Virtual Reality in the Neuroscience of Multisensory Integration and Consciousness of Bodily Self

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In normal situations, we feel that our awareness resides inside our body. This concept of self-consciousness, as well as how it interacts with one’s body boundary, has been a central question in philosophy, psychology, and neuroscience. In the past five years, studies utilizing virtual reality technology have discovered that our consciousness of bodily self involves multisensory integration, with vision playing an especially important role. Carefully matching the visual and tactile events in time, but not in space, can then induce out-of-body experience as well as false ownership of other limbs and bodies. Here we briefly review studies that capitalize on the visual and temporal strength of virtual reality, as well as their results that shed light on the issue of multisensory integration and body ownership.


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The experience of body ownership has long been thought to be the firmest truth of one’s existence. This is because we experience, and perhaps also learn to expect, that our self-awareness is located behind our eyes and inside our body. However, in some cases of brain damage, there are patients who cannot attribute their limbs as belonging to themselves (somatoparaphrenia or asomatognosia), while some patients cannot perceive touch on their own limbs (with the feeling of ownership intact; hemianesthesia). These two cases do not always occur together, suggesting the interesting possibility that the perception of one’s limb, and the feeling of owning that particular limb, can be dissociated. Indeed, in healthy adults, this dissociation can also be demonstrated with the rubber hand illusion (RHI), where seeing a fake hand been touched in synchrony with the tactile input from one’s own hand can induce the illusion of ownership over the fake hand [7].

In the section below, we will first describe what cognitive science has learned from the RHI about visuo-tactile integration and limb ownership. But most importantly, beyond physical apparatus, we will introduce how visual technology such as virtual reality (VR) has opened a new door to studying multisensory integration and helped advance our understanding of the phenomenon of body ownership and self-consciousness.

BEFORE VIRTUAL REALITY

The usage of illusions, whether of single or multiple sensory modalities, has been a very important tool in approaching the topic of multisensory integration and consciousness in psychophysics. This is perhaps because the fundamental nature of an illusion lies in the failure of the perceptual system to do its job accurately. And as such, the breakdown of such system (or the conditions that lead to such breakdown) can be quite informative of the inner workings of the brain. Before the introduction of VR, cognitive and neuropsychologists relied on physical apparatus to induce illusory limb ownership. A good example is the RHI, where synchronized visual and tactile stroking can somehow fool the brain to attribute the fake hand to one’s own body, causing the participants to report feeling the rubber hand as their own (Fig. 1(a); [7]). This illusion occurs despite the fact that all participants are fully aware of the presence of the fake rubber hand, implying cognitive impenetrability. In fact, during the illusion, when the rubber hand or finger is bent backward to a normally painful position, participants would show heightened arousal on the skin conductance response (SCR), as if the injury was inflicted on their own hand [2]. Therefore, one’s lifelong experience of a stable body image and limb representation can be negated and temporarily altered within a few
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The astounding effect of the RHI implies the dominance of vision over other senses in terms of limb and body ownership. Based on this concept, it is curious whether the logic of the RHI can be applied to other parts of the body, or perhaps the entire body? This is not an easy task, as the fake body has to be stroked in perfect synchrony with the participants’ own body, requiring at least two experimenters with flawless synchronisation. To overcome this, and without the aid of VR, researchers have made clever use of mirrors so that participants’ own movements can be reflected and seen in real time, but from an unfamiliar perspective. Well over a century ago, Stratton devised a mirror hat that was very much like an inverted-vision goggle, with mirrors arranged in a way so that he was looking at himself from a position above the head (Fig. 1(b)). He subjectively reported feeling being outside of his own body, perhaps floating, and seeing his new visual body as someone strangely familiar but not of his own. Stratton’s subjective report is echoed by a recent study by Altschuler and Ramachandran, where the authors placed two mirrors facing each other such that the two mirrors are reflecting off of each other. This setup allowed their participants to face mirror A, while seeing the back of their body from mirror A’s reflection of mirror B. Upon stroking their cheeks and viewing their back reflections simultaneously, participants often report feeling as if they are standing outside of their bodies and stroking someone else’s face [1]. This is similar to the whole-body form of the RHI, although the phenomenon of ownership is slightly different. But most important, participants had a mild form of out-of-body experience (OBE), which will soon become the main research focus of VR. From these examples, it is clear how vision plays a critical role in the process of multisensory integration and forming body ownership, just like the RHI. This property of visual dominance is particularly important as it is a recurring theme in the literature of multisensory integration (e.g., Ref. [18]), and is what makes VR an appealing tool in the investigation of bodily self-consciousness.

