of a virtual reality system

A virtual reality system typically delivers a left- and right-eye image to form a stereo pair, ideally with an active stereo system — one in which there is no leakage of the left-eye image to the right eye, and vice versa. The images are generated in the graphics pipeline of a computer system, and are updated in real time. The computer maintains a database that describes a particular scene, including geometric, radiant, acoustic, behavioural and physical information. The images that a participant sees are renderings of the database: perspective projections of the three-dimensional geometry onto the two-dimensional displays, with objects coloured according to computer graphics lighting models. The rendering is determined by the head position and orientation of the participant, which must be tracked in real time by a tracking system. The tracking system continually sends a stream of head-position and orientation data to the computer, which is therefore able to generate the appropriate stereo images.

Virtual objects are encapsulations of particular nodes in the database and the programming scripts that determine their behaviour. They typically represent meaningful aspects of the environment — for example, some geometry plus associated radiant information might represent a chair. Some objects might be passive (for example, the walls of a room) and others active (for example, virtual people). Therefore, the human participant can interact with objects in the environment to a greater or lesser degree. Typically, nothing can be done with entirely passive objects, such as the walls of a room, but a chair, for example, might be 'picked up' and moved to another location, and the representation of a virtual human might appear to be aware of the participant, speak to him or her, and show various types of behaviour. This is possible because, owing to the head-tracking data, the program that controls a virtual human will have access to the position of the participant's head and the direction of its orientation. For the participant to be able to interact with the environment — for example, by picking up objects — there must be further tracking besides head tracking. Typically, at least one hand is also tracked, often simply by the person holding the equivalent of a computer mouse — a three-dimensional pointing device with buttons that has a 6-degrees-of-freedom tracker attached to it.

The concept of presence

Some measure of the utility of a VE application is required because of the need for optimal allocation of scarce computational, display and tracking resources within given economic and technical constraints. One approach is to follow an application-specific route and optimize resources on the basis of task performance. For example, if a VE were used to train surgeons, the success of skill transfer from the virtual to the real world could be used to indicate the effectiveness of the VE. A different approach would be to measure the effectiveness of VE applications by using the idea of presence, which is a concept that applies across applications.

So what is presence? The common view is that presence is the sense of being in a VE rather than the place in which the participant's body is actually located[7–12]. Generic knowledge about factors that influence presence can be applied to many different scenarios. Presence in this sense can be measured in various ways, and these are summarized in BOX 2.

A fundamentally different view is that presence is "...tantamount to successfully supported action in the environment"[13,14]. The argument is that reality is formed through actions, rather than through mental filters and that "...the reality of experience is defined relative to functionality, rather than to appearances". The key to this approach is that the sense of 'being there' in a VE is grounded on the ability to 'do' there. These ideas have been expressed in other body-centred approaches, in which it is argued that a close match between kinaesthetic proprioception and the stream of sensory data is essential[15,16]. For example, if the visual flow indicates a walking motion, presence should be increased if the participant's body movements correspond to real walking.

Experimental studies of presence

What factors influence the reported presence in VEs? There have been several factorial-design experimental studies, most of which have investigated the influence of various display and interaction styles.

Display parameters. The graphics frame-rate is positively correlated with reported presence, and the critical minimal frame-rate seems to be ~15 Hz[17]. This was confirmed by a study that used changes in heart rate as a surrogate for presence when subjects looked over a virtual precipice[18] (the 'pit room' scenario — see FIG. 3). A lower latency between head movement and display update was also found to be associated with increased heart rate in response to this stressful environment[19]. In addition, head tracking, stereopsis and geometric field of view are all associated with higher reported presence[20–23].

Visual realism. Surprisingly, the evidence so far does not support the contention that visual realism is an important contributory factor to presence, and only one study, which used a driving simulator, has shown this to be the case[24]. Another study found that the display of dynamic shadows in an environment was associated with higher reported and behavioural presence compared with the display of static shadows or no shadows.

