Investigating a minimal condition to induce illusory body ownership using virtual reality

(バーチャルリアリティを用いた身体所有感錯覚誘発における最小条件の解明)

January 2021

Doctor of Philosophy (Engineering)

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別紙４－１（課程博士（英文））

Date of Submission（month day, year）: January 8th, 2021

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Abstract（Doctor）

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Approx. 800 words

Humans have a desire to have an ideal body. It seems that we want to change our self-image or self-consciousness by changing their own body. However, it has not been understood how to change the self-image. I assumed that the self-image could be updated by accumulating a temporary change of bodily self-consciousness. To investigate this issue, it is firstly required to investigate how to change bodily self-consciousness. Several studies have shown that we can change our body through illusory body ownership induced by visual-tactile and visual-motor synchronizations. A recent invisible body study has shown that stroking an empty space with a brush and stroking the subject's body at the same time produce body ownership in an empty space. This finding suggests a minimal condition for body ownership in visual-tactile synchronization. However, a minimal condition in the visual-motor synchronization is still unclear. It is one of the most fundamental issues to identify minimal conditions for the body ownership because we can change our bodily self-consciousness based on those minimal conditions. Therefore, the aim of this thesis was to investigate a minimal condition to induce illusory body ownership by visual-motor synchronization.

Study I aimed to test whether the illusory ownership of an invisible body could be induced by the method of visual-motor synchronicity and if the illusory invisible body could be experienced in front of the observer similar to the full-body ownership illusion. Participants observed left and right white gloves and socks in front of them, at a distance of 2 m, in a virtual room through a head-mounted display. The white gloves and socks were synchronized with the observers' actions. In the experiments, we tested the effect of synchronization, and compared this to a whole-body avatar, as measuring self-localization drift. We observed that visual hands and feet were sufficient to induce illusory body ownership, and this effect was as strong as using a whole-body avatar. The illusory ownership was also supported by a shift of proprioceptive self-localization.

Study II aimed to develop a method to separate the body ownership of full-body from that of body parts. Scrambled stimuli that disrupt the spatial relationship by randomizing the positions of body parts from the original/normal body part layout stimulus was developed to induce only body part ownership. We found that participants felt as if the space between the gloves and socks was their bodies only in the normal layout condition. They felt as if the gloves or socks were part of their bodies in both normal and scrambled conditions, but the feeling was stronger in the normal layout condition than in the scrambled body condition.

Study III aimed to investigate whether we can have illusory ownership of the invisible body with an elongated arm by presenting only hands and feet with modifying the position of the hands. As a result, the illusory body ownership to the body with a long arm was induced to an invisible body by synchronizing only gloves and socks with participants' movement. Learning of the invisible long arm gradually changed the reaching behavior to use the long arm more frequently than the normal arm. Thus, the body scheme could be changed by changing the position of the hand by maintaining the spatial relationship of body parts and visual-motor synchronicity in the same directions between the virtual body and the actual body.

Study IV aimed to see whether a re-association of the different body parts is induced by visual-motor synchrony in healthy adults. We focused on the re-association of the real right thumb with a virtual left arm because although the right thumb and the left arm are different in size and laterality, the directions of their movements are similar. We found that participants felt as if their right thumb had become the left arm and illusory body ownership of the virtual left arm was induced more in the visual-motor synchronous condition than in the asynchronous one.

To summarize minimal conditions to induce body ownership by the visual-motor method, the full-body illusion needs a spatial relationship and the synchronous movement of the hands and feet, while the body part ownership needs the synchronous movement of the body parts in motion directions and angles. The size, symmetry, or laterality does not have to be identical between the actual body and the virtual body. It has been proved that the body scheme can be changed by maintaining the minimal condition by modifying other parameters. The final goal is to update the self-image by accumulating temporary changes in bodily self-consciousness, and our findings should contribute to developing a method to change our bodily self-consciousness.

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List of Abbreviations

RHI Rubber hand illusion

BPO Body part ownership

FBI Full-body illusion

HMD Head-mounted display

SCR Skin conductance response

VR Virtual reality

1PP First-person perspective

3PP Third-person perspective

Chapter 1

Introduction

This thesis hypothesized that the self-concept can be updated by accumulating temporary change of body and investigated the minimum conditions for temporary body modification. Specifically, we investigated what factor is important to body ownership (feel that the body belongs to me) that caused through the integration of multisensory bodily signals by presenting and controlling several bodies using virtual reality (VR). Solving this question find the optimal method for a long-term change of body.

1.1 Desire to change the body

Many people are not satisfied with their current physical body. They are working hard every day to get close to their ideal body with muscle training, diet, plastic surgery, or makeup. However, the human body does not change immediately, nor does it change strikingly. Besides, when changing the body, the current physical restrictions are greatly affected. Thus, changing the body was extremely difficult, despite many people striving to achieve it.

1.2 A world where we can change our body freely

On the other hand, VR technology which has been rapidly developing in recent years has made it possible to modify the body without restriction of the original body. Capturing the movement of the body with a motion capture system and reflecting it in an avatar, it became possible to move the avatar like a self-body. These technologies have been generally used not only for research but also for entertainment. As a result, VR makes it easier and safer to change the body to become the ideal one. However, the current method for changing the body is temporary.

1.3 How can we change the self completely?

Gallagher discussed the self in two: the narrative self and the minimal self (Gallagher, 2000). The narrative self is a self that is consistently continuous from the past to the future and is the self that is told as the main character of the story. The minimal self is a self that appears temporarily rather than continuously and appears by sensory information and body movements. Minimal self can be divided into a sense of body ownership that the moving body belongs to oneself and a sense of agency that the movement belongs to oneself when moving the body.

If we can change the narrative self and the minimal self, we will be able to completely change the self. If we use VR to present a virtual body that moves in conjunction with our movement, the virtual body feels as if our own body (Body ownership), and the movement of the virtual body feels as if our movement (Agency). Therefore, the minimal self can be modulated by VR. On the other hand, it is difficult to change a consistent self as the narrative self because it is temporary that we can change our body in VR at present, and we use the real body for most of our life. Also, the coherence of the narrative self that the past self, the present self, and the future self are the same is related to memory, and it seems that memory manipulation is also necessary to update the narrative self. In summary, current technology allows update the minimal self, and to update the narrative self completely is difficult. It should not be pessimistic that the narrative self cannot be completely changed. For example, if memories can be changed, we cannot believe the consistency between ourselves yesterday and ourselves now. Changing all narrative self is difficult and dangerous. What about partially updating the narrative self from the present to the future by accumulating a minimal self? This guarantees the coherence of the self before and after the change. Some studies suggest that the update of the minimal self affects the narrative self, such as people become more childish by owning a child's body (Banakou et al., 2013), people help others after the Superman experience (Rosenberg et al., 2013), and gender identity is changed fluidly by perceptual body-sex change illusion (Tacikowski et al., 2020). Therefore, there is a possibility that the narrative self can be updated by accumulating the minimal self for a long period.

1.4 General aim

First of all, we need to understand the minimal self to update the narrative self. Minimal self is thought to be caused by the integration of multisensory bodily signals. However, it is not clear which element is important. To update the minimal self for the long term, it is necessary to find out the important elements for the minimal self and to update the body effectively and efficiently. In this thesis, we focused on body ownership in the minimal self, and we aimed to investigate the minimal conditions for inducing illusory body ownership. Agency is different from body ownership, and it is easy to occur if the temporal synchronization of movement is maintained. Therefore, we focused on extracting the minimum condition from the body ownership which has complicated occurrence conditions. The next chapter reviews the conditions to induce illusory body ownership and discuss the minimal condition that is currently known.

Chapter 2

Literature review

2.1 Illusory body ownership

Humans can have illusory ownership of part of a fake body. In the rubber hand illusion (RHI), an experimenter simultaneously strokes a rubber hand and the participant's hand with a brush. The participants feel as if the rubber hand is their own hands when they observe only the rubber hand (Botvinick & Cohen, 1998; Manos Tsakiris & Haggard, 2005). When the RHI is induced, the proprioceptive sensation of the hand drifts toward the rubber hand. However, Rohde et al., (2011) suggest that proprioceptive drift does not correlate with the illusion. The RHI does not occur when the rubber hand is rotated 90 degrees or replaced with a wood-stick, suggesting that the RHI is not based on purely bottom-up processes, but also modulated by top-down influences originating from the appearance of one's own body (Manos Tsakiris & Haggard, 2005). Ide (2013) showed that the anatomical plausibility of hand posture affects the RHI; For the left hand, the illusion was stronger when the rubber hand was placed at 0°, 45°, 90° (easy to mimic with the actual left hand), and 315° than 180°, 225°, 270° (difficult to mimic with the actual left hand by the anatomical constraint). Thus, the incongruence in bottom-up visual and proprioceptive signals could explain why the RHI is eliminated or decreased with the rotated rubber hand. The similar finding has been reported in the fMRI study(H Henrik Ehrsson et al., 2004); When the rubber hand is put in the same posture as the real hand, the illusion is induced and the premotor cortex showed stronger activation than when the rubber hand is rotated 180 degrees. In those studies, the illusion is induced by visual-tactile synchronicity. The virtual hand illusion(Sanchez-Vives et al., 2010) and the moving rubber hand illusion (Kalckert & Ehrsson, 2012, 2014) have both been reported using visual-motor synchronicity. In the virtual hand illusion, a virtual arm is presented on a screen synchronized with the participant's hand movements. The participants then feel as if the virtual arms are their own.

2.2 Full-body illusion (FBI): from body part to full body

The RHI induces the illusory ownership of body parts (BPO: body part ownership) but does not induce that of a whole body. The illusory ownership of a full-body has been investigated (FBI: full-body illusion). In the FBI, participants feel as if a mannequin (Petkova & Ehrsson, 2008) or a full-body avatar (Gonzalez-Franco et al., 2010; Maselli & Slater, 2013b; Slater et al., 2010) is their own body due to visual-motor or visual-tactile synchronicity. The FBI using a mannequin is induced by stroking the mannequin and the participant's body at the same time, while the participant observes the stroked abdomen from the position of the mannequin's head through a head-mounted display (HMD). In a FBI of a virtual reality avatar, the avatar moves synchronously with a participant's movements (Gonzalez-Franco et al., 2010), or visual-tactile stimuli are presented using virtual balls and vibrations (Maselli & Slater, 2013b). The FBI is stronger and more likely to be induced through a visual-tactile experience from the first-person perspective (1PP) than the third-person perspective (3PP) (Maselli & Slater, 2013b; Slater et al., 2010). In the 1PP, participants observed the virtual room and the virtual body from the point of view of the virtual body's eyes. In the 3PP, the position of participants (the point of view) was horizontally shifted 1 m (Slater et al., 2010) or 40 cm (Maselli & Slater, 2013b) away to the right of the virtual body; Participants could see the virtual body when they turn their head left. When participants observe a fake body from the front (facing each other), the FBI does not occur (Petkova, Khoshnevis, et al., 2011; Preston et al., 2016). On the other hand, the FBI can be induced when participants observe a body from the 3PP under certain conditions (Aspell et al., 2009; Lenggenhager et al., 2007; Lenggenhager et al., 2009). Participants observe a fake body from behind using an HMD while an experimenter simultaneously strokes the back of the fake body and that of the participant. When the visual and tactile strokes are synchronized, participants experience the FBI with the fake body, and their self-location drifts towards the fake body. In these studies, participants observe the fake body from behind. However, the self-localization effect has not been replicated in some studies (Hänsel et al., 2011; Heydrich et al., 2013; Bigna Lenggenhager et al., 2011), and thus it is controversial. The FBI from the 3PP is a kind of self-recognition similar to recognizing oneself in a mirror according to Petkova, et al. (2011) and Ehrsson (2012). Also, proprioception contributes to the FBI from the 1PP because the virtual body or mannequin can be presented in the same position as the physical body position. Some studies reported the FBI by mere visual observation (Carey et al., 2019; Keenaghan et al., 2020). These studies suggest that visual-proprioception is enough to induce the FBI and proprioception is also an important factor for the illusion. Considering the difference between 1PP and 3PP from the perspective of proprioception, the inconsistency between proprioception and the visual body may be the cause of the weakening of the FBI in 3PP.

2.3 Full-body illusion vs. body part ownership

As mentioned above, the FBI and BPO are induced by visual-tactile synchronization or visual-motor synchronization (Figure 1). Is the FBI simply a collection of BPOs? Are these fundamentally different phenomenon? Several studies have discussed the difference between BPO and the FBI. Blanke & Metzinger (2009) and Blanke (2012) claim that body part ownership and the FBI are fundamentally different in terms of bodily self-consciousness. They proposed the following components of bodily self-consciousness: self-identification (this body belongs to me), self-position (I am here), and first-person perspective (I am looking at the world from this position), and the FBI satisfies all of these and can experimentally manipulate the components of bodily self-consciousness.

In brain activity, the bilateral premotor cortex, intraparietal sulcus, and cerebellum are associated with the RHI (Ehrsson et al., 2005; Ehrsson et al., 2004). Activity in the right posterior insula and right frontal operculum correlates with the proprioceptive drifts in the RHI, although the activation in these areas does not increase in the synchronous illusion condition compared to the control conditions (M. Tsakiris et al., 2007). Activity in the extrastriate body area reflects the intensity of the RHI (Limanowski et al., 2014). On the other hand, activity in the ventral premotor cortex reflects the FBI; the FBI is only induced using visual-tactile stimuli when the body segment connects to a body (Gentile et al., 2015; Petkova, Björnsdotter, et al., 2011). These studies suggest that the FBI and BPO are essentially different in the aspects the bodily-self consciousness and brain activity. In this thesis, we also discuss body ownership in terms of body parts and full-body.