AFTER VIRTUAL REALITY

With the clever use of fake hand and mirrors, psychologists have started the investigation of sensory integration and body ownership by creating sensory conflicts between vision, touch, and proprioception. What does VR have to offer in this line of research? As previously mentioned, the dominance of vision in the process of multisensory integration is the cause of most body illusions. Therefore, the flexibility of VR that allows researchers to deliberately create vivid visual experiences that are ‘mismatched’ from
the bodily signals is appealing. This allows the researchers to investigate how far would the brain perform multimodal integration and solve their inconsistencies, even ones that are artificially created by the experimenter, based on vision alone.

To continue on the fascinating phenomenon of OBE, two independent research teams led by Blanke [14] and Ehrsson [9] developed two similar, but different, ways of experimentally inducing OBE using a head-mounted display (HMD). Both studies had a video camera directly feeding to the HMD such that participants were seeing what the video camera was seeing, on line. Blanke and colleagues [14] placed the camera 2 m behind the participants so that the participants were looking at their own body sitting 2 m in front of themselves (Fig. 2(a)). These authors then stroked participants’ back, like the RHI. While seeing their body, sitting in front of them and been touched in perfect synchronization as their tactile sensations from the back, participants often experience OBE as if the virtually-viewed body was their own. This feeling of OBE can be verified subjective via survey and objectively via measures like the proprioceptive drift [7]. In this case, participants’ identification of their own body drifted forward in space towards the virtual body seen 2 m in front of them. In the study by Ehrsson (2008), the author used a similar camera setup, but stroked the participants’ chest and the empty space slightly below the camera (assuming the camera is the eye, the empty space would correspond to where the virtual chest is) simultaneously (Fig. 2(b)). This is a tougher task, as it requires the experimenter to synchronize his/her left and right hand for the stroking. Participants, on the other hand, while looking at the stroking and feeling it on their chest, identified themselves with the camera that is “seeing” the stroking. This version of the OBE causes the participants to drift backward in space towards the camera (where the virtual eyes and chest are) and disown their own body that they are seeing in HMD. Here, although the two examples differ slightly in the techniques employed, both nonetheless are good examples of how VR (or visual technologies in general) can expand the scope of research in body ownership. The Lenggenhager et al. study is exactly like a full-body version of the RHI, where seeing a virtual body been touched synchronously induced the feeling of owning that body. The Ehrsson study is similar in principle: participants identified themselves with an invisible virtual body behind them (where the camera is) because that is where the stroking is seen. Therefore, to resolve the conflict between vision and touch, the brain somehow decides that the mind must exist outside the current body border, which gives rise to the interesting OBE that moves forward [14] or backward [9] in space. In addition to standing and sitting, these two techniques have also been used in participants who are lying face-down on bed (with the camera above them), a position more resembling to the typical clinical occurrences of OBE. Similarly, participants felt either ‘sinking’ toward the floor or ‘floating’ toward the camera, where touch is seen [15]. Again, these studies demonstrate that the sense of self is located where touch is visually observed, confirming the idea that our consciousness of bodily self and body ownership is mostly determined by vision.

Since the aforementioned OBE experiments, more studies have utilized VR to investigate the nature of body ownership (e.g., Ref. [5]). Of these studies, the mannequin illusion and the body-swap illusion [21] are two examples of particular interest. In the mannequin illusion, the mannequin is equipped with a camera on its head, pointed down towards it body, while the participant wears a HMD...
that receives input from the camera. This allows the participant to look down, but sees the mannequin body instead. Synchronized stroking of the mannequin and participants’ abdomen would soon cause the participants to feel owning the mannequin’s body. Thus, the experimenter has taken one step beyond the original OBE experiments and attached participants’ self identification to a body different from their own. Importantly, passively receiving touch is not the only way to achieve OBE via VR and HMD. If one replaces the mannequin with a real experimenter, and have the participant and the experimenter repeatedly shake or squeeze each other’s hand in synchrony, participants report feeling as if they have swapped bodies with the experimenter [21]. This illusion can be validated with SCR, where participants showed higher SCR when seeing a knife threat in VR towards the experimenter’s hand (now felt as their own) instead of their real hand. Thus, OBE and body-swapping can also be achieved by visually synchronizing one’s own actions with that of another person. All in all, findings from this series of studies using VR suggest that our consciousness of bodily self is a product of visuotactile integration, and such self consciousness can escape the physical boundary of our body if visual events in VR can be constructed in a way that matches the tactile events in time (i.e., synchronized stroking or hand shake) but not in space (i.e., proprioceptive location of the hand or body).