Figure 2 | **Head-mounted display. a** | A participant wearing a head-mounted display (HMD). This ideally blocks out all surrounding light. Two images are displayed, one for the left eye and the other for the right eye. Neither eye can see anything of the image for the opposing eye. The HMD position and orientation is tracked, and the computer updates the image according to perspective projections from the point of view of each eye. **b** | A participant in a CAVE-like environment. He is wearing three-dimensional shutter glasses and physiological monitoring equipment so that real-time read-outs of his heart rate, galvanic skin response and respiration are available. The background scene shows a virtual party that has recently been used in a study of social phobia.

However, this could not be attributed directly to visual realism, and might have been related to the more convincing display of dynamics[25]. In a further experiment, a group of people carried out a task in a simplistic virtual simulation of a real laboratory that was delivered through a head-tracked HMD, and another group of people carried out the same task in a real laboratory. There was no significant difference in the mean reported presence between the two groups[26].

In an experiment that exploited the pit room, the scene was displayed at various levels of realism (line drawings, without and with textures, and with photo-realism) in a between-groups design. Although all participants showed a significant increase in heart rate when they encountered the precipice, there were no significant differences in heart rate or reported presence between the different rendering conditions[27].

Sound. Anecdotal reports indicate that sound has a highly significant impact on presence, and one study showed that spatialized sound was associated with higher reported presence than either no sound or non-spatialized sound[28]. Another showed that the use of person-specific head-related transfer functions (HRTFs) was significantly and positively associated with reported presence and illusory self-motion[29]. The HRTF is a filter function that is based on the shape of the head and pinnae of the ears, and which results in a highly realistic reconstruction of three-dimensional sound. Often, general-purpose HRTFs are used, as obtaining person-specific HRTFs is time-consuming.

Further evidence of the importance of the auditory modality for presence is found in studies of 'inverse presence' — what happens to people's presence in physical reality when they experience a sudden and lasting loss of hearing. This seems to have a profound impact on their sense of reality and their sense of being in the real world[30,31].

Haptics. Several studies have focused on the influence of haptic feedback on presence. One study investigated the influence of haptics on co-presence[32] — the sense of being with another person in a VE[33]. The experiment was designed so that participants who were located at remote sites where they were unable to see or hear each other could, nevertheless, feel the forces that each exerted on the hand of the other by jointly moving a ring along a wire in a VE. For each participant, regardless of the order of presentation, the combination of visual and haptic feedback was shown to be associated with greater reported co-presence than was visual feedback of the ring and wire alone[32].

Although general haptic feedback is not yet attainable, it can be cheaply simulated with so-called 'static haptics'. A VE is delivered through a HMD so that the participant cannot see the surrounding real world, and there are simple versions of physical objects (such as table tops) in correspondence with their virtual counterparts. When the person reaches out to touch a (virtual) table top, they feel a simple plasterboard version of it in the same physical place, if not with the expected tactile characteristics. In the pit-room experiment, one group of participants stood on a small wooden ledge in correspondence with the edge of the pit, so that their feet would feel as if they were astride the edge[18] (FIG. 3b). This condition significantly increased heart rate compared with that observed when the ledge was absent.

Virtual body representation. When a VE is delivered through a HMD, the participants cannot see their own bodies — a situation that people can find shocking. Several studies have considered the relationship between the participant and their 'virtual body', and its influence on presence.

One study showed that reported presence was increased when the body was represented by a complete (if crude) virtual body, compared with simple representation by a three-dimensional-arrow cursor[34]. In this study, if participants moved their real right arm, they would see their virtual right arm (or the cursor) move in synchrony. However, if they moved their real left arm, the virtual left arm would not move, as it was not tracked. Some participants found this disturbing, and the debriefing questionnaires featured statements such as "I thought there was really something wrong with my [left] arm". Some individuals went to great lengths to align themselves with their virtual bodies, positioning their feet exactly where they saw their virtual feet to be.