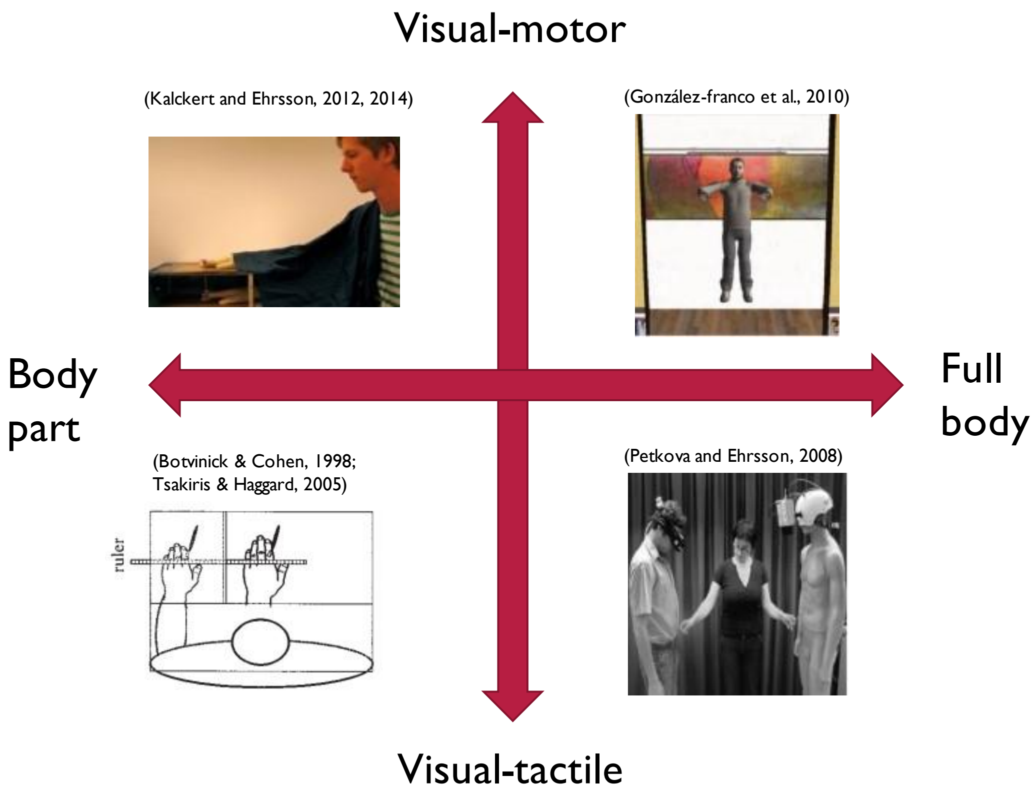


Figure 1: Methods to induce illusory body ownership

2.4 Visual-tactile synchronization vs. visual-motor synchronization: effect of agency

What about the difference between visual-tactile synchronization and visual-motor synchronization? In the Visual-motor method, a sense of agency (the feeling that this movement is one's own (Gallagher, 2000)) is induced because participants move and the virtual body follows it. Agency is induced even under the condition that the body ownership is not elicited such as rotating the rubber hand 180 degrees (Kalckert & Ehrsson, 2012), classical RHI (Botvinick & Cohen, 1998; Manos Tsakiris & Haggard, 2005) leads only the body ownership, therefore, these senses are considered to independent. Several studies have investigated the relationship between the agency and body ownership. Some studies indicated the strongness of body ownership is equal between the visual-tactile method and the visual-motor method (Kalckert & Ehrsson, 2014; Riemer et al., 2013; Manos Tsakiris et al., 2006). However, some studies implied the visual-motor method leads to strong body ownership (Dummer et al., 2009; Kalckert & Ehrsson, 2012; Kokkinara & Slater, 2014), and some studies have opposite results (Walsh et al., 2011). Thus, this topic is under discussion. According to Kalckert & Ehrsson (2014) consideration, the visual-motor method has a large amount of information, therefore there is also a lot of information that causes conflicts. For these reasons, it is considered that there is no difference between the visual-motor method and the visual-tactile method. It is also claimed that multiple sensory integrations are important, the type of sensory information is not important. The procedure differs depending on the paper, and even with the visual-motor method, some have tactile stimulation by touching the desk during exercise, and some that do not. The difference between the visual-motor method and the visual-tactile method might be caused by the difference in experimental conditions and experimental environment.

Some studies suggest that the agency is important for the unitary bodily experience. Kilteni et al. (2012) mentioned that the sense of embodiment (The sense that emerges when the properties of a body are processed as if they were the properties of one's own physical body) in VR is induced by conjunction with body ownership, self-location, and agency. Additionally, Tsakiris et al. (2006) reported that voluntary action of one finger gave body ownership to other fingers, and it was not induced by passive movement. This result suggests that voluntary action creates a unitary bodily experience. In this thesis, we used the visual-motor method because the agency is important for creating a unitary bodily experience, this method is standard in VR application, and our goal is to acquire a body in VR. In this method, the body can move freely and interact with others and the environment.

2.5 Semantic constraints in illusory body ownership

Several studies showed that body ownership is induced by visual-tactile synchronization or visual-motor synchronization, but semantic information also affects the illusory body ownership. In the rubber band illusion, the illusion does not occur when the position is anatomically impossible (the rubber hand rotated 90 degrees (Manos Tsakiris & Haggard, 2005) or 180 degrees (Ehrsson et al., 2004; Kalckert & Ehrsson, 2012)). When an object such as a wood stick is presented instead of the rubber hand, body ownership is not induced (Tsakiris & Haggard, 2005). Similarity with the real body also affected the illusion, and the strength of the illusion decreased if the texture of the fake hand did not resemble the participant’s hand (Haans et al., 2008). Tsakiris (2010) proposed a model of how these semantic constraints work in body ownership. Firstly, a comparison of the body model (visual, anatomical, and structural characteristics of the body) with the appearance of the object. Secondly, the posture of the body and the posture of the object are compared. Finally, multisensory bodily signals integrated and body ownership occur. These studies indicated that semantic factors affect body ownership. However, some studies have reported that the illusion can be induced in different genders (Slater et al., 2010) or skin (Maister et al., 2013; Peck et al., 2013). In summary, the anatomical position and human-like fake body are necessary for illusory body ownership, and the similarity between a fake body and a real body seems to be not critical.

2.6 Invisible body illusion: minimal condition by the visual-tactile synchronization

As mentioned above, body ownership is affected by semantic factors. On the other hand, invisible body illusions suggest that semantic factors are not necessary for inducing body ownership. In the invisible hand illusion (Guterstam et al., 2013), an experimenter stroked the participant's hand and the empty space at the same time with a brush. Then, body ownership is induced in an empty space. The invisible hand illusion can be extended to the whole body by stroking the space corresponding to the body part of the participant, the FBI is induced in an empty space (D'Angelo et al., 2017; Guterstam et al., 2015). Interestingly, the size of the invisible body can also be changed, the size perception of an object is affected by the size of the invisible body participants perceived (van der Hoort & Ehrsson, 2016). This result suggests that our body perception affects other perceptions even in the absence of a visual body. These invisible body studies imply a minimal condition to induce body ownership in the visual-tactile method.

2.7 Overview

Invisible body by visual-tactile method suggests that visual information of the body is not necessary for inducing the illusory body ownership. Thus, the synchronous stroke of body and space by brush is a minimal condition in the visual-tactile method to induce illusory body ownership. The general aim of this thesis was to investigate a minimal condition of the illusory body ownership by the visual-motor method. We discuss the BPO and FBI separately in terms of bodily self-consciousness (Blanke, 2012; Blanke & Metzinger, 2009).

Study I: Dynamic Invisible Body Illusion Aim

Study I aimed to test whether the illusory ownership of an invisible body could be induced by the method of visual-motor synchronicity and if the illusory invisible body could be experienced in front of the observer similar to the full-body ownership illusion.

Study II: Scrambled Body Illusion Aim

Study II aimed to develop a method to separate the FBI and BPO. Scrambled stimuli that disrupt the spatial relationship by randomizing the positions of body parts from the original/normal body part layout stimulus to induce only BPO.

Study III: Invisible Long Arm Aim

Study III aimed to investigate whether we can have illusory ownership to the invisible body with an elongated arm by presenting only hands and feet with modifying the position of the hands.

Study IV: Re-association of Body Parts Aim

Study IV aimed to see whether a body-part re-association is induced by visual-motor synchrony in healthy adults. We focused on the re-association of the real right thumb and a virtual left arm because although the right thumb and the left arm are at different laterality and size, the directions of their movements are similar.

To summarize, **Study I** and **III** investigated the minimal condition in the FBI, **Study IV** investigated the minimal condition in the BPO, and **Study II** investigated the difference between the FBI and BPO.

Chapter 3

Study I: Dynamic Invisible Body Illusion

Abstract

Body ownership can be modulated through illusory visual-tactile integration or visual-motor synchronicity/contingency. Recently, it has been reported that illusory ownership of an invisible body can be induced by illusory visual-tactile integration from a first-person view. We aimed to test whether a similar illusory ownership of the invisible body could be induced by the active method of visual-motor synchronicity and if the illusory invisible body could be experienced in front of and facing away from the observer. Participants observed left and right white gloves and socks in front of them, at a distance of 2 m, in a virtual room through a head-mounted display. The white gloves and socks were synchronized with the observers' actions. In the experiments, we tested the effect of synchronization, and compared this to a whole-body avatar, measuring self-localization drift. We observed that visual hands and feet were sufficient to induce illusory body ownership, and this effect was as strong as using a whole-body avatar.

3.1 Introduction

Illusory body ownership (Blanke, 2012; Blanke & Metzinger, 2009; Kilteni et al., 2015) can be induced to a virtual body by visual-tactile contingent stimulation (Armel & Ramachandran, 2003; Bertamini & O'Sullivan, 2014; Botvinick & Cohen, 1998; H. H. Ehrsson, 2007; Farmer et al., 2012; Guterstam et al., 2013, 2015; Guterstam & Ehrsson, 2012; Haans et al., 2008; Kilteni et al., 2016; B. Lenggenhager et al., 2007; Bigna Lenggenhager et al., 2009; Maister et al., 2013; Petkova & Ehrsson, 2008; Pomés & Slater, 2013; Rohde et al., 2011; Manos Tsakiris et al., 2010; Manos Tsakiris & Haggard, 2005; van der Hoort & Ehrsson, 2016) or visual-motor congruent actions (Banakou et al., 2013; Gonzalez-Franco et al., 2010; Peck et al., 2013; Sanchez-Vives et al., 2010). The Rubber Hand Illusion is representative of visual-tactile-stimulation induced illusory body ownership. Stroking a participant's hand and a rubber hand with paintbrushes at the same time causes illusory body ownership of the rubber hand if the participant sees only the rubber hand and paintbrush (Botvinick & Cohen, 1998; Manos Tsakiris & Haggard, 2005). Virtual Reality systems have often been used for induction of visual-motor-contingent body ownership. When visual body movements are presented using a head-mounted display (HMD) and are synchronized with a participant's actual body movements, he/she feels the virtual body as his/her own body (Gonzalez-Franco et al., 2010; Sanchez-Vives et al., 2010). The methods to cause illusory body ownership can be categorized into *passive* contingent visual-tactile stimulation and *active* synchronicity of visual body stimuli and motor actions. The active method induces a sense of agency in addition to body ownership and generally induces stronger body ownership than the passive method (Kokkinara & Slater, 2014).

The conscious experience of ownership of body parts such as the Rubber Hand Illusion (Armel & Ramachandran, 2003; Bertamini & O'Sullivan, 2014; Botvinick & Cohen, 1998; Farmer et al., 2012; González-Franco et al., 2014; Guterstam et al., 2013; Haans et al., 2008; Kilteni et al., 2016; Kilteni, Normand, et al., 2012; Maister et al., 2013; Martini et al., 2015; Rohde et al., 2011; Sanchez-Vives et al., 2010; Tieri et al., 2015; Manos Tsakiris et al., 2010; Manos Tsakiris & Haggard, 2005) and the experience of global ownership such as Full-body Ownership (Banakou et al., 2013; Gonzalez-Franco et al., 2010; Guterstam et al., 2015; Kilteni et al., 2013; Kokkinara & Slater, 2014; B. Lenggenhager et al., 2007; Maselli & Slater, 2013a; Normand et al., 2011; Peck et al., 2013; Petkova & Ehrsson, 2008; Pomés & Slater, 2013; Slater et al., 2010; van der Hoort & Ehrsson, 2016) should be considered separately to understand self-consciousness (Blanke & Metzinger, 2009). The studies of Full-body Ownership contribute to investigate the idea of "minimal phenomenal selfhood", that is, the conscious experience of being a self, and relate to the embodiment and the simplest form of self-consciousness (Blanke & Metzinger, 2009). The out-of-body experience has been investigated in neurological and clinical studies (Blanke et al., 2002, 2004; Metzinger, 2005). During an out-of-body experience, a person has the feeling of seeing their own body and the environment from a viewpoint that is distant from the physical body. It has been observed that brain damage and stimulus to the temporo-parietal junction can induce the out-of-body experience. Thus, the temporo-parietal junction is a critical region for the conscious experience of the normal self and its embodiment (Blanke & Arzy, 2005).

Out-of-body experiences can be linked to illusory body ownership using passive visual-tactile stimulation (H. H. Ehrsson, 2007; Guterstam & Ehrsson, 2012; B. Lenggenhager et al., 2007; Pomés & Slater, 2013). Lenggenhager et al. (2007) presented a virtual body in front of the participant, and visually synchronized tactile sensation to his/her back to induce the full-body ownership illusion. The illusory body ownership of the virtual body caused the participant's proprioceptive self-localization to drift toward the virtual body (B. Lenggenhager et al., 2007; Bigna Lenggenhager et al., 2009). Pomés & Slater (2013) replicated the study of Lenggenhager et al. (2007) by measuring behavioral responses to a threat to a virtual body and included a questionnaire on the proprioceptive drift. They found significant perceptions of both a participant's own body drifting toward the virtual body placed in front, and the virtual body moving backward in the synchronous condition. A significant positive correlation was observed between the feeling of illusory-body drift forward and responses to the threat, although the feeling of illusory body ownership and response to the threat were not significantly different between the synchronous and asynchronous conditions. Thus, the proprioceptive drift forward is associated with a greater response to the threat, while the feeling that the virtual body is moving backward decreases the response to the threat.

The proprioceptive drift of own body-part location was originally reported in the Rubber-Hand-Illusion studies (Botvinick & Cohen, 1998; Manos Tsakiris & Haggard, 2005). Thus, the drift of proprioceptive self-body or body-part location has been considered as one of the behavioral measurements of illusory body ownership. However, it is reported that proprioceptive drift depends on the duration of visual-tactile sensations; the drift occurs with synchronous, asynchronous, or no tactile stimulation using short and frequent stimulations, and is prevented only by continuous exposure to asynchronous stimulation (Rohde et al., 2011). Thus, the feeling of ownership cannot be measured by the proprioceptive drift alone.

Body ownership can be induced in a wide variety of bodies (Farmer et al., 2012; Kilteni, Normand, et al., 2012; Maselli & Slater, 2013a; Normand et al., 2011; Slater et al., 2010) or still objects (Armel & Ramachandran, 2003). Various studies have investigated how the experience of body ownership to different bodies changes human behavior and implicit social attitudes (Banakou et al., 2013; Kilteni et al., 2013; Maister et al., 2013; Peck et al., 2013; Rosenberg et al., 2013). Illusory body ownership in different skin colors decreases implicit racial bias (Maister et al., 2013; Peck et al., 2013). Adults' illusory body ownership to a child body avatar modulates child-like implicit attitudes as well as object-size perception (Banakou et al., 2013). Thus, illusory body ownership can be induced to various bodies in different shapes, colors, and ages. In passive visual-tactile contingent stimulations, the synchronicity of visual and tactile stimuli is critical to induce such illusions, while in active visual-motor stimulations, the synchronicity of visual stimuli and motor action is critical.

Recently, it has been reported that body ownership can be induced to an empty space by presenting visual-tactile stimuli (Guterstam et al., 2013, 2015; van der Hoort & Ehrsson, 2016). An entire invisible body ownership is induced when participants observe a paintbrush moving in an empty space and by defining the contours of an invisible body through an HMD from a first-person perspective while receiving simultaneous touches on the corresponding parts of their real body. The illusory ownership of an entire invisible body reduces autonomic and subjective social anxiety responses caused by standing in front of an audience (Guterstam et al., 2015). In contrast, an illusion of missing body parts through illusory ownership of an amputated virtual body can be induced by eliminating a virtual (visual) body part and not applying physical touches to the body part corresponding to the missing part (Kilteni et al., 2016). This illusory experience of amputation decreases corticospinal excitability of the illusory amputated body part.

The purpose of our study was to test whether the illusory ownership of an invisible body could be induced by the active method of visual-motor synchronicity, and if the illusory invisible body could be experienced in front of the observer similar to the full-body ownership illusion.