In addition to the acquisition of another body, advances have also been made in terms of disowning one’s limb or body using VR. For example, in the disappearing hand trick, Newport and Gilpin (2011) had their participants look at their hands through a VR screen while, unbeknownst to the participants, the image of their hands moved slowly inward toward the midline. The movement was done slow enough such that participants could not detect the displacement, and thus were not aware that the VR image of their hands was much closer than the actual distance. When the experimenter turned off the image of the right hand and asked participants to reach for it with their left hand, the visual illusory distance caused participants to reach short and land on an empty space. This induced a visuotactile disintegration, and participants reported feeling as if they have disowned, or lost, their right hand. There was no unusual sensations from the right hand though, except that it felt colder, which is a physiological response often associated with psychological disownership (Moseley et al. 2011). Lower SCR was also observed with needle threat to the disowned hand, which is consistent with the SCR pattern from the body-swap illusion. This disappearing hand trick made clever use of a VR-induced visual illusory displacement that is further confirmed by the lack of touch of the left hand, causing the brain to disintegrate the unseen and unfelt right hand, despite accurate proprioceptive signals. Similar experiment was also done using HMD, showing that OBE is achieved at the expense of disowning one’s own body [12]. In this study, the researchers found that when participants are experiencing the OBE illusion, their SCR towards a knife threat is higher when the threat is near their virtual body than their real body. This result suggests that participants have somehow disowned their real body in order to achieve the OBE. Thus, with the use of HMD and SCR, these authors showed that the brain cannot attribute selfhood to two separate bodies simultaneously. Rather, the acquisition of a body, even an illusory one in VR, can only be done at the expense of disowning the real body.

Although the precise neural mechanisms underlying the occurrences of clinical OBE is currently unclear, patient studies have implicated that OBE may be a result of the temporoparietal junction’s failure to integrate multisensory information [3, 4, 6]. Recently, an fMRI study has successfully located the neural correlates behind the mannequin illusion, and found activations in bilateral ventral premotor and left intraparietal cortices to be associated with illusory body ownership [20]. These areas coincide well with the neural correlates of peripersonal space processing [11, 17, 28], suggesting that our self-consciousness of the body, as well as the space around us, might share a
common network of brain regions. An interesting application of neuroengineering here would be the use of neurostimulation techniques, such as transcranial magnetic stimulation or transcranial direct current stimulation (Liang and Juan, this issue), to excite premotor and intraparietal cortices and artificially induce OBE without visual tricks. Indeed, magnetic and electrical stimulation has been proven successful in inducing excitation in various neural regions, thereby improving cognitive function such as visual working memory [29] and inhibitory control [13]. It would be interesting to see if neurostimulation can be used to replace VR, or be used in conjunction with VR to intensify the effect of OBE.