Body engagement. When participants wear a HMD, they are usually tethered by cables that reach from the back of the HMD to the main computer. Although they can stand and move around, the range of movement with a traditional electromagnetic tracker is limited. Therefore, to cover extensive distances within the VE, some method other than physical walking is required. The usual solution is to activate movement using a mouse-button press on a hand-held three-dimensional pointing device. It was noticed in early studies that many participants — especially those reporting a high degree of presence — were almost unable to move by button pressing, and repeatedly attempted to walk. To reduce the dissociation between proprioception and sensory data, an alternative approach was for subjects to 'walk in place' to simulate walking[35]. Experimental results showed that, on average, the participants who moved through the environment using this method reported a significantly higher sense of presence than those who used the mouse-button method. This study was extended by the incorporation of another experimental group who could walk significant distances with the use of a wide-area tracking system[36]. The mean reported

Box 2 | **Measuring presence**

1. To what extent did you have a sense of being in place X?

Not at all 1 2 3 4 5 6 7 Very much so

2. To what extent were there times during the experience when X became the 'reality' for you, and you almost forgot about the 'real world' of the laboratory in which the whole experience was really taking place?

Never 1 2 3 4 5 6 7 Almost all the time

3. When you think back about your experience, do you think of the virtual X more as *images* that you saw, or more as *somewhere that you visited*?

Only as images that I saw 1 2 3 4 5 6 7 Somewhere that I visited

The measurement of presence is an important challenge in presence research. A common approach is to ask participants to carry out a task in a virtual environment (VE) and then answer a questionnaire. The questions have ordinal scales that anchor responses between two extremes — for example, with 1 meaning 'no presence' in the VE and 7 meaning 'complete presence' (see figure)[17,68,69].

Questionnaire-based methods have been shown to be unstable, in that prior information can change the results[70]. There is also evidence that typical questionnaires cannot discriminate between presence in a VE and physical reality[26]. The use of questionnaires has also been challenged by the observation that they cannot avoid a methodological circularity — asking questions about 'presence' might bring about the very phenomenon that the questionnaire is supposed to be measuring[71].

Behaviour can also be used to measure presence. If participants in a VE behave as if they are in an equivalent real environment, this is a sign of presence. Examples include the looming response[8], postural sway[72,73], after-effects[74] and the resolution of conflicting multi-sensory cues[25]. These behavioural measures typically require the introduction of features into the environment that would cause a bodily response (such as swaying in response to a moving visual field or ducking in response to a flying object).

A specialization of the behavioural approach is to use physiological measures, such as electrocardiogram recordings or galvanic skin responses. If the normal physiological response of a person to a particular situation is replicated in a VE, this is a sign of presence. The use of physiological measures as surrogates for presence has also been attempted, although so far this approach has been limited to situations in which the physiological response is obvious (such as a response to a feared situation)[18]. Physiological responses to mundane situations, such as being in a virtual room that contains a table and some chairs, are less obvious.

Another method that can be used to measure presence is based on the idea of eliciting moments in time at which breaks in presence (BIPs) occur[37]. A BIP is any perceived phenomenon during the VE exposure that launches the participant into awareness of the real-world setting of the experience, and, therefore, breaks their presence in the VE. Examples include gross events, such as collisions with the equipment, or more subtle effects, such as seeing a tree as a pixel map rather than a solid object. There is evidence that BIPs are associated with physiological responses[75], and because they could potentially occur in any environment, the VE does not necessarily need to be stressful.

presence was highest for the 'real walkers', followed by those who walked in place, with the three-dimensional-mouse-button pressers showing the lowest presence. Other studies have shown a significant positive association between overall body mobilization and reported presence[15,37].