In Experiment 1-1, we tested whether illusory body ownership can be induced by presenting only visual gloves and socks in synchrony and consistent with the observer's own movements. The gloves and socks were presented in front of and facing away from the observers, in third-person perspective. We compared the synchronous condition, i.e. the virtual gloves and socks moved synchronously with the observer's action, with the asynchronous condition, i.e. the gloves and socks moved independently of the observer's action. In Experiment 1-2, we compared the invisible condition, i.e. where only gloves and socks were presented, with the visible body condition so that a whole-body avatar was presented. The whole-body avatar was also presented in front of and facing away from the observers. In these experiments, after participants moved their own body by observing the avatar stimuli for 5 min, a threat stimulus appeared suddenly (see the Methods section for details). Then, participants answered a questionnaire (see Figs 1 and 2). Finally, in Experiment 1-3, we tested whether self-localization drift could occur with illusory body ownership induced by only visual gloves and socks. When illusory body ownership occurs with the virtual invisible body in front of the participant, self-location will drift toward the virtual invisible body similar to the full-body ownership illusion (B. Lenggenhager et al., 2007). All experiments were conducted in within-group designs where all subjects (20, 20, and 10 naïve participants for Experiment 1-1, 1-2, and 1-3, respectively) performed all conditions (synchronous vs asynchronous conditions in Experiment 1-1 and 1-3, and visible and invisible bodies in Experiment 1-2).

3.2 Experiment 1-1

3.2.1 Methods

Participants

Twenty naïve volunteers (all male, mean 21.9 years old ± 0.91 standard deviation (SD)) participated in Experiment 1-1. They were recruited using posters placed on walls in the Toyohashi University of Technology, and by an announcement made in an undergraduate course lecture 'Human Information Processing' of the university irrespective of course credit. All participants were undergraduate or graduate students of Toyohashi University of Technology. All participants for all experiments gave written informed consent, and had healthy vision and were physically healthy. All experiments were approved by the Ethical Committee for Human-Subject Research at Toyohashi University of Technology, and all experiments were performed in accordance with the committee's guidelines and regulations.

Apparatus

Visual stimuli were presented by an HMD (Oculus Rift DK2, 1920 × 1080 pixel, 90 × 110-degree field of view, refresh rate 75 Hz), and appropriately updated with the observer's head motion. Head-tracking was 6 degrees of freedom. Yaw, roll, and pitch of participants' heads were sensed by a gyro sensor embedded in the HMD (sampling rate 1 kHz). Positions of the head (x, y, z) were sensed by an optical motion sensor (Microsoft Kinect v2; sampling rate 30 Hz, 512 × 424 pixel resolution). The optical motion sensor also captured the participants' body movements. A computer (DELL XPS 8700, OS: MS-Windows 8.1, RAM: 16.0 GB, CPU: Intel Core i7-4790 @ 3.60 GHz, GPU: AMD Radeon R9 270) controlled the stimuli and motion sensor.

Stimuli and conditions

Participants observed visual motions of white gloves and socks 2 m in front of and facing away from them in a virtual room (Figure 2). There was no virtual body in their actual body position. They actually put on white gloves and socks during the experiments. The stimuli were presented either synchronously or asynchronously with the observer's actions in real time. In the synchronous condition, the gloves and socks moved synchronously with participant's hands and feet motions.

However, there was a system delay of approximately 80 ms and the spatial discrepancy (error) was within 10 cm. In the asynchronous condition, the stimuli were replayed from recordings of another person's actions.

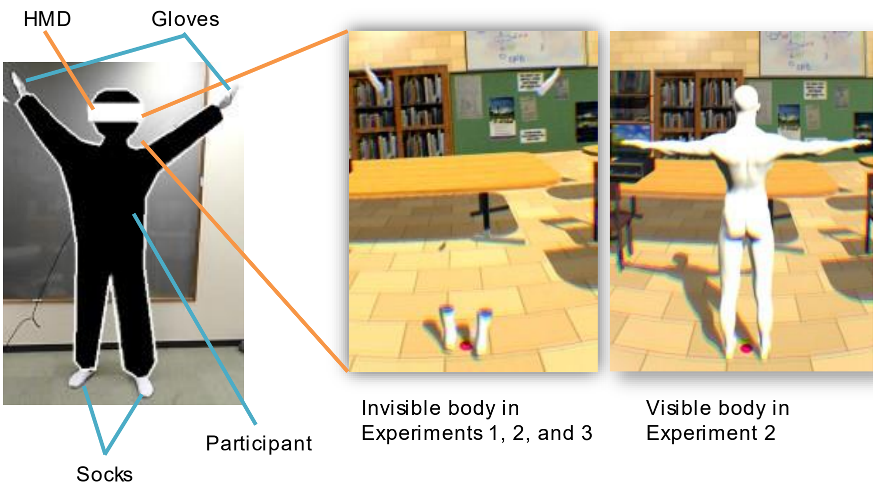


Figure 2: Schematic of the visual-motor synchronous stimuli. (Left) Participants wore white gloves and white socks, and moved freely. (Center) White gloves and white socks were presented as the invisible body stimuli in Experiments 1–1, 1-2, and 1-3 using an HMD. (Right) A whole body avatar was presented in the visible body condition in Experiment 1-2.

Procedures

Participants observed virtual white gloves and socks through the HMD, while they moved their arms and legs freely for 5 min. Then, a knife intended to stimulate the startle response appeared and rotated to cut between the gloves and socks. Participants were asked to answer a questionnaire after each trial to evaluate the illusory body ownership. Each participant performed four trials (2 conditions × 2 repetitions) in either SAAS (S: synchronous condition, A: asynchronous condition) or ASSA order. Thus, the experiment was conducted in within-group design.

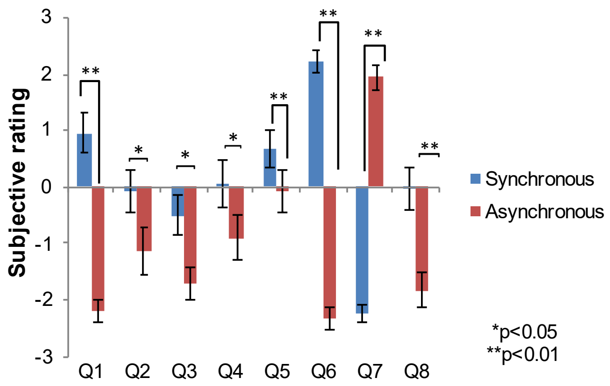
In the questionnaire, participants were asked to rate eight items on a seven-level Likert scale ranging from −3 (I did not feel that at all) to 3 (It felt extremely strong) after observing the virtual scene.

1. It felt as if the space between the socks and gloves was my body.
2. It felt as if my body was drifting toward the space between the socks and gloves.
3. It seemed as if I might have more than one body.
4. It felt as if my body became transparent.
5. It seemed as if there is a whole body between the socks and gloves.
6. The movement of the socks and gloves seemed to be my movement.

7. The movement of the socks and gloves seemed to be another person's movement.
8. It felt as if I was cut by a knife.

3.2.2 Results

Participants ($n = 20$) rated the illusory body ownership higher when the virtual gloves and socks moved synchronously with their own movements than the asynchronous condition (Q1 in Figure 3). The feeling of proprioceptive drift toward the invisible body was higher in the synchronous than the asynchronous condition (Q2). They felt as if their own body became transparent (Q4) more in the synchronous than the asynchronous condition. However, the result of Q4 (transparency) in the synchronous condition was approximately 0 (neutral) so the feeling of a transparent body was not obviously stronger relative to the asynchronous condition, although participants did perceive the illusory (invisible) body between the gloves and the socks (Q5) more strongly in the synchronous than the asynchronous condition. Overall, participants did not feel as if they were cut by the knife that suddenly appeared in the asynchronous condition (Q8); although the response in the synchronous condition was higher than the asynchronous condition, its score was approximately 0 (neutral).
These findings were supported by statistical tests, where the Wilcoxon signed-rank test indicated that the ratings of seven questions were significantly higher in the synchronous condition than the asynchronous condition. The probability of superiority of dependent measures (PS_{dep}) indicated the effect size. The findings were; (Q1 [body ownership]: $z = 3.84$, $p < 0.0001$, $PS_{dep} = 0.95$; Q2 [proprioceptive drift]: $z = 1.96$, $p = 0.050$, $PS_{dep} = 0.6$; Q3 [multiple bodies]: $z = 2.41$, $p = 0.015$, $PS_{dep} = 0.65$; Q4 [transparent body]: $z = 2.23$, $p = 0.024$, $PS_{dep} = 0.6$; Q5 [illusory body perception]: $z = 3.12$, $p = 0.001$, $PS_{dep} = 0.75$; Q6 [synchronous movement]: $z = 3.94$, $p < 0.0001$, $PS_{dep} = 1$; Q8 [body cut]: $z = 3.45$, $p < 0.0001$, $PS_{dep} = 0.85$). The rating of Q7 [asynchronous movement] was significantly higher in the asynchronous condition than the synchronous condition (Q7: $z = -3.93$, $p < 0.0001$, $PS_{dep} = 1$). The participants answered that the gloves and socks moved synchronously with their actions in the synchronous condition (Q6) and moved asynchronously in the asynchronous condition (Q7).



Q1	It felt as if the space between the socks and the gloves was my body.
Q2	It felt as if my body was drifting toward space between the socks and the gloves.
Q3	It seemed as if I might have had more than one body
Q4	It felt as if my body became transparent.
Q5	It seemed as if there is a whole body between the socks and the gloves.
Q6	The movement of the socks and the gloves seemed to be my movement.
Q7	The movement of the socks and the gloves seemed to be other person's movement.
Q8	I felt as if I was cut by a knife.

Figure 3: **Results of Experiment 1-1. Subjective ratings of questionnaires. The error bars indicate SE.**

3.3 Experiment 1-2

3.3.1 Methods

Participants

Twenty naïve volunteers (all male, mean 22.55 years old ± 1.36 SD) participated in Experiment 1-2. None of them participated in Experiment 1-1.

Stimuli and conditions

Apparatus was identical to Experiment 1-1. There were two conditions: the invisible body condition and visible body condition (see Figure 2). The invisible body condition was identical to the synchronous condition in Experiment 1-1. In the visible body condition, a whole-body avatar was presented and moved synchronously with the participant's actions, in front of and facing away from the participants similarly to the invisible condition. We chose an adult male model in solid white as the whole-body avatar because the participants were all male adults, and its color was identical to the socks and gloves in the invisible condition.

Procedures

The stimulus for the startle response was changed to the colliding motion of a table because it was more natural. After 5 min observation for each trial, a similar questionnaire as in Experiment 1-1 was used to evaluate the illusory body ownership. Each participant performed four trials (2 conditions × 2 repetitions) in either IVVI (I: invisible condition, V: visible condition) or VIIV order (within-group design).

In the questionnaire, participants were asked to rate eight items on a seven-level Likert scale ranging from −3 (I did not feel that at all) to 3 (It felt extremely strong) after observing the virtual scene. Q3 and Q8 were changed from Experiment 1-1.

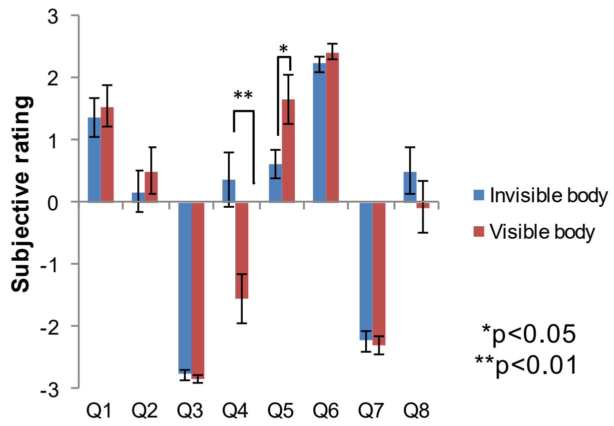
1. It felt as if the space between the socks and gloves was my body.
2. It felt as if my body was drifting toward the space between the socks and gloves.
3. It seemed as if my body became a floor.
4. It felt as if my body became transparent.
5. It seemed as if there is a whole body between the socks and gloves.
6. The movement of the socks and gloves seemed to be my movement.
7. The movement of the socks and gloves seemed to be another person's movement.
8. It felt as if I collided with the table.

3.3.2 Results

The results of the experiments ($n = 20$) did not indicate statistical differences between the invisible body condition, i.e. only the gloves and socks were presented, and the visible body condition, i.e. a whole-body avatar was presented, in any questions except for Q4 [transparent body] ($z = 3.42$, $p < 0.001$, $PS_{dep} = 0.75$) and Q5 [illusory body perception] ($z = -1.98$, $p = 0.048$, $PS_{dep} = 0.75$;Figure 4). As there were no differences in the feelings of body ownership (Q1: $z = -0.77$, $p = 0.459$, $PS_{dep} = 0.6$) and proprioceptive drift (Q2: $z = -1.13$, $p = 0.283$, $PS_{dep} = 0.55$), the illusory body ownership of the invisible body seems equivalent to the visible body. However, the visible avatar was not perceived as transparent, and was more clearly perceived as a whole body rather than an invisible body.

Q3 [Body is floor] was a control question to check random responses, and overall scores were close to the minimum value of −3, irrespective of the visibility condition. The participants answered that the virtual stimuli moved synchronously with their actions irrespective of the visibility condition because the virtual stimuli were synchronized with the participants' actions in all trials of Experiment 1-2 (Q6 [synchronous movement]: $z = -1.3696$, $p = 0.212$, $PS_{dep} = 0.5$; Q7 [asynchronous movement]: $z = 0.26$, $p = 0.826$, $PS_{dep} = 0.3$).

The scores of Q8 [collision with a table] were generally 0, irrespective of the visibility condition ($z = 1.49$, $p = 0.151$, $PS_{dep} = 0.5$). Thus, the feeling of threat was not different between the visible and invisible conditions, and feelings were not strong or clear.



Q1	It felt as if the space between the socks and the gloves was my body.
Q2	It felt as if my body was drifting toward space between the socks and the gloves.
Q3	It seemed as if my body became a floor.
Q4	It felt as if my body became transparent.
Q5	It seemed as if there is a whole body between the socks and the gloves.
Q6	The movement of the socks and the gloves seemed to be my movement.
Q7	The movement of the socks and the gloves seemed to be other person's movement.
Q8	It felt as if I collided with the table.

Figure 4: **Results of Experiment 1-2. Subjective ratings of questionnaires. The error bars indicate SE.**

3.4 Experiment 1-3

3.4.1 Methods

Participants

Ten volunteers (all male, mean 22.2 years old ± 0.87 SD) who participated in Experiment 1-1 participated in Experiment 1-3.

Stimuli and conditions

Stimuli and conditions were identical to Experiment 1-1 except for the control trials. We added two control trials that presented only a virtual room without gloves and socks at the beginning and end of the experiment.

Procedures

After observing the stimuli for 5 min, the participants' proprioceptive self-location was measured. The participants in a black scene of the HMD were moved backward by the experimenter immediately after observing the stimuli in the manner identical to that of Lenggenhager et al. (2007). The moving distance was random, between 2.5 m to 3.5 m. The participants were asked to actually walk and return to the original position where they were observing the virtual scene. In the walking return period, the scene in the HMD remained black. Thus, this task was performed without vision. Each participant performed two control trials (the beginning and the final trials), and four experimental trials (2 conditions × 2 repetitions) in ether SAAS (S: synchronous condition, A: asynchronous condition) or ASSA order. Thus, there were in total six trials (within-group design). In the control trials that were conducted before and after the experimental trials, participants performed the self-localization task after observing the identical room without the socks or gloves by moving their body for 5 min. The self-location data measured in the synchronous and asynchronous conditions were subtracted by the self-location data in the control condition (calibration).