CLINICAL APPLICATIONS
Experimentally-induced OBE via VR can be a promising tool to treat chronological pain associated with limb ownership, if vision can be deliberately manipulated to overcome pain from touch and proprioception. A textbook analogue in neuropsychology would be the mirror visual feedback therapy that is used to treat amputees with phantom limb and phantom pain [22]. In the case of phantom limb, some amputees can ‘feel’ their amputated hand intact as if it is still attached to the stump. This becomes pathological when the phantom limb is locked into an uncomfortable position (mostly for hands that were paralyzed before amputation), causing excruciating pain (i.e., phantom pain) that cannot be treated because the phantom limb is simply nonexistent. The mirror visual feedback therapy capitalizes on the logic that vision outweighs touch and proprioception in the process of multisensory integration, and used sagittally-positioned mirror that reflects amputees’ intact hand onto the position of the phantom hand. Upon viewing their visually-resurrected phantom hand, amputees usually report being able to move their immobile phantom hands, thereby relieving phantom pain. Following the same logic, a recent study by Schmalzl and colleagues [23] attempted to use the OBE and the mannequin illusion on amputees to ‘stretch out’ their retracted phantom hand (i.e., telescoping) and relieve phantom pain. They found that amputees could experience both an intact or amputated mannequin body as their own, with accurate touch sensations from the intact hand or the phantom space of the mannequin. Critically, during the mannequin illusion, participants’ representation of their retracted phantom limb seemed to be ‘stretched’ out to normal length (the stroking position, whether on hand or empty space, needs to be carefully measured), and two out of four of their participants felt relief to their phantom pain. This use of the VR and the mannequin illusion offers a promising start to the clinical application of experimentally-induced OBE, and is a good example of deliberately inducing false visuoactive and proprioceptive correspondence for clinical purposes.

Another interesting application of the OBE may be psychological, such as treating racial biases in normal population. One recent study using the RHI demonstrated that participants can experience ownership over rubber hands belonging to a different racial group [10]. Interestingly, participants who experienced the illusion more vividly showed a decrease in implicit racial bias after the illusion, suggesting that illusory ownership of a different-colored body can effectively reduce racial bias in that individual without his or her awareness. No study of similar nature was done with OBE in VR, but it is reasonable to expect an even stronger effect with the full-body illusion, such as the body-swap illusion, and thereby implicitly reducing various social stereotypes in participants.

FUTURE DIRECTIONS
Judging from the wealth of OBE studies that have flourished within the past few years, it is clear that the use of VR has dramatically advanced cognitive neuroscientists’ understanding of multisensory integration and body ownership. It is helpful to note that all of the above examples were done visually. That is, the false visual experience in VR was vivid and real enough such that an interesting conflict to the tactile and proprioceptive senses was created, something that would otherwise not have happened in nature. Thus, while some might think that VR can hardly be categorized as neuroengineering, the experimental value of VR lies in its ability to visually fool the brain, thereby allowing researchers to create well-controlled visual stimuli (even nonrealistic ones) to study how the brain performs sensory integration and derives conclusions regarding limb ownership and body borders. Clever uses of these internal sensory conflicts should enable cognitive neuroscientists to reverse-engineer their way to gain insight to the human brain and self-consciousness. In the next few years, it is reasonable to expect a rapidly growing number of multisensory studies utilizing VR. But most importantly, we hope more studies will apply the concept of multisensory integration and VR for clinical purposes such as rehabilitation and pain relief, a promising start that has just begun [23].

What can cognitive neuroscience do for VR and other visual technologies? In the future, it would be fruitful if cognitive neuroscientists can also help shape the next generations of VR technology by contributing what we already know about the senses and the brain. Critically, findings from cognitive neuroscience are especially important to VR technologies that require extensive interaction on the users’ part, such as devices using augmented reality that projects users’ cognitive processes externally so that the environment becomes an extension of human cognition. For example, imagine that in the future, environmental and navigational information are visually communicated to the user via displays on the glass lenses, or on the windscreen of the car, how should the machine subtly
capture the users’ attention without creating a dangerous walking or driving situation? Also, how much information should be displayed at a time so that the system does not overload the users’ visual short-term memory? Designing these visual technologies with the human cognition in mind will positively transform neuroengineering to cognitive neuroengineering (e.g., U.S. Patent Application No. US 13/547,715, Publication No. US20130166197 A1, Published June(2013).

Here we have briefly reviewed how VR has given rise to many interesting experiments and advanced our understanding of the processes behind multisensory integration. Beyond body ownership, VR has also become a useful tool in other areas of cognitive neuroscience research, such as spatial cognition (e.g., Ref. [25]) and driving behavior (e.g., Ref. [16]). Indeed, understanding how human cognition interacts with the visual world is not only the door to grasping the consciousness of bodily self, but also many other real world issues including user-centered design and driving safety. Thanks to the advancement and availability of VR, that door may just be within the reach of modern cognitive neuroscience.

References and Notes