Therapeutic applications of presence

One application of VEs that cannot work in the absence of presence is their exploitation for various forms of psychotherapy[38–40] — in particular, the management of anxiety. As part of a treatment programme, a patient might be placed in a VE depicting a situation that triggers their anxiety. The greater the similarity in response between the real-life and virtual situations, the greater the chance that the VE can be successfully used as part of the therapy programme. In this section, we present evidence that patients do experience presence in VEs.

Phobias. The first reported psychological intervention in this domain was the application of VEs to acrophobia (fear of heights). In a pilot study[41], individuals were found to show acrophobic symptoms in a VE, and, therefore, showed a high degree of presence. The scenarios included an elevator ride, a bridge and a view from a tall building. In a study that used these VEs for graded exposure therapy, significant reductions in anxiety were observed over an 8-week period in an experimental group compared with a control group on a waiting list[42]. In another study, an *in vivo* treatment group was compared with a virtual reality exposure group, and similar improvements were seen in both groups, which indicates that virtual reality exposure is equivalent to *in vivo* exposure[43]. Another study on the fear of flying[44] produced similar improvements between an *in vivo* exposure group and a virtual reality group, and 6-month and 1-year follow-up studies showed that these improvements were maintained[45].

Arachnophobia has been studied using similar methods[46–48]. A static haptics approach was used, in which a toy spider was placed in the same position as a virtual spider, so that participants could feel as well as see a spider. In this case, tactile augmentation produced better treatment results than visual simulation alone.

Social anxiety. Scenarios relating to anxiety that involves other people are more difficult to recreate within a VE. The modelling and dynamic rendering of a virtual human that can purposefully interact with a real person — for example, through speech recognition, the generation of meaningful sentences, facial expression, emotion, skin colour and tone, and muscle and joint movements — is still beyond the capabilities of real-time computer graphics and artificial intelligence. Surprisingly, however, there is strong evidence that people respond to relatively crude virtual humans as if they were real people.

We considered a particular type of social phobia — fear of public speaking. Individuals who were thought to be within the normal range of public speaking anxiety were exposed to virtual audiences in a seminar-style setting. The audiences showed three different types of behaviour — static and neutral, dynamic with positive responses towards the speaker, or dynamic with negative responses towards the speaker[49] (BOX 3). Each participant experienced only one of these conditions. The statistical results