3.4.2 Results

We found that the proprioceptive self-location drifted forward more clearly in the synchronous condition than the asynchronous condition ($n = 10$, $t(9) = 3.101$, $p = 0.013$, $d = 0.98$; Figure 5). Thus, proprioceptive self-location drift to the invisible body was perceived only for the gloves and socks.

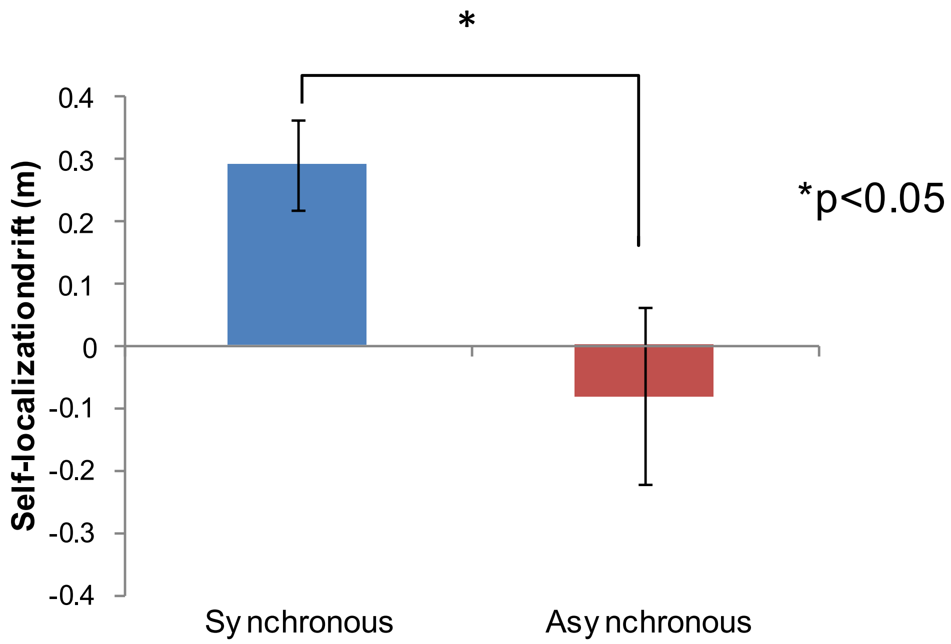


Figure 5: **Results of Experiment 1-3. Drifts in the self-localization task.**

3.5 Discussion

We tested whether body ownership could be induced to an invisible body using virtual socks and gloves synchronized with a participant's movement. We evaluated body ownership by subjective ratings and the self-localization task. We found that in the body ownership induced by only socks and gloves, observers perceived a complete body between socks and gloves, and the proprioceptive self-localization drift toward the invisible body was similar to the one observed in the full-body ownership illusion (B. Lenggenhager et al., 2007).

In both Experiments 1-1 and 1-2, the feelings of threat to the invisible body and the visible body were not clear, even in the synchronous condition. This may have been caused by the weak illusory body ownership; the score of body ownership was 0.95 (of 3.0 maximum) for the invisible body in Experiment 1-1, 1.38 for the invisible body and 1.55 for the visible body in Experiment 1-2. In the experiments, the exposure time for the visual-motor synchronicity was 5 min. Prolonged exposure may enhance illusory body ownership and feelings toward the threat. Furthermore, one may argue that the low score of the threat is reasonable because the illusory owned body is invisible and the space where the knife cuts is empty. In Experiment 1-2, however, we did not find any difference between the invisible body and the visible body. The participants perceived the invisible body as being interpolated between gloves and socks, similar to the illusory contour or the amodal completion phenomena (Michotte et al., 1991). Thus, invisibility cannot account for the low feelings toward the threat. In a further study, as another measure of the startle response, physiological measures (Armel & Ramachandran, 2003; González-Franco et al., 2014; Martini et al., 2015) such as skin conductance response (Armel & Ramachandran, 2003) or event-related cortical potentials (González-Franco et al., 2014) should be employed to clarify these findings.

One may argue that the first-person perspective of the virtual body should be used instead of the third-person perspective (rear view of own body). In experiments for illusory body ownership from the first-person perspective, participants are looking down at their own body and/or looking at a mirror placed in front of them. However, in our preliminary observations, we could feel illusory body ownership to the invisible body from the socks and gloves both from the first-person view and from a viewpoint behind the invisible body. By using the latter, we can measure the proprioceptive self-localization drift. Thus, we adopted the third-person perspective (rear view of own body).

We found that the proprioceptive self-localization drifted to the invisible body area ahead of the participant. This result supports the conclusion that illusory body ownership occurs owing to the invisible body being interpolated between gloves and socks, as do the results of the subjective ratings. Recently, it has been reported that the size perception of external objects is modulated by changing the size of the illusorily owned invisible body (van der Hoort & Ehrsson, 2016). Therefore, we should try to conduct similar experiments on size perception by using our visual-motor active method.

We showed that visual hands and feet are enough to induce illusory body ownership. However, it is unclear whether hands and feet are a minimal or necessary condition for body ownership. This is a limitation of our study and should be investigated in a future study to understand the cognitive mechanism of body ownership.

The illusion of full-body ownership is useful to investigate the idea of minimal phenomenal selfhood for understanding self-consciousness. Virtual-reality techniques enable illusory body ownership to be more flexible. For example, the strength of the body ownership illusion decreases when the virtual body is more transparent, while the pain sensitivity increases as the strength of body ownership in the semi-transparent condition increases (Martini et al., 2015). The feeling of ownership of a virtual arm and its vicarious agency were decreased by the visual discontinuity of the arm for both static and dynamic postures (Tieri et al., 2015). However, we did not find a significant difference between the gloves and socks condition and the whole body condition. These contradictory results may be owing to the difference between a discontinuity or relatively small gap in a body part for body-part ownership and the empty space between hands and feet for full-body ownership, but we need further study in the future.

Relevant to the present study, we may be able to identify the minimal or necessary condition of the Full-body Illusion or the border between the Full-body Illusion and the body-part ownership illusion by visual-motor synchronicity. Neural mechanisms of body-part ownership and full-body ownership seem different[1]. We presented only the gloves (hands) and socks (feet) as body parts, but obtained the Full-body Illusion. If we can identify the border between the Full-body Illusion and the body-part ownership illusion and manipulate it without varying the visual stimuli by using a simple experimental parameter, the experimental paradigm would contribute to clarify the difference in neural mechanisms by combining it with a brain imaging technique in future research.

Chapter 4

Study II: Scrambled Body Illusion

Abstract

Illusory body ownership can be induced in a body part or a full-body by visual-motor synchronisation. A previous study indicated that an invisible full-body illusion can be induced by the synchronous movement of only the hands and feet. The difference between body part ownership and the full-body illusion has not been explained in detail because there is no method for separating these two illusions. To develop a method to do so, we scrambled or randomised the positions of the hands and feet and compared it with the normal layout stimulus by manipulating visual-motor synchronisation. In Experiment 2-1, participants observed the stimuli from a third-person perspective, and the questionnaire results showed that the scrambled body stimulus induced only body part ownership, while the normal layout stimulus induced both body part ownership and full-body ownership when the stimuli were synchronous with participants' actions. In Experiment 2-2, we found similar results as with the first-person perspective stimuli in a questionnaire. We did not find significant skin conductance response difference between any conditions in either Experiment 2-2 or 2-3. These results suggest that a spatial relationship is necessary for the full-body illusion, but not for body part ownership.

4.1 Introduction

Body part ownership. Humans can have illusory ownership of part of a fake body. In the rubber hand illusion, an experimenter simultaneously strokes a rubber hand and the participant's hand with a brush. The participants feel as if the rubber hand is their own hands when they observe only the rubber hand (Botvinick & Cohen, 1998; Manos Tsakiris & Haggard, 2005). When the rubber hand illusion is induced, the proprioceptive sensation of the hand drifts toward the rubber hand. However, Rohde et al., (2011) suggest that proprioceptive drift does not correlate with the illusion. The rubber hand illusion does not occur when the rubber hand is rotated 90 degrees or replaced with a wood-stick, suggesting that the rubber hand illusion is not based on purely bottom-up processes, but also modulated by top-down influences originating from the appearance of one's own body(Manos Tsakiris & Haggard, 2005). Ide (2013) showed that the anatomical plausibility of hand posture affects the rubber-hand illusion; For the left hand, the illusion was stronger when the rubber hand was placed at 0°, 45°, 90° (easy to mimic with the actual left hand), and 315° than 180°, 225°, 270° (difficult to mimic with the actual left hand by the anatomical constraint). Thus, the incongruence in bottom-up visual and proprioceptive signals could explain why the rubber-hand illusion is eliminated or decreased with the rotated rubber hand. The similar finding has been reported in the fMRI study(H Henrik Ehrsson et al., 2004); When the rubber hand is put on the same posture as real hand, the illusion is induced and the premotor cortex showed stronger activation than when the rubber hand is rotated 180 degrees. In those studies, the illusion is induced by visual-tactile synchronicity. The virtual hand illusion(Sanchez-Vives et al., 2010) and the moving rubber hand illusion (Kalckert & Ehrsson, 2012, 2014) have both been reported using visual-motor synchronicity. In the virtual hand illusion, a virtual arm is presented on a screen synchronised with the participant's hand movements. The participants then feel as if the virtual arms is their own.

Full-body illusion (FBI). The rubber hand illusion induces the illusory ownership of body parts, but does not induce that of a whole body. The illusory ownership of a full-body has been investigated (full-body illusion). In the full-body illusion, participants feel as if a mannequin (Petkova & Ehrsson, 2008) or a full-body avatar(Gonzalez-Franco et al., 2010; Maselli & Slater, 2013b; Slater et al., 2010) is their own body due to visual-motor or visual-tactile synchronicity. The full-body illusion using a mannequin is induced by stroking the mannequin and the participant's body at the same time, while the participant observes the stroked abdomen from the position of the mannequin's head through a head-mounted display (HMD). In a full-body illusion of a virtual reality avatar, the avatar moves synchronously with a participant's movements(Gonzalez-Franco et al., 2010), or visual-tactile stimuli are presented using virtual balls and vibrations(Maselli & Slater, 2013b). The full-body illusion is stronger and more likely to be induced through a visual-tactile experience from the first-person perspective than the third-person perspective (Maselli & Slater, 2013b; Slater et al., 2010). In the first-person perspective, participants observed the virtual room and the virtual body from the point of view of the virtual body's eyes. In the third-person perspective, the position of participants (the point of view) was horizontally shifted 1 m(Slater et al., 2010) or 40 cm (Maselli & Slater, 2013b) away to the right of the virtual body; Participants could see the virtual body when they turn their head left. When participants observe a fake body from the front (facing each other), the full-body illusion does not occur (Petkova, Khoshnevis, et al., 2011; Preston et al., 2016). On the other hands, the full-body illusion can be induced when participants observe a body from the third-person perspective under certain conditions (Aspell et al., 2009; B. Lenggenhager et al., 2007; Bigna Lenggenhager et al., 2009). Participants observe a fake body from behind using an HMD while an experimenter simultaneously strokes the back of the fake body and that of the participant. When the visual and tactile strokes are synchronised, participants experience the full-body illusion with the fake body, and their self-localisation drifts towards the fake body. In these studies, participants observe the fake body from behind. However, the self-localisation effect has not been replicated in some studies (Hänsel et al., 2011; Heydrich et al., 2013; Bigna Lenggenhager et al., 2011), and thus it is controversial. The full-body illusion from the third person perspective is a kind of self-recognition similar to recognising oneself in a mirror according to Petkova, et al. (2011) and Ehrsson (2012). Also, Maselli & Slater (2013) discussed that the difference in the illusion strength between the first-person perspective and the third-person perspective can be explained by their theory.

Invisible body illusion. Illusory body part ownership and the full-body illusion can be adapted to create an invisible body illusion. The invisible body illusion is induced by visual-tactile synchronicity (invisible hand (Guterstam et al., 2013), invisible full-body (Guterstam et al., 2015), and invisible small or large body(van der Hoort & Ehrsson, 2016)) or visual-motor synchronicity(Kondo et al., 2018). In the visual-tactile method, an experimenter strokes a participant’s body with a brush and the participant observes the corresponding movement of the brush in empty space through an HMD. In the visual-motor method, participants observe virtual gloves and socks that move synchronously with their own movements. They then feel as if the space between the gloves and socks is their own body, and the invisible body is perceived by interpolating the body parts. This result suggests that the spatial relationship of body parts and the synchronous movement of the hands and feet are important to induce the full-body illusion.

Body part ownership versus the full-body illusion. Several studies have discussed the difference between body part ownership and the full-body illusion. Blanke & Metzinger (2009) and Blanke (2012) claim that body part ownership and the full-body illusion are fundamentally different in terms of bodily self-consciousness. The bilateral premotor cortex, intraparietal sulcus, and the cerebellum are associated with the rubber hand illusion(H. Henrik Ehrsson et al., 2005; H Henrik Ehrsson et al., 2004). Activity in the right posterior insula and right frontal operculum correlates with the proprioceptive drifts in the rubber hand illusion, although the activation in these areas does not increase in the synchronous illusion condition compared to the control conditions (M. Tsakiris et al., 2007). Activity in the extrastriate body area reflects the intensity of the rubber hand illusion (Limanowski et al., 2014). On the other hand, activity in the ventral premotor cortex reflects the full-body illusion; the full-body illusion is only induced by means of visual-tactile stimuli when the body segment connects to a body(Gentile et al., 2015; Petkova, Björnsdotter, et al., 2011). Even though several studies have investigated the difference between body part ownership and the full-body illusion, the difference has not been well understood because an experimental method to separate these two illusions has not yet been developed.

Aim and hypothesis. In this study, we aimed to develop a method to separate and compare these two illusions. Our previous study suggested that the appropriate spatial relationship of body parts and the synchronous movement of hands and feet are sufficient for the full-body illusion(Kondo et al., 2018). Thus, we hypothesised that the full-body illusion requires the spatial relationship of body parts similar to our normal body in addition to visual-motor synchronisation, while body part ownership is induced by means of visual-motor synchronisation without the appropriate spatial relationship. Based on this hypothesis, we developed scrambled stimuli that disrupt the spatial relationship by randomising the positions of body parts from the original/normal body part layout stimulus to induce only body part ownership. Only the gloves and socks were presented both in the normal layout stimulus and the scrambled stimulus as synchronous or asynchronous to the participants' actions (Figure 6). We then investigated the ownership of body parts and a full-body by comparing the scrambled body stimulus with the normal body part layout stimulus. We hypothesised that participants could have illusory ownership of a full-body only when the hands and feet had the normal spatial relationship (normal layout) and were synchronous to their actions, while they could have illusory ownership of hands and feet even from the scrambled stimulus that was synchronous with their actions. In the scrambled stimuli, we did not change the orientation of body parts, and changed only the spatial relationship (position) because it is known that the rotation prevents the body part ownership illusion(H Henrik Ehrsson et al., 2004; Manos Tsakiris & Haggard, 2005).

In Experiment 2-1, we measured the body part ownership and full-body illusion after the observation of the stimuli using a questionnaire and a self-localization task. Participants observed the gloves and socks from a third-person perspective (behind the stimuli) for the self-localization task. We expected that if they felt as if the invisible body in the front were their own full-body, they might move toward the invisible body (further forward from the initial position).