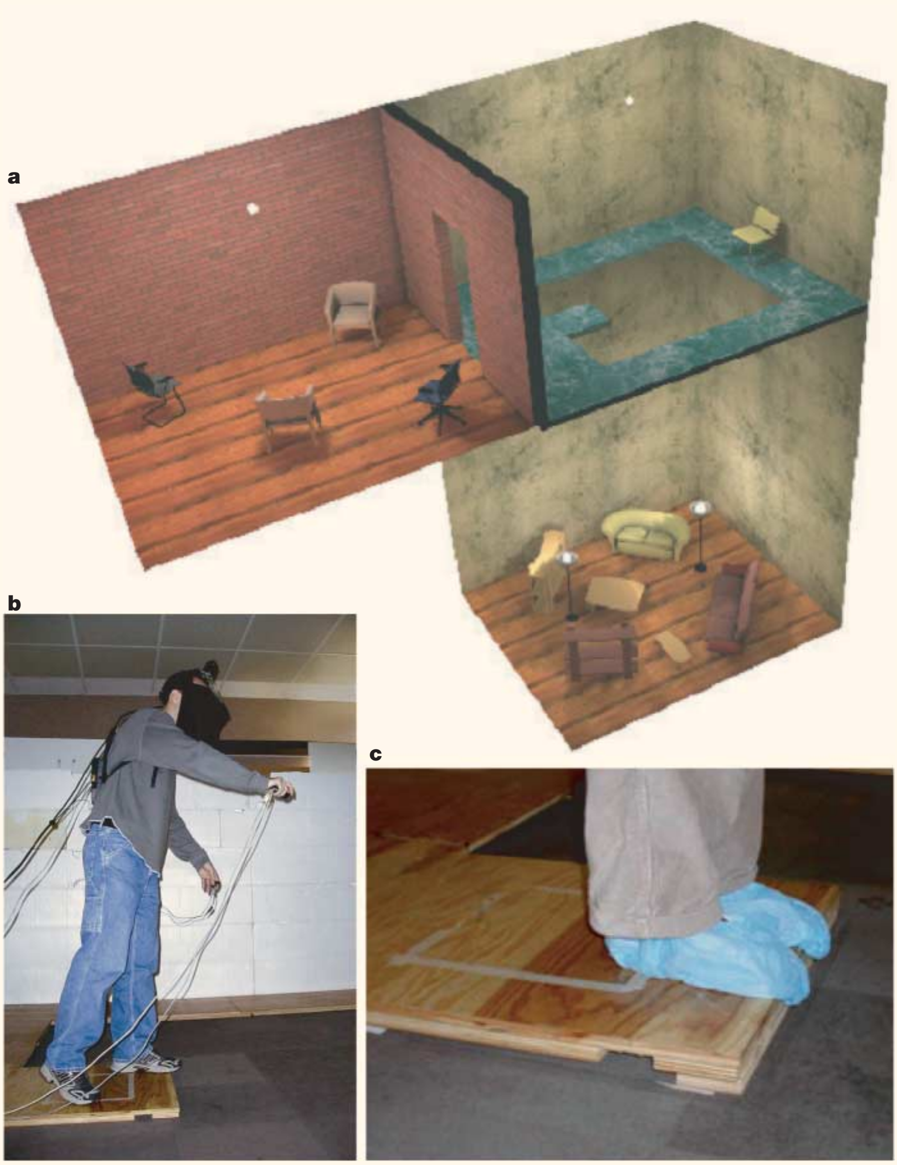


Figure 3 | **The 'pit room'. a** | This virtual environment (VE) is often used to assess presence. A participant enters the left-most room, which can be used for familiarization with the VE system and the learning of any procedures, such as how to move around or select objects. The participant is then given the task of going into the next room, selecting an object that has been left on the plank that overlooks the pit and then taking it to the other side of the room. A participant's reactions to the pit are quantified in various ways: behaviourally, through physiological measurements (heart and respiratory rate or galvanic skin response) or through subsequent questionnaires. In the experiments that have been carried out, almost all individuals make their way to the other side of the room by carefully edging themselves around the sides of the room and along the ledge, even though they know that there is no pit there. **b**,**c** | 'Static haptics'. Participants were positioned by small but real ledges, which added to the effect of standing over a real pit, and which significantly increased the heart rate of participants compared with when the ledge was absent. Images courtesy of the Department of Computer Science, University of North Carolina at Chapel Hill, USA.

indicated that for those who were immersed with the positive or static audience, their reported anxiety correlated with their usual anxiety about public speaking. However, those who experienced the negative audience tended to show unusually strong anxiety reactions, which included changes in body posture, skin colour and overall demeanour.

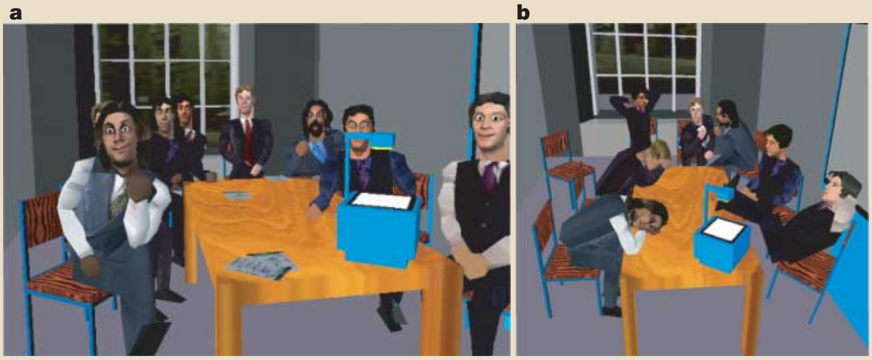
The comments made by the participants in debriefing interviews (BOX 3) were even more interesting than the statistical results. These comments might not seem particularly surprising, given the 'hostility' of the negative audience, but it is important to remember that the situation was entirely virtual. These findings illustrate the power of virtual reality in evoking a presence response.