In Experiment 2-2, participants observed the gloves and socks from the first-person perspective to examine whether the body ownership illusion was stronger from the first-person perspective. A questionnaire and skin conductance response (SCR) were used to investigate the body part ownership and full-body illusion. A virtual wheel cutter cut an empty space between the gloves and socks (Figure 7). We expected that if the full-body illusion was induced in the empty space, the SCR would increase when the cutter cut the empty space.

In Experiment 2-3, we measured the SCR to the sudden appearance of the virtual wheel cutter, similarly to Experiment 2-3. However, the timings of the threatening events were random to prevent participants' anticipation.

All experiments were conducted in within-subject design; all participants (16 naïve participants for Experiment 2-1, 16 naïve participants for Experiment 2-2, and 20 naïve participants for Experiment 2-3) experienced all four conditions (a combination of normal layout and scrambled bodies, and synchronous and asynchronous movements).

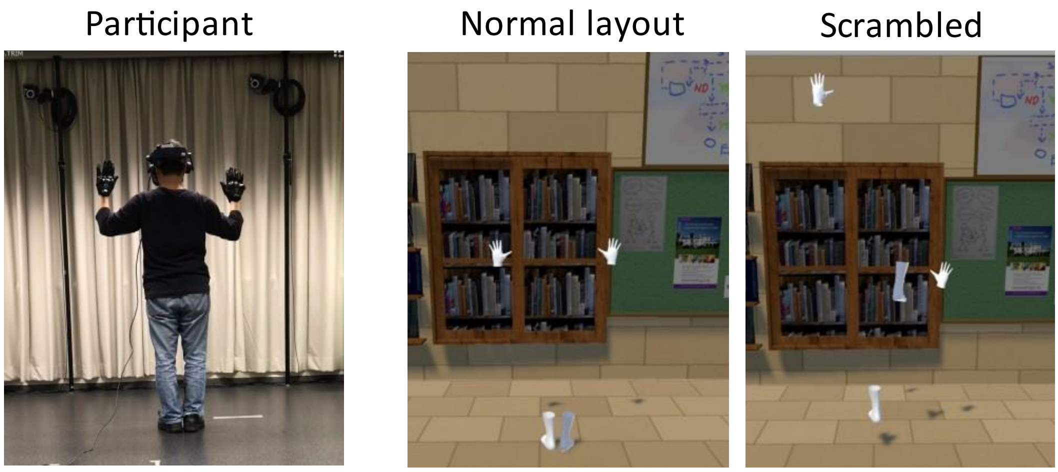


Figure 6: **An example of a participant's posture (left), the corresponding normal layout stimulus (middle), and the scrambled stimulus (right).**

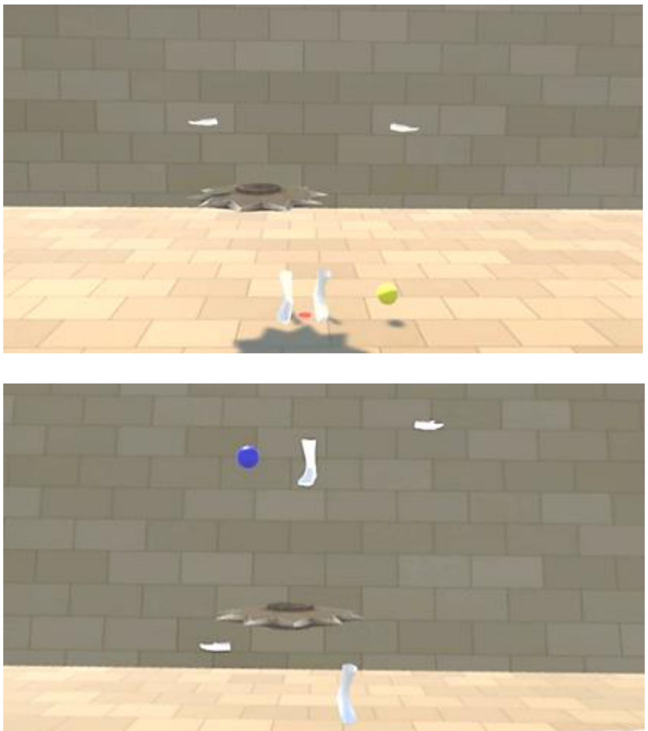


Figure 7: **A virtual wheel cutter and virtual gloves and socks in a virtual mirror.**

4.2 Experiment 2-1

4.2.1 Methods

Participants

Sixteen male volunteers (mean age 21.44 ± 1.46 (*SD*)) participated in Experiment 2-1, and were not aware of the hypothesis or naïve to the study. They had healthy vision and physical abilities and provided written informed consent before the experiment. One participant was excluded from the data of the self-localisation task due to a problem. This study was approved by the Ethical Committee on Human-Subject Studies of Toyohashi University of Technology and conformed to the committee's guidelines and regulations.

Apparatus

Experimental stimuli were generated by a computer using a Unity Engine and presented through a head-mounted display (HTC Vive Pro, 1440 × 1600 pixel per eye, 110° diagonal, refresh rate 90 Hz).

Participants wore gloves and socks with four motion trackers (VIVE Tracker 2018; spatial resolution: within 1 mm; sampling rate: better than 60 Hz; delay: less than 44 ms).

Stimuli and conditions

Virtual gloves and socks were presented in the same positions as the participants' hands and feet (normal layout condition) or random positions (scrambled condition) in the third-person perspective (Fig. 1); the virtual gloves and socks were 2 m in front of the participants, similar to Kondo et al. (2018) The participants always observed the stimuli from behind them (rear view of the body stimuli). In the scrambled body condition, the positions of the gloves and socks were within the ranges of −50 cm to +150 cm and 0 cm to +200 cm from the original vertical positions, respectively (Figure 8; + indicates up and − down). The gloves and socks moved synchronously or asynchronously with the participant's hand and foot movements. In the asynchronous condition, another person's previously recorded motions of the gloves and socks were played irrespective of participant motion; two motions for the normal layout condition and two for the scrambled body condition were prepared and used.

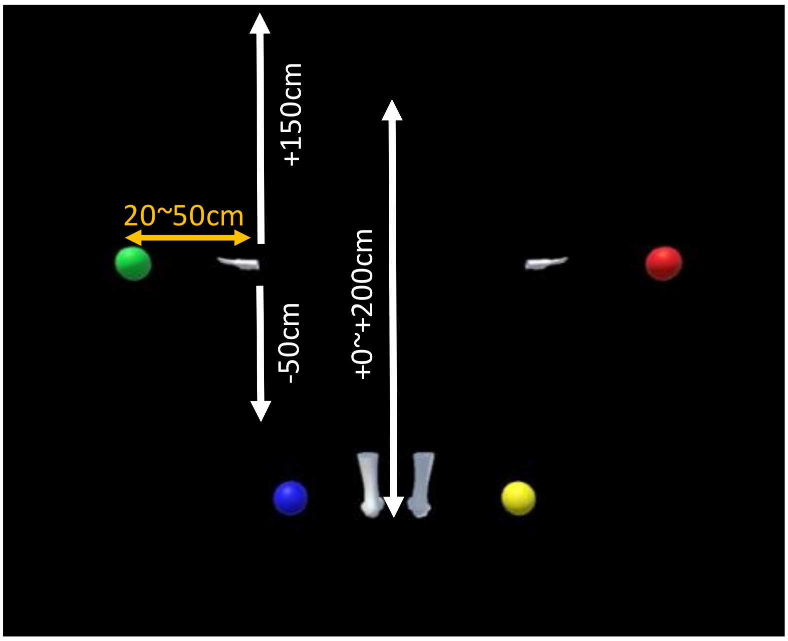


Figure 8: Range of body part positions in the scrambled condition (white), and the range of ball appearance positions (orange).

Procedure

After participants observed a dark scene for 10 seconds, they observed the gloves and socks from the third-person perspective. A virtual ball appeared on the left or right side of the left-hand or right-hand gloves or socks, respectively, within the range of 20 cm to 50 cm outward from the original position of the participant's hands and feet as measured at the end of the dark scene (Figure 8). The virtual ball appeared in one of four colours corresponding to the participant's right/left hands/feet in a random position. The participants touched the balls with their corresponding hands or feet in random order for 10 minutes. When a ball was touched, it disappeared and reappeared at a different position after 2 seconds (ball task). In the asynchronous condition, the movement of the gloves and socks was a replay of pre-recorded motions. For the ball task, we connected the participants' hands and feet to invisible gloves and socks (empty spaces) that moved synchronously. The initial position of the invisible body parts was the same as the visible gloves and socks for each trial. After the ball task, the participants performed the self-localisation task (B. Lenggenhager et al., 2007). First, they were led to an initial position, then moved backwards (2.5, 2.75, 3.0, 3.25, or 3.5 m randomly) and asked to walk to their initial position. All task procedures were conducted without the aid of vision. Finally, they completed a questionnaire comprising eight items on a seven-point Likert scale from −3 ('I did not feel that at all') to 3 ('I felt it very strongly').

Questionnaire

1. It felt as if the space between the gloves and socks was my body.
2. It felt as if the gloves were part of my body.
3. It felt as if the socks were part of my body.
4. It seemed as if I could perceive a whole body between the gloves and socks.
5. It felt as if my body was drifting toward the space between the gloves and socks.
6. The movement of the gloves and socks seemed to be my movement.
7. The movement of the gloves and socks seemed to be another person's movement.
8. It seemed as if my body became a floor.

The first question concerned full-body ownership; the second and third, body part ownership; the fourth, the perception of the invisible body by interpolating the hands and feet; the fifth, the subjective drift of self-location; and the sixth and seventh, the degree of self-agency. The eighth question was a control question to check participants' unreliable or random responses.

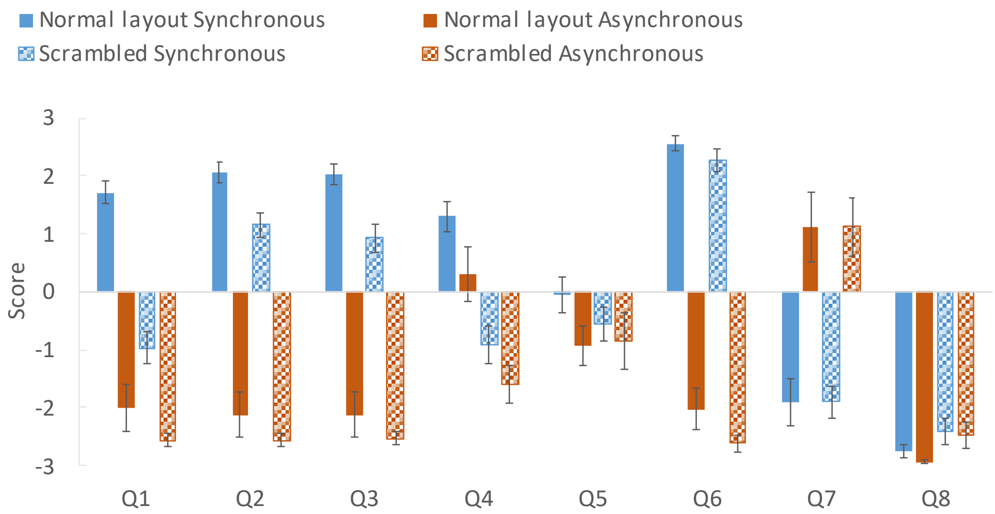
All participants performed eight experimental trials (within-subject design: two body conditions and two synchronisation conditions with two repetitions) in random order and two control trials at the beginning and end of the experiment. Before the trials, the participants touched 10 balls to practise the ball task in the normal layout and synchronous condition.

4.2.2 Results

Questionnaire

We conducted the Shapiro-Wilk test to check the normality of the results of the questionnaire, and found that the data could not be assumed to have come from a normally distributed population. Therefore, we applied the Wilcoxon signed-rank test to analyse the results of the questionnaire (body: normal layout, scrambled; synchronisation: synchronous, asynchronous; $N = 16$). P-values were corrected by the Bonferroni method.

The results of the questionnaire (scored on a seven-point Likert scale from −3 to 3) are summarised in Figure 9. The participants were more likely to feel that the space between the gloves and socks was their own body in the normal layout body condition than in the scrambled condition only when the stimuli moved synchronously (Q1: $z = 3.53$, original $p < 0.001$, adjusted $p < 0.001$, effect size $r = 0.88$). They were more likely to feel that the space between the gloves and socks was their own body in the synchronous condition than in the asynchronous condition in both the normal layout condition (Q1: $z = 3.47$, original $p < 0.001$, adjusted $p < 0.001$, $r = 0.87$) and the scrambled condition (Q1: $z = 3.31$, original $p < 0.001$, adjusted $p < 0.001$, $r = 0.83$). Data of all participants are provided as Supplementary Material.



Q1	It felt as if the space between the gloves and socks was my body.
Q2	It felt as if the gloves were of my body.
Q3	It felt as if the socks were of my body.
Q4	It felt as if I could perceive a whole body between the gloves and socks.
Q5	It felt as if my body was drifting toward the space between the gloves and socks.
Q6	The movement of the gloves and socks seemed to be my movement.
Q7	The movement of the gloves and socks seemed to be another person’s movement.
Q8	It seemed as if my body became a floor.

Figure 9: Results of the questionnaire in Experiment 2-1. Error bars indicate SE.

They were more likely to feel that the gloves (Q2) or socks (Q3) were part of their own bodies in the normal layout condition than in the scrambled condition when the stimuli moved synchronously (Q2: $z = 3.11$, original $p < 0.001$,adjusted $p = 0.0051$, $r = 0.78$, Q3: $z = 3.33$, original $p < 0.001$, adjusted $p < 0.001$, $r = 0.83$), and were more likely to feel that the gloves (Q2) or socks (Q3) were part of their own bodies in the synchronous condition than in the asynchronous condition in both the normal layout condition (Q2: $z = 3.42$, original $p < 0.001$, adjusted $p < 0.001$, $r = 0.85$; Q3: $z = 3.47$, original $p < 0.001$, adjusted $p < 0.001$, $r = 0.87$) and the scrambled condition (Q2: $z = 3.54$, original $p < 0.001$, adjusted $p < 0.001$, $r = 0.89$; Q3: $z = 3.53$, original $p < 0.001$, adjusted $p < 0.001$, $r = 0.88$).

They were also more likely to feel that there was a whole body (invisible body) between the gloves and socks in the normal layout condition than in the scrambled condition in both the synchronous condition (Q4: $z = 3.45$, original $p < 0.001$, adjusted $p < 0.001$, $r = 0.86$) and the asynchronous condition (Q4: $z = 3.22$, original $p < 0.001$, adjusted $p = 0.0022$, $r = 0.81$).

There was no significant difference between the synchronous condition and the asynchronous condition with either the normal layout body (Q4: $z = 1.87$, original $p = 0.068$, adjusted $p = 0.41$, $r = 0.47$) or the scrambled body in the perception of an invisible body (Q4: $z = 1.72$, original $p = 0.093$, adjusted $p = 0.56$, $r = 0.43$).