Paranoid ideation. Paranoid ideation is characterized by suspiciousness and the belief that one is being followed, plotted against or persecuted. One experiment tested whether the range of paranoid thoughts typically present in a normal population (excluding people with psychosis) could be reproduced within a VE[50,51,52]. The participants, whose degree of paranoia had been assessed in advance, were asked to explore a virtual library (BOX 4). The virtual characters in the library were programmed to look at the participants and make facial expressions while maintaining a neutral attitude towards them. Statistical analysis of a subsequent questionnaire indicated that paranoid thoughts were triggered in the virtual reality in correlation with participants' propensities to experience these thoughts in everyday reality. Although there was no sound in these environments, some participants reported hearing comments, which were obviously illusory. It is remarkable that people reacted so strongly to the virtual characters, even though, objectively, they all knew that nobody was really there.

Post-traumatic stress disorder. Post-traumatic stress disorder (PTSD) can occur when a person is subjected to life-threatening catastrophic events. People with PTSD have difficulty in settling down to a normal life, and have recurrent flashbacks, sleep disturbances and a host of other debilitating symptoms. The group that has been studied the most in relation to virtual reality therapy is Vietnam War veterans. Two main scenarios were developed — a helicopter flight over hostile terrain, and a clearing in the jungle where helicopters might be landing. Desensitization treatment of the veterans led to significant improvements in their symptoms[53,54]. A recent virtual reality study with a survivor of the terrorist attack of 11th September 2001 also led to significant improvements, although no long-term follow-up has been reported[55].

Pain distraction. Presence in a VE involves transporting a participant's consciousness to a place other than that in which the physical body is actually located. A potentially powerful application of this process is pain distraction — if the body is experiencing a situation that would be painful in physical reality but the person feels present in a virtual reality, they should perceive less pain. Several experimental studies have provided preliminary evidence to support this idea[56–57]. A typical strategy is to present people with a situation that is contradictory to the type of pain that they are experiencing. For example, when undergoing treatment for burns, they might be placed in an environment

Box 3 | **A virtual environment that represents a seminar audience**



Panel a shows a positive audience and panel b shows a negative audience. The characters do not look realistically human, but their behaviour has been modelled on observations from real meetings, although greatly exaggerated both positively and negatively. Participants are asked to give short talks to a virtual audience that could have a positive, negative or neutral attitude towards the speaker. A response to the virtual audience similar to the response that the same person would have to a real audience is considered to indicate a high presence in the virtual environment. The testimonies shown below illustrate that the participants' responses to the virtual characters went above all rational considerations of what is real, and the physiological responses measured in these participants showed that people responded similarly to how they would in a real environment.

Responses to the positive audience

"It was clear that the audience was really positive and interested in what I was saying and it made you feel like telling them what you know."

"I felt great. Finally nobody was interrupting me. Being a woman, people keep interrupting you in talks much more … But here I felt people were there to listen to me."

"They were staring at me. They loved you unconditionally, you could say anything, you didn't have to work."

Responses to the negative audience

"It felt really bad. I couldn't just ignore them. I had to talk to them and tell them to sit up and pay attention. Especially the man on the left who put his head in his hands; I had to ask him to sit up and listen … I entered a negative feedback loop where I would receive bad responses from the audience and my performance would get even worse … I was performing really badly and that doesn't normally happen."

"I was upset, really thrown. I totally lost my train of thought. They weren't looking at me and I didn't know what to do. Should I start again? I was very frustrated. I felt I had no connection to them. They weren't looking at me. I just forgot what I was talking about."

that depicts snow and ice, and be given the task of throwing snowballs[58]. Although none of the studies carried out so far have been methodologically watertight, the evidence points to the idea that the 'transportation of consciousness to another place' is strong enough to diminish sensations of pain.

Neuroscience and presence research

We believe that VE technology provides an excellent tool for neuroscience research. It allows the creation of sensory environments that can be replicated almost identically and that are under the full control of the experimenter, including the creation of scenarios and conditions that are too expensive or dangerous, or even impossible to create in physical reality. It also easily supports the creation of 'magical' scenarios — for example, the dissociation of sensory modalities from one another. However, what we would really like to highlight are the conceptual interactions between the apparently distant fields of presence and neuroscience research, and we start by considering perception.

Presence and perception. One unexpected result of virtual reality studies is that the realism of the display seems to be far less important for presence than are other parameters, such as head tracking, frame rate, sound and interaction methods. This result has led to the concept of 'minimal cues' — the minimal elements that a VE must include to induce presence[59]. How much can we simplify 'reality' in a VE and still induce presence in a participant? How many sensory modalities need to be stimulated, and which minimal multisensory stimulation works best for each task? To any neuroscientist studying perception, it would seem obvious that such questions go to the roots of the mechanisms of sensory perception: what are the building blocks of our perceived world? What proportion of our perception is determined by the external world and what proportion is determined by our internal state? The fact that minimal cues are enough to induce presence implies that the absence of some degree of sensory information is not distracting, and is probably filled in by cortical processing[60,61].

Top-down influences on perception can also be investigated by giving specific tasks or prior information to participants entering VEs, and subsequently determining how their perception was affected. These studies can range from the perception of simple stimuli to the perception of social situations, using virtual characters. Actual stimuli received by the participants can be reconstructed (including eye-tracked visual scenes) and compared with the perceived stimuli. It could be argued that, when studying perception, neuroscience and presence research are asking similar questions from different starting points, and virtual reality provides a unique tool with which to answer those questions.

The possibility of dissociating stimuli that are invariably inseparable in the real world opens up many possibilities in the study of perception, and, in particular, self-perception. The fact that individuals feel present in environments in which their own body is represented by some bizarre form implies that this 'new' body has been somehow internalized. Future studies in VEs on how we relate to our virtual body, to the stimuli that it receives or how a virtual body is internalized could be of great importance in understanding how the body's internal representation is generated in the brain. By disrupting distinct streams of information that are physiologically bound together (visual, motor and proprioceptive), we can learn about their individual contributions to the mechanisms of self-perception and motor control. In the real world, we calibrate our movements mainly through feedback from visual and proprioceptive afferents. A virtual world can be programmed so that when our real arm moves up, our virtual arm moves forward, creating a discrepancy between visual and propioceptive information[62]. Individuals rapidly adapt to such disruptions, and learn to operate in the new conditions. The temporal dynamics of this adaptation, which reflect the plasticity of the system, could also be measured.

VEs also provide a useful tool for studying brain activation during spatial navigation[63,64], and, in a broader sense, offer a framework in which to analyse the factors (auditory, visual and vestibular cues) that are required to

Box 4 | **A virtual environment representing a library**

The images show two different views of a virtual library. This environment was used to conduct studies on paranoia. Participants were asked to walk around the library and to report their experiences afterwards. Virtual characters in the library occasionally looked at the participants and changed their facial expressions, for example, smiling or making other emotionally neutral expressions. No sound was delivered during the study.

Below, we quote some of the remarks made by the participants during post-experimental interviews, which illustrate the sense of presence that people felt in the virtual environment and their responses to these visually unrealistic virtual characters:

"The two people to the left, I didn't like them very much – well, I don't know, maybe because when I entered the room I felt I was being watched and then they started talking about me. The other people were more neutral and more inviting except the guy with the beard."