There was no significant difference between the body condition and the synchronisation conditions on the subjective drift of self-location (Q5 Normal Layout Synchronous vs. Scrambled Synchronous: $z = 1.09$, original $p = 0.29$, adjusted $p = 1.00$, $r = 0.27$). There was no significant difference between the synchronous condition and the asynchronous condition (Q5 Normal Layout Synchronous vs. Normal Layout Asynchronous: $z = 1.86$, original $p = 0.066$, adjusted $p = 0.39$, $r = 0.46$; Scrambled Synchronous vs. Scrambled Asynchronous: $z = 0.79$, original $p = 0.46$, adjusted $p = 1.00$, $r = 0.20$).

The participants were more likely to feel that the movements of the gloves and socks were their own movements in the synchronous condition than in the asynchronous condition in both the normal layout condition (Q6: $z = 3.54$, original $p < 0.001$, adjusted $p < 0.001$, $r = 0.88$) and the scrambled condition (Q6: $z = 3.53$, original $p < 0.001$, adjusted $p < 0.001$, $r = 0.88$), and were more likely to feel that the movements of the gloves and socks were someone else's movements in the asynchronous condition than in the synchronous condition in both the normal layout condition (Q7: $z = -2.68$, original $p < 0.001$, adjusted $p < 0.001$, $r = 0.67$) and the scrambled condition (Q7: $z = 3.01$, original $p = 0.0013$, adjusted $p = 0.0079$, $r = 0.75$).

The eighth question ('It seemed as if my body became a floor') was a control question to test the reliability of participants' judgments. No significant difference was found for the control question.

Self-localisation drift

One participant was excluded from the data of the self-localisation task after colliding with a wall during the task. We measured the distance between the initial position and the estimated position in the self-localisation task and subtracted the value of the control trial from that of the experimental trials to control participants' individual differences. We conducted a two-way repeated-measure ANOVA to analyse the results of the self-localisation task (Body: normal layout, scrambled; Synchronisation: synchronous, asynchronous; $N = 15$).

There was no significant difference for either the *x* (left-right) axis (No main effect of the body: $F(1, 14) = 0.35, p = 0.56, \eta_p^2 = 0.024$; No main effect of synchronisation: $F(1, 14) = 0.039, p = 0.85, \eta_p^2 = 0.0027$; No interaction: $F(1, 14) = 2.39, p = 0.14, \eta_p^2 = 0.15$) or the *y* (forward-backward) axis (No main effect of the body: $F(1, 14) = 0.27, p = 0.61, \eta_p^2 = 0.019$; No main effect of synchronisation: $F(1, 14) = 0.0039, p = 0.95, \eta_p^2 = 0.0003$; No interaction: $F(1, 14) = 0.57, p = 0.46, \eta_p^2 = 0.039$), as shown in Figure 10. Thus, we did not find any drift in the proprioceptive self-location.

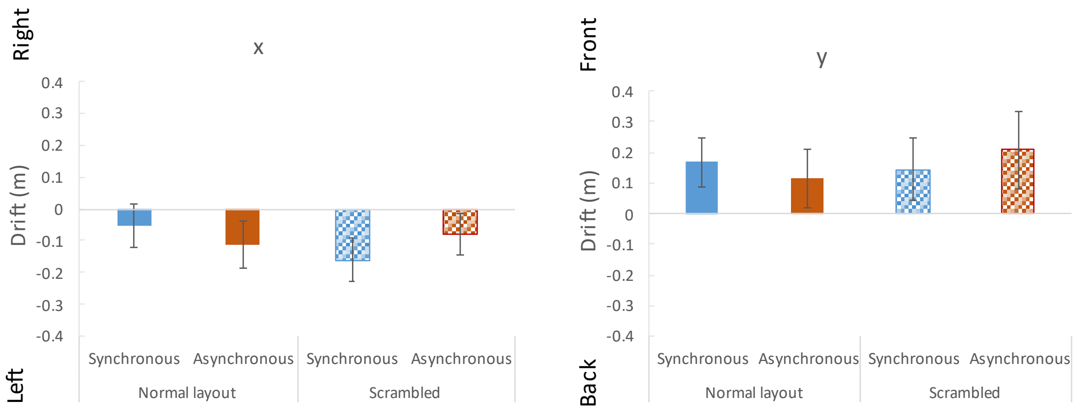


Figure 10: **Results of self-localisation drift in Experiment 2-1. Error bars indicate SE.**

4.3 Experiment 2-2

4.3.1 Methods

Participants

Eighteen naïve volunteers (17 males and 1 female, mean age 22.9 ± 3.04 (SD)) participated in Experiment 2-2. Two had participated in Experiment 2-1 four month ago. Two participants were excluded from the data due to procedural problems; the data of sixteen participants were analysed (mean age 23.4 ± 3.72 (SD)).

Apparatus

BIOPAC MP 160 and wireless PPG and EDA amplifiers (BN-PPGED) were used to record the skin conductance response (SCR). A wireless transmitter (BN-PPGED) was placed on a participant's left wrist. Two disposable electrodes (EL507) were pasted to the distal phalanges of their left middle and ring fingers. Two lead cables (BN-EDA-LEAD2) connected the wireless transmitter to the electrodes. SCR data were recorded at 1000 Hz. Other equipment was identical to Experiment 2-1.

Stimuli and conditions

Participants observed the virtual gloves and socks from the first-person perspective and the stimuli through a virtual mirror 2 m in front of them. When they touched the balls, they were asked to look at the balls in front of (not in) the mirror to observe the gloves and socks. A virtual wheel cutter appeared and spun to the left of the participants at the end of each trial. One second after its appearance it passed between the gloves and socks (empty space) in 3 seconds and disappeared. In the scrambled condition, the gloves and socks were in four fixed positions (left gloves: −50 cm; right gloves: +100 cm; left socks: +200 cm; right socks: +50 cm from the original vertical position) so the cutter could pass through an empty space between them. The other stimuli and conditions were identical to Experiment 2-1.

Procedure

Participants performed the ball task for 10 minutes, and then remained standing in a T-pose and continued looking down until the end of the trial when the notification appeared on the HMD. After 10 seconds, the spinning cutter appeared and passed between the gloves and socks. Finally, they completed a questionnaire comprising twelve items on a seven-point Likert scale from −3 to 3.

Questionnaire

1. It felt as if the space between the gloves and socks in front of the mirror was my body.
2. It felt as if the space between the gloves and socks in the mirror was my body.
3. It felt as if the gloves in front of the mirror were part of my body.
4. It felt as if the gloves in the mirror were part of my body.
5. It felt as if the socks in front of the mirror were part of my body.
6. It felt as if the socks in the mirror were part of my body.
7. It seemed as if I could perceive a whole body between the gloves and socks in front of the mirror.
8. It seemed as if I could perceive a whole body between the gloves and socks in the mirror.
9. It felt as if I had been cut by the cutter.
10. The movement of the gloves and socks seemed to be my movement.
11. The movement of the gloves and socks seemed to be another person's movement.

12. It seemed as if my body became a floor.

The first question concerned full-body ownership (the second: in the mirror); the third and fourth, body part ownership (the fifth and sixth: in the mirror); the seventh, the perception of the invisible body by interpolating the hands and feet (the eighth: in the mirror); the ninth, the subjective startle response; and the tenth and eleventh, the degree of self-agency. The twelfth question was a control question to check random responses.

All participants performed eight experimental trials (within-subject design: two body conditions and two synchronisation conditions with two repetitions) in random order. Before the experimental trials, the participants touched 10 balls to practise the ball task in the normal layout and synchronous condition.

4.3.2 Results

Eighteen participants performed the experiment, but two were excluded from the questionnaire and skin conductance response (SCR) because one did not look down when the cutter appeared and the SCR data was not recorded, while the other also did not look down when the cutter appeared and the Vive Tracker was removed during the ball task.

We conducted the Shapiro-Wilk test to check the normality of the results of the questionnaire and SCR, and found that the data could not be assumed to have come from a normally distributed population. Therefore, we conducted a Wilcoxon signed-rank test to analyse the results of the questionnaire and SCR (body: normal layout, scrambled; synchronisation: synchronous, asynchronous; $N = 16$). *P*-values were corrected by the Bonferroni method.

Questionnaire

The results of the questionnaire (seven-point Likert scale from −3 to 3) are summarised in Figure 11. Participants were more likely to feel that the space between the gloves and socks was their own body in the synchronous condition than in the asynchronous condition both in the normal layout condition (Q1 (in front of mirror): $z = 3.42$, original $p < 0.001$, adjusted $p < 0.001$, effect size $r = 0.85$; Q2 (in mirror): $z = 3.52$, original $p < 0.001$, adjusted $p < 0.001$, $r = 0.88$) and scrambled conditions (Q1: $z = 2.98$, original $p < 0.001$, adjusted $p = 0.0059$, effect size $r = 0.75$; Q2: $z = 3.18$, original $p < 0.001$, adjusted $p = 0.0015$, $r = 0.80$); the effect was larger in the normal layout condition. The score was higher in the normal layout condition than in the scrambled condition both in the synchronous condition (Q1: $z = 3.30$, original $p < 0.001$, adjusted $p < 0.001$, effect size $r = 0.83$; Q2: $z = 3.19$, original $p < 0.001$, adjusted $p = 0.0015$, $r = 0.80$) and the asynchronous condition (Q1: $z = 2.55$, original $p = 0.0078$, adjusted $p = 0.047$, effect size $r = 0.64$; but not significant for Q2 $z = 2.26$, original $p = 0.031$, adjusted $p = 0.188$, effect size $r = 0.57$); the effect was much larger in the synchronous condition. Thus, the participants felt as if the space between the gloves and socks was their own body only in the synchronous and normal layout condition (average scores Q1: 1.91, Q2: 1.69).

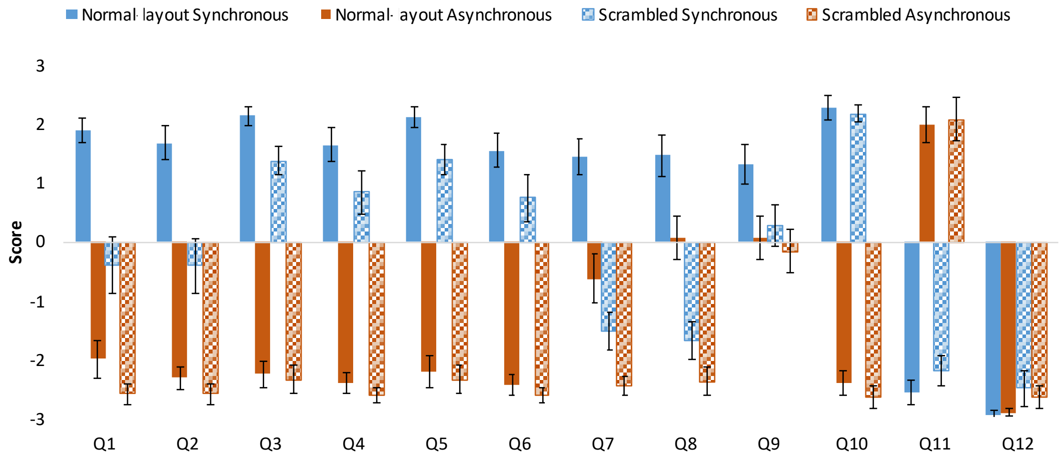
They were more likely to feel that the gloves (Q3 (in real space), Q4 (in mirror)) or socks (Q5 (in real space), Q6 (in mirror)) were part of their own bodies in the synchronous condition than in the asynchronous condition in both the normal layout condition (Q3: $z = 3.54$, original $p < 0.001$, adjusted $p < 0.001$, $r = 0.88$; Q4: $z = 3.52$, original $p < 0.001$, adjusted $p < 0.001$, $r = 0.88$; Q5: $z = 3.52$, original $p < 0.001$, adjusted $p < 0.001$, $r = 0.88$; Q6: $z = 3.52$, original $p < 0.001$, adjusted $p < 0.001$, $r = 0.88$) and the scrambled condition (Q3: $z = 3.52$, original $p < 0.001$, adjusted $p < 0.001$, $r = 0.88$; Q4: $z = 3.52$, original $p < 0.001$, adjusted $p < 0.001$, $r = 0.88$; Q5: $z = 3.52$, original $p < 0.001$, adjusted $p < 0.001$, $r = 0.88$; Q6: $z = 3.52$, original $p < 0.001$, adjusted $p < 0.001$, $r = 0.88$). The score was higher in the normal layout condition than in the scrambled condition in the synchronous condition (Q3: $z = 2.84$, original $p = 0.0035$, adjusted $p = 0.021$, $r = 0.71$; Q4: $z = 2.73$, original $p = 0.0048$, adjusted $p = 0.029$, $r = 0.68$; Q5: $z = 2.96$, original $p < 0.001$, adjusted $p = 0.0059$, $r = 0.74$).

They were more likely to feel that there was a whole body (invisible body) between the gloves and socks in front of the mirror in the synchronous condition than in the asynchronous condition both in the normal layout condition (Q7: $z = 2.90$, original $p = 0.0018$, adjusted $p = 0.011$, effect size $r = 0.73$) and scrambled condition (Q7: $z = 2.53$, original $p = 0.0078$, adjusted $p = 0.047$, effect size $r = 0.63$); the effect was larger in the normal layout condition. The score was higher in the normal layout condition than in the scrambled condition both in the synchronous condition (Q7: $z = 3.41$, original $p < 0.001$, adjusted $p < 0.001$, effect size $r = 0.85$) and the asynchronous condition (Q7: $z = 2.95$, original $p = 0.0015$, adjusted $p = 0.0087$, effect size $r = 0.74$). Only in the normal layout condition were participants more likely to feel that there was a whole body (invisible body) between the gloves and socks in the mirror in the synchronous condition than in the asynchronous condition (Q8: $z = 2.75$, original $p = 0.0042$, adjusted $p = 0.025$, effect size $r = 0.69$). The score was higher in the normal layout condition than in the scrambled condition both in the synchronous condition (Q8: $z = 3.53$, original $p < 0.001$, adjusted $p < 0.001$, effect size $r = 0.88$) and the asynchronous condition (Q8: $z = 3.25$, original $p < 0.001$, adjusted $p = 0.0015$, effect size $r = 0.81$). Thus, the participants surely felt as if there was an invisible body between the gloves and socks only in the synchronous and normal layout conditions (average scores Q7 (in front of mirror): 1.44, Q8 (in mirror): 1.47).

They were more likely to feel as if they would be cut by the cutter in the synchronous condition than in the asynchronous condition only in the normal layout condition (Q9: $z = 2.56$, original $p = 0.0078$, adjusted $p = 0.047$, effect size $r = 0.64$), and it was not significant in the scrambled conditions (Q9: $z = 0.83$, original $p = 0.43$, adjusted $p = 1.00$, effect size $r = 0.21$). Thus, they felt as if they would be cut by the cutter when the full-body illusion was induced rather than when only body part ownership occurred.

The participants were more likely to feel that the movements of the gloves and socks were their own movements in the synchronous condition than in the asynchronous condition in both the normal layout condition (Q10: $z = 3.54$, original $p < 0.001$, adjusted $p < 0.001$, $r = 0.88$) and scrambled conditions (Q10: $z = 3.54$, original $p < 0.001$, adjusted $p < 0.001$, $r = 0.89$). They were more likely to feel that the movements of the gloves and socks were someone else's movements in the asynchronous condition than in the synchronous condition in both the normal layout condition (Q11: $z = -3.54$, original $p < 0.001$, adjusted $p < 0.001$, $r = 0.89$) and scrambled conditions (Q11: $z = -3.54$, original $p < 0.001$, adjusted $p < 0.001$, $r = 0.88$).