"It was probably more real to me than I expected it to be. At some point, I was trying to navigate around a table and almost found myself saying sorry to the person sitting there. I felt that they were getting annoyed with me for doing that…"

"It was really weird, because they were all definitely in on something and they were all trying to make me nervous. It was clear that they were trying to mock me, they kept on looking at me and when I looked back, they were uuhh … The guy with the suit was really weird because he kept smiling at me and it was quite sinister."

generate a sense of space. In VEs, navigation can be dissociated from the proprioception that is associated with locomotion, and can induce incorrect visual–proprioceptive cues, thereby providing a tool that can be used to determine the role of visual or proprioceptive inputs in the generation of internal spatial representations.

Presence and consciousness. The phenomenon of presence is based on the transportation of consciousness into an alternative, virtual reality so that, in a sense, presence is consciousness within that virtual reality. The fact that different layers (external world, self-representation and even part of the extended self) can be altered in a highly controlled way in a VE means that virtual reality can be exploited to scientifically analyse the basis of consciousness. According to Damasio, "consciousness occurs when we can generate, automatically, the sense that a given stimulus is being perceived in a personal perspective; the sense that the stimulus is 'owned' by the organism involved in the perceiving; and, last but not least, the sense that the organism can act on the stimulus (or fail to do so)"[65]. All of these criteria can be fulfilled when a person is immersed in a VE, and many aspects can be manipulated experimentally.

Immersion in a VE can transform the consciousness of a person in the sense that they respond to the virtual place and to events within that place, feel their body to be in that place, and even transform their body ownership to 'their' body that they see in that place. This process can have observable effects on the real body of the person in terms of conscious and volitional behaviours (for example, deciding to walk around a pit rather than fly across it), and non-conscious behaviours, such as changes in heart rate, breathing and skin conductance. Presence occurs when there is successful substitution of real sensory data by computer-generated sensory data, and when people can engage in normal motor actions to carry out tasks and to exercise some degree of control over their environment. By 'successful', we mean that the person responds to the virtual stimuli as if they were real. Responses should be considered at every level, from unconscious physiological behaviours through automatic reactions, and from conscious volitional behaviours through to cognitive processing — including the reporting of the sense of 'being there'. Interestingly, this can take place despite every participant's absolute knowledge that the VE is fake. However, consciousness will not transform when, for example, the frame rate is below a certain level or when the field of view is too narrow, although it might do so when these (and other structural factors) are at appropriate settings, regardless of the level of realism of the content displayed in the VE. In this situation, people behave as if conscious in the place and situation that is depicted by the VE, even though, at a higher cognitive level, they are aware that the situation is not real and that the place is not really there.

One strategy that has been used in the experimental study of consciousness has focused on brain processing of information in the absence of conscious awareness. This applies to two situations, first when the unconsciousness is the result of a pathological condition[66], and second when subjects unconsciously process and act on subliminal sensory information[67]. Taking the view of presence as given in the previous paragraph, just as the complement of consciousness is unconsciousness, the complement of presence would be a failure of people in a VE to respond to events as if they were real. Of course, there is an infinite number of ways that people might not respond to virtual events as if they were real. If the particular failure to respond is to do 'nothing', is this 'doing nothing' equivalent to not being conscious? When does presence imply consciousness and consciousness imply presence? These are interesting avenues that have yet to be explored.

Conclusions

We argue that presence research should be opened up beyond the domain of computer science and other technologically orientated disciplines, and become a mainstream part of neuroscience. Of course, virtual reality can be and is being used as a tool for neuroscience studies, and many of these studies, which relate to perception, path-finding, self-representation and sense of self, will also contribute to the understanding of presence. But — and this is our main point — not only is virtual reality a tool for neuroscience, but the presence experience that it engenders is also an object of study in its own right. Moreover, this concept of presence is sufficiently similar to consciousness that it could help to advance research within that domain.

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Competing interests statement

The authors declare no competing financial interests.

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