The twelfth question ('It seemed as if my body became a floor.') was a control question to test the reliability of participants' judgments. No significant difference was found on the control question.



Q1	It felt as if the space between the gloves and socks in front of the mirror was my body.
Q2	It felt as if the space between the gloves and socks in the mirror was my body.
Q3	It felt as if the gloves in front of the mirror were part of my body.
Q4	It felt as if the gloves in the mirror were part of my body.
Q5	It felt as if the socks in front of the mirror were part of my body.
Q6	It felt as if the socks in the mirror were part of my body.
Q7	It seemed as if I could perceive a whole body between the gloves and socks in front of the mirror.
Q8	It seemed as if I could perceive a whole body between the gloves and socks in the mirror.
Q9	It felt as if I was cut by the cutter.
Q10	The movement of the gloves and socks seemed to be my movement.
Q11	The movement of the gloves and socks seemed to be another person's movement.
Q12	It seemed as if my body became a floor.

Figure 11: Results of the questionnaire in Experiment 2-2. Error bars indicate SE.

Skin conductance response

The magnitude of the SCR was calculated as the difference between the maximum value and the minimum value of the skin conductance during the 0–5 s after the appearance of the cutter; this procedure was adopted from previous studies (Guterstam et al., 2013, 2015; Petkova, Khoshnevis, et al., 2011; Petkova & Ehrsson, 2008). We expected that the magnitude of the SCR would be larger when the full-body illusion was induced than when only body part ownership occurred. However, there was no significant difference between the synchronous and asynchronous condition in the normal layout condition ($z = -0.52$, original $p = 0.63$, adjusted $p = 1.00$, $r = 0.13$), or between the normal layout condition and the scrambled condition in the synchronous condition ($z = -0.41$, original $p = 0.71$, adjusted $p = 1.00$, $r = 0.10$), as shown in Figure 12.

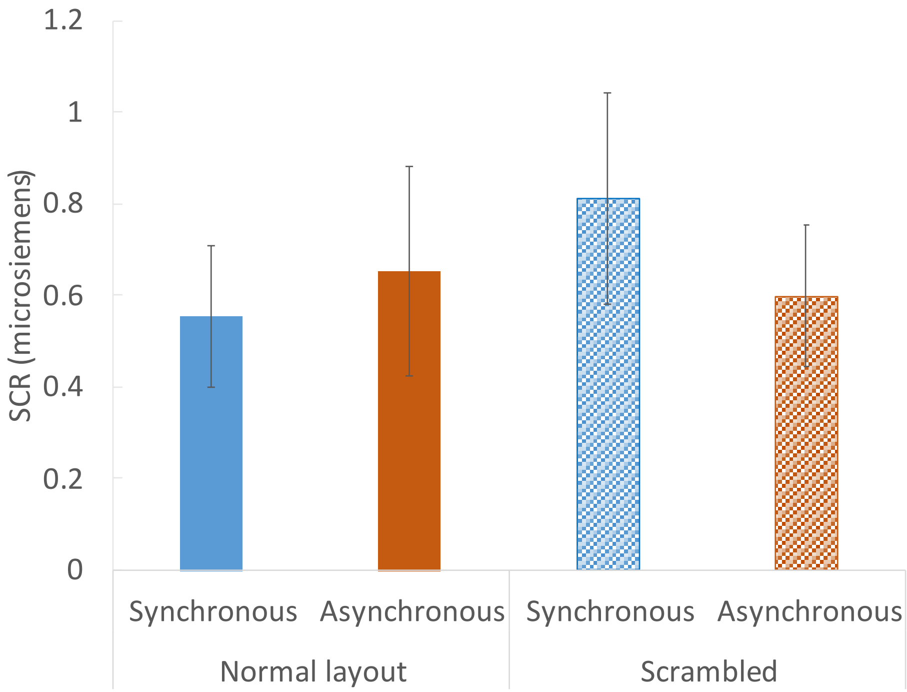


Figure 12: **Results of the SCR in Experiment 2-2. Error bars indicate SE.**

However, there is also a potential methodological concern. Participants were asked to remain standing in a T-pose (standing straight, holding their arms out horizontally) and continue looking down until the end of the trial when the word 'T-Pose' appeared in a notification on the HMD. Ten seconds after the T-pose, the cutter appeared and cut the empty space. The skin conductance tended to increase just after the 'T-Pose' notification appeared. Therefore, the notification might have evoked the SCR, inhibiting the responses for the cutting threat. In Experiment 2-3, we removed this anticipating procedure, and presented the cutter three times at random timings during participants' movements.

4.4 Experiment 2-3

4.4.1 Methods

Participants

Twenty naïve and new volunteers (18 males and 2 females, mean age 22.2 ± 1.28 (*SD*)) participated in Experiment 2-3.

Apparatus, Stimuli, and Conditions

The apparatus, stimuli, and conditions were identical to Experiment 2-3.

Procedure

Participants performed the ball task for 12 minutes. In the last 2 minutes, the spinning cutter randomly appeared and passed between the gloves and socks three times.

All participants performed four experimental trials (within-subject design: two body conditions and two synchronisation conditions) in random order. Before the experimental trials, the participants touched 10 balls to practise the ball task in the normal layout and synchronous condition.

4.4.2 Results

Twenty participants performed the experiment and we measured the SCR without the questionnaire. None of them experienced the other experiments. The magnitude of the SCR was calculated as the difference between the maximum and minimum value of the skin conductance during the 0–5 s after the appearance of the cutter. We conducted the Shapiro-Wilk test to check the normality of the results of the SCR, and found that the data could not be assumed to have come from a normally distributed population. Therefore, we conducted a Wilcoxon signed-rank test to analyse the results of the SCR. We expected that the magnitude of the SCR would be larger when the full-body illusion was induced than when only body part ownership occurred. However, there was no significant difference between the synchronous and asynchronous conditions in the normal layout condition ($z = 0.26$, original $p = 0.81$, adjusted $p = 1.00$, $r = 0.058$), or between the normal layout condition and the scrambled condition in the synchronous condition ($z = 0.11$, original $p = 0.93$, adjusted $p = 1.00$, $r = 0.025$), as shown in Figure 13.

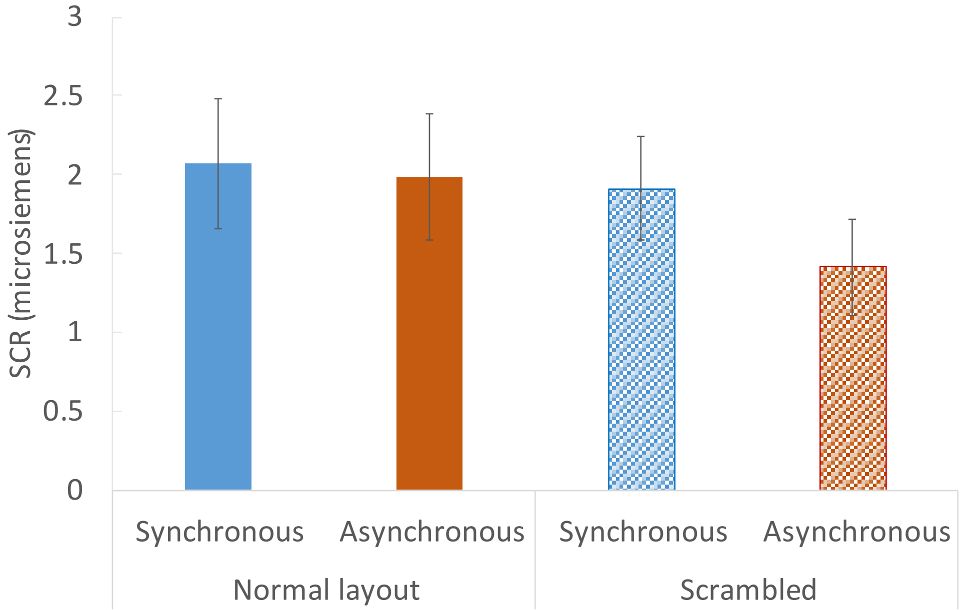


Figure 13: **Results of the SCR in Experiment 2-3. Error bars indicate SE.**

4.5 Discussion

In this study, we developed techniques to investigate the scrambled body and compared body part ownership and the full-body illusion. We found that participants felt as if the space between the gloves and socks was their own bodies only when the normal layout stimuli were synchronous with their movements both in the third- and first-person perspective (Experiment 2-1 Q1, Experiment 2-2 Q1, Q2: Full-body illusion). They felt as if the gloves or socks were part of their own bodies in both body conditions (Experiment 2-1 Q2, Q3; Experiment 2-2 Q3, Q4, Q5, Q6: body part ownership), and the feeling was stronger in the normal layout condition than in the scrambled body condition. The invisible whole body was more likely to be perceived by interpolating the hands and feet when the body parts were normally presented than when they were scrambled, and the stimuli were more synchronous than asynchronous with the participants' actions (Experiment 2-1 Q4:, Experiment 2-2 Q7, Q8: invisible body). We did not find self-localisation drift in the questionnaire (Experiment 2-1 Q5) or in the behavioural task. We did not find significant SCR differences between any conditions by a threatened event in either Experiment 2-2 or 2-3.

The results suggest that the spatial relationship between normal body parts is necessary for the full-body illusion, but not for body part ownership. Thus, the appropriate spatial relationship of body parts with visual-motor synchronisation is a critical factor for full-body ownership.

Body part ownership was induced by the synchronously moving scrambled body parts without full-body ownership. Thus, the spatial relationship would not be a necessary condition for body part ownership, while visual-motor synchronisation would be an independent critical factor. However, the spatial relationship improved body part ownership. It is still not clear whether the spatial relationship directly affects body part ownership or if full-body ownership increases body part ownership.

We could extract body part ownership from full-body ownership because the scrambled body part condition elicited body part ownership without full-body ownership. However, whether full-body ownership can be induced without body part ownership is an open question. This question is our next research target.

In Experiment 2-1, participants observed virtual body parts from the third-person perspective (behind the virtual body) because it was difficult for the participants to see the virtual body parts, especially in the scrambled condition, and there was a possibility that the scrambled body parts would be obscured. However, the body ownership illusion might be weaker in the third-person than in the first-person perspective. Several studies found that when participants observed a mannequin from the front, the full-body illusion was not induced (Petkova, Khoshnevis, et al., 2011; Preston et al., 2016). Petkova et al. (2011) and Ehrsson (2012) claim that the full-body illusion from the third-person perspective is a kind of self-recognition similar to recognising oneself in a mirror. In body part ownership, the rubber hand illusion is weakened when the rubber hand is in a distant position (Aimola Davies et al., 2013; Lloyd, 2007). Thus, our method using the third-person perspective might weaken illusory body ownership.

Therefore, participants observed the stimuli from the first-person perspective and observed the stimuli through the virtual mirror in Experiment 2-2. Illusory body ownership can be induced when a body is presented in a mirror(Gonzalez-Franco et al., 2010; Preston et al., 2016); there was no significant difference between the mirror condition and the first-person perspective condition in terms of body ownership(Preston et al., 2016). Thus, we used the virtual mirror to present a whole image of the body parts.

We expected participants' self-localisation drift toward the virtual body only in the normal layout and synchronous condition in Experiment 2-1 with the third-person perspective. However, there was no significant difference in any of the conditions. This may have been caused by the weakened ownership of the illusory body with the third-person perspective and/or the inclusion of the body parts stimuli. However, some studies report that the feeling of body ownership cannot be measured by proprioceptive drift alone (Abdulkarim & Ehrsson, 2016; Holle et al., 2011; Rohde et al., 2011). Thus, we should consider the results of the self-localisation task separately from the results of the questionnaire. Our negative results partly support the view that the self-localisation task does not measure body ownership, and that it is different from the proprioceptive drift that is used to quantify the rubber hand illusion.

We measured the SCR when the cutter cut the empty space between the gloves and socks in Experiments 2-2 and 2-3. We expected that the SCR would increase when the full-body illusion was induced; however, there was no significant difference in SCR between any of the conditions, suggesting that the feeling of illusory body ownership of the invisible body created by our method might be too weak to elicit SCR. There is another potential concern regarding the SCR results: The sample size was too small to analyse the SCR (N=16 in Experiment 2-2, N=20 in Experiment 2-3).

It is the most critical limitation of the present study that our findings rely only on subjective measures (questionnaire). One may argue that participants who experienced all four conditions may simply give higher scores to the stimulus that feels more natural irrespective of the feeling of body ownership. Thus, the normal layout and synchronous condition could be rated higher in most questions. However, we instructed participants to answer the questionnaire appropriately, and the data obtained were quantitative (different between questions). The results for the control questions (Q8 in Experiment 2-1 and Q12 in Experiment 2-2) were appropriate. To overcome the limitation of the questionnaire, we need to measure SCR with a larger sample size and a more powerful threatening event. One may argue that the between-subject design could be better than the within-subject design to prevent learning effects, especially when any physiological evidence was not found as in our experiments. It would be better to compare our study with another experiment using a between-subject design in future studies.

Chapter 5

Study III: Invisible Long Arm Illusion

Abstract

We feel as if a fake body is our own body by synchronicity between the fake body and the actual body (illusory body ownership) even if the body has a different shape. In our previous study, we showed that illusory body ownership can be induced to an invisible body through the synchronous movement of just the hands and feet. In this study, we investigated whether illusory body ownership can be induced to the invisible body even when the arm length of the invisible body was different from the usual body. We modified the length of arm of a full-body avatar or changed the position of the hand of the invisible body stimulus, and found that the illusory body ownership was induced to the transformed body by synchronous movement. Participants' reaching behavior gradually changed to use the longer arm more during the learning of the transformed body.

5.1 Introduction

Illusion of ownership to different bodies

We can feel as if a fake body is our own body even if the body has a different shape and color. It is called "illusory body ownership" (Kilteni et al., 2015), and it is induced by presenting tactile stimuli synchronized with visual stimuli (Botvinick & Cohen, 1998) or presenting visual stimuli synchronized with an observer's movement (Gonzalez-Franco et al., 2010). The method for illusory body ownership is categorized as passive method or active method. The rubber hand illusion (Botvinick & Cohen, 1998; Manos Tsakiris & Haggard, 2005) is famous as the passive method. Observers feel as if a rubber hand is their own hand. For inducing the illusion, the rubber hand is put next to their actual hand hidden from their view, and both the rubber hand and their hand were stroked by a brush at the same time. The visible rubber hand stroked by the brush is perceived as their own hand. In the active method, observers feel as if an avatar reflected in the mirror is their own body when the avatar moves synchronously with the observers' movement (Gonzalez-Franco et al., 2010).

Several studies have reported that the illusory body owner-ship can be induced to various body shapes and colors. For example, the illusory ownership can be induced to elongated hands (Armel & Ramachandran, 2003; Kilteni, Normand, et al., 2012), six finger hands (Hoyet et al., 2016), large belly body (Normand et al., 2011), child body (Banakou et al., 2013), a very small body or large body (van der Hoort et al., 2011; van der Hoort & Ehrsson, 2016).

Illusion of ownership to transformed hands and arms

Arms and hands are important body parts because we often use them to interact with others and objects. Their tactile sensation is particularly sensitive and their motor control is very fine (WEINSTEIN & S., 1968). Thus, researchers were motivated to focus on the illusory ownership of hands and arms.

Armel & Ramachandran (2003) showed that the illusory body ownership can be induced to a rubber hand with a longer arm by stroking the observers' hand and the rubber hand at the same time using the subjective ratings of questionnaire and the skin conductance response (SCR) to a threat to the rubber hand.

Kilteni et al. (2012) showed that the illusory body ownership for the virtual long arm using the combination of active and passive methods. In their experiment, the virtual arm was presented through a head-mounted display (HMD), and it was elongated gradually. The virtual long arm was synchronized with the observers' movement. Moreover, observers kept touching a virtual table that was located at an actual table so that observers could experience a tactile sensation (touch) with the table. It enhanced illusory ownership of the virtual hand. Their results suggest that illusory body ownership occurred up to three times of the observers' actual arm length. To sum up, illusory body ownership can be induced in both cases that the arm is long from the outset (Armel & Ramachandran, 2003) and that the arm is gradually elongated (Kilteni, Normand, et al., 2012).

Metamorphosis hand (Ogawa et al., 2016) is a work where humans play a virtual piano with a dynamically transforming computer graphics hand. A sensor (Leap motion) detected the observer's hand and presented computer rendered graphics of a hand that was metamorphosed and synchronized with the observer's movement on the piano. They can play the piano even if the hand possesses ten fingers or if the fingers become elongated.

G. Levin et al has published art works called Augmented Hand Series (Levin et al., 2014). This work transforms the image of the observer's hand using a camera in real time, and there are various types of the transformation such as increasing and decreasing the number of fingers, and attaching a small hand to a fingertip.

These studies tell us that we can have an illusory ownership of a virtual hand and arm and it can be transformed. Even in the field of art, transformation of the hand and arm is getting popular. We aimed to investigate if we can have an illusory ownership to an elongated arm using the "invisible body" paradigm, that is described in the following section.

Illusory ownership to invisible body

It is reported that the illusory body ownership could be induced to an invisible body using active method or passive method (Guterstam et al., 2013, 2015; Kondo et al., 2018; van der Hoort & Ehrsson, 2016). In the passive method, illusory body ownership can be induced to an empty space by stroking an observer's body hidden from view and in an empty visual space at the same time (Guterstam et al., 2013, 2015; van der Hoort & Ehrsson, 2016). Illusory ownership is also induced to smaller and larger invisible bodies (van der Hoort & Ehrsson, 2016).

Illusory ownership of an invisible body can be induced by synchronous movement of just the hands and feet, and observers perceive the whole body by complementing between hands and feet (Kondo et al., 2018). This active method is more freely able to move the body than the passive method. The illusory body ownership is stronger in the active method than the passive method (Kokkinara & Slater, 2014).

Purpose

We aimed to investigate whether we can have an illusory ownership to the invisible body with an elongated arm by presenting only hands and feet with modifying the position of the hands. We employed a task of proprioceptive-pointing with the distant hand and measured body sway as potential measurements in addition to the subjective ratings using a standard questionnaire.

In Experiment 3-1, we measured illusory body ownership of a visible whole body with a long arm using the subjective ratings, and measured body sway after experiencing illusory body ownership. We hypothesized that illusory body ownership is induced to the long-arm body when the hands and feet moved synchronously with the subject's movements, and their body tilts toward the normal arm to maintain body posture. In Experiment 3-2, we investigated whether the illusory body ownership can be induced to the invisible long arm body by presenting only hands and feet using the subjective ratings. We measured proprioceptive pointing of the hand of elongated arm. In Experiment 3-3, to see the learning process of the elongated-arm body, we investigated the illusory body ownership for the invisible long arm body through measuring reaching behaviors and body sway in time series as well as the subjective ratings.

5.2 Experiment 3-1

5.2.1 Methods

Participants

Eight volunteers (all male, mean age 22.125 years old ± 2.23 standard deviation (SD), mean height 168.43cm±4.83SD, all right-handed) participated in Experiment 3-1. They had healthy vision and physical ability. All participants gave written informed consent before the experiment. All of the experiments were approved by the Ethical Committee for Human-Subject Research at Toyohashi University of Technology, and all experiments were performed in accordance with the committee's guidelines and regulations.

Apparatus

A computer (OS: Windows 10, RAM: 16.0GB, CPU: Intel Core i5-6400, GPU: GeForce GTX 1080) controlled a head-mounted display (Oculus Rift DK2, each eye 960x1080 pixel, 90 x 110 deg, refresh rate 75 Hz). A motion capture system (Microsoft Kinect v2, Sampling rate 30 Hz) acquired participants' movements and imported the data to the computer. The delay was within 80 ms and the measurement error was within 10 cm. A force plate (NEC Medical Systems EB1101) acquired the participants' center of gravity and sent the data to the computer via Arduino (sampling rate 75 Hz).

Stimuli and Conditions

We presented a white full-body avatar from the first-person perspective and a virtual room created by Unity. The length of the arm of the avatar was one of three types: standard (78 cm), a longer left arm (128 cm), and a longer right arm (128 cm). In long arm conditions, both upper and lower arms were stretched 25 cm while the elbow joint bent at the same angle as participants. The avatar was originally

195-cm tall, and fitted (shortened) to the participants' actual height while maintaining its aspect ratio. The avatar moved synchronously (or asynchronously) with participants’ movements captured by Kinect. In the asynchronous condition, the ava-tar moved based on pre-recorded motion data. A mirror reflected the avatar in front of the avatar/participant (Figure 14).

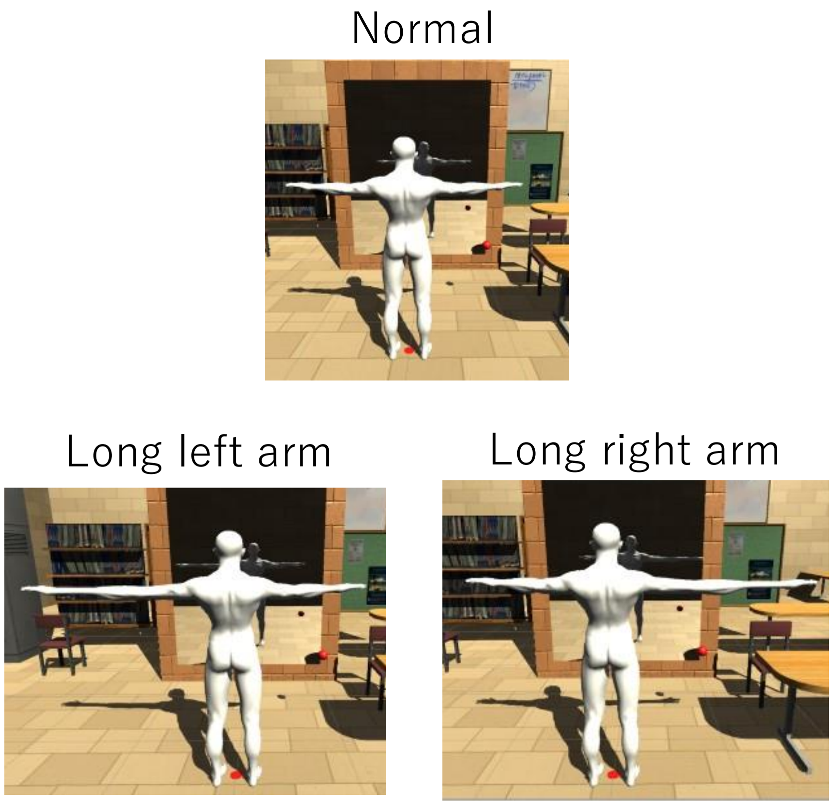


Figure 14: White full-body avatar. These images were from the third-person view as schematic. However, actually participants viewed the stimuli from the first-person view of the avatar in front of a mirror.

Procedure

Participants wearing the HMD stood at the center of the force plate located 2.75 m away from Kinect. They observed stimuli through the HMD with both eyes. The reaching phase (5 min) was followed by the posture phase (1 min). They observed a whole-body avatar from the first-person view and a red ball, and were asked to reach for the ball. We did not ask them to use either right or left hand, nor to do it as quickly as possible. Balls were made to appear randomly in the range of 60 cm (right: 30 cm, left: 30 cm) from the viewpoint, 1.3-1.6 m height from the floor, and 50-60 cm ahead. Another ball appeared 2s after reaching until the end of phase (5 min). Then, the screen of HMD was blacked out and they stood naturally with their arms by their side for 1 min while their center of gravity was measured. Finally, they were asked to rate eight items in 7-level Likert scale -3 (not feeling at all) to

3 (very strongly felt).

1. It felt as if the white body I saw when looking down was my body. 2. It felt as if the white body in the mirror was my body. 3. It felt as if my right arm became longer. 4. It felt as if my left arm became longer. 5. It felt like the movement of the white body was my movement. 6. It felt like the movement of the white body was another's movement. 7. It felt like my body posture tilted more than usual. 8. It felt as if my body became a floor.

Each participant performed 12 trials in a random order of combinations of the three body conditions (standard, long left arm, long right arm), the two synchronization conditions (synchronous, asynchronous) and two repetitions.

5.2.2 Results

One participant was excluded from the analysis because he stopped the experiment due to leg pain.

Subjective Ratings

Two-way repeated measure analysis of variance (ANOVA) was performed for each question (Body: normal, long left, long right; Synchronicity: synchronous, asynchronous). The avatar was felt as their own body in the synchronous than the asynchronous condition irrespective of arm length (Figure 15; Main effect of synchronicity: Q1 $F(1,6)=16.11$, $p=.007$, $\eta p2=0.73$; Q2 $F(1,6)=17.77$, $p=.006$, $\eta p2=0.75$; No interaction or main effect of body). Own arm was felt as if it was elongated only when the corresponding avatar's arm was elongated and synchronously moved with the participant (Interaction: Q3 $F(2,12)=6.46$, $p=.012$, $\eta p2=0.52$; Q4 $F(2,12)=22.79$, $p=.0001$, $\eta p2=0.79$; Multiple comparisons with Shaffer's method: $ps<.05$). The participants felt as if the avatar was moved by their selves in the synchronous condition, and moved by another in the asynchronous condition, irrespective of arm length (Main effect of synchronicity: Q5 $F(1, 6) = 45.12$, $p = .0005$, $\eta p2 = 0.88$; Q6 $F(1, 6) = 58.71$, $p = .0003$, $\eta p2 = 0.91$; No interaction or main effect of body). They felt as if their posture did not tilt (stable) in the normal arm rather than the longer left/right arm conditions irrespective of synchronicity (Main effect of body: Q7 $F(2,12)=5.07$, $p=.0253$, $\eta p2=0.46$, though no significance in multiple comparisons; No interaction or main effect of synchronicity). Q8 was a control question to check participants attitude to the questionnaire, and the answers were valid (all were -3).

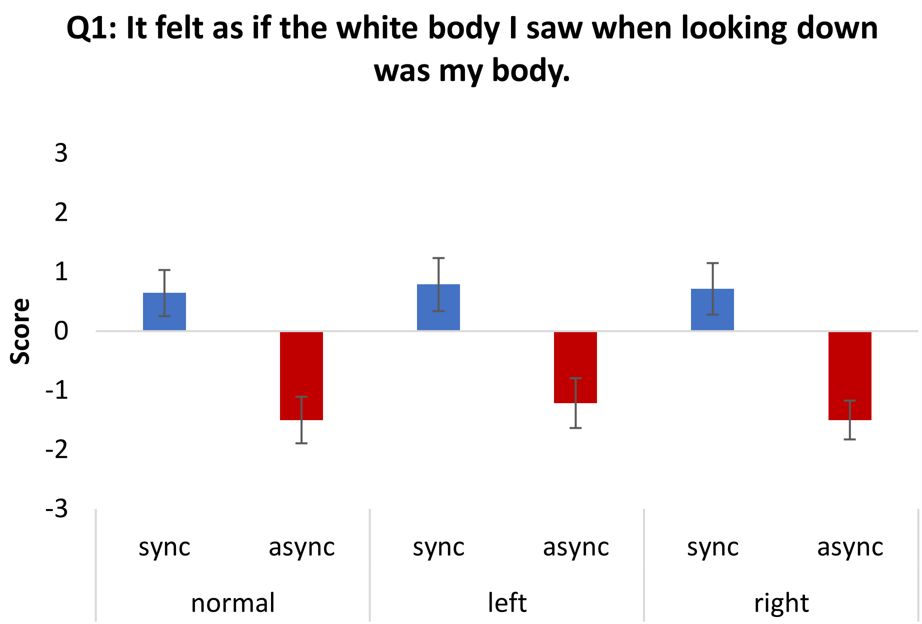


Figure 15: **Results of subjective ratings (Q1)**

Body Sway

Body sway was relatively larger in the first 10s, then getting stable. Thus, we extracted the average center of gravity of the first 10s after baseline processing using the final 10s data. Two-way repeated measures ANOVA showed that the center of gravity shifted rightward in the synchronous condition irrespective of the arm length (Figure 16; Main effect of synchronicity: $F(1,6)=8.32$, $p=.0279$, $\eta p2 = 0.58$; No interaction or main effect of body).

We also calculated total path length of 60s and applied Two-way ANOVA, but did not find any significant effect.

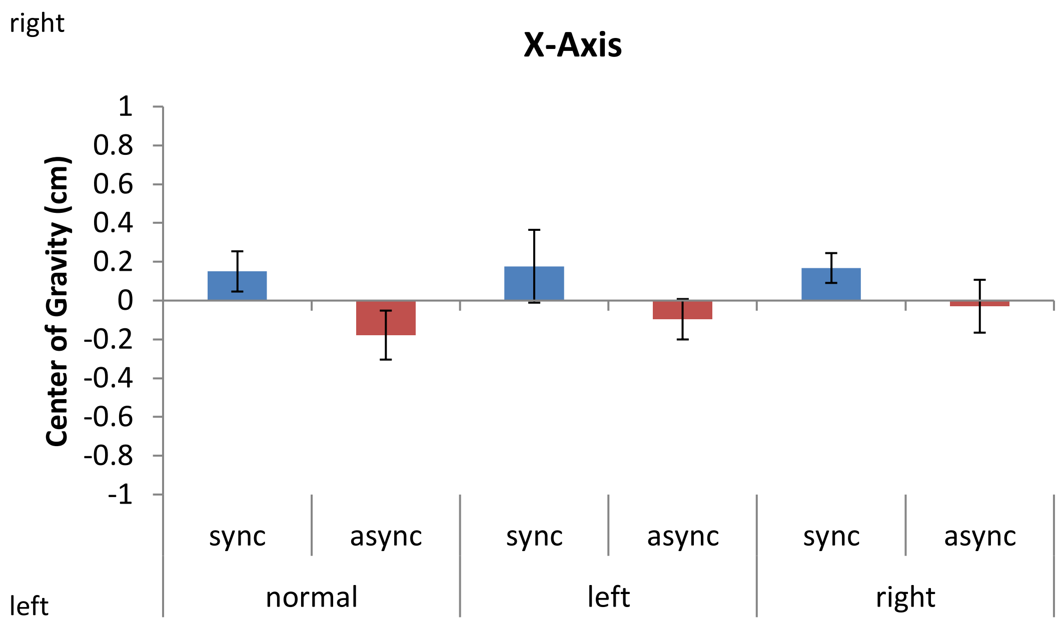


Figure 16: Center of gravity (x)

5.3 Experiment 3-2

5.3.1 Methods

We investigated whether the illusory body ownership could be induced to the invisible body complementing hands and feet with a longer arm by changing the position of the left or right glove.

Methods

Seven volunteers (all male, mean age 22.14 years old ± 1.574 SD, 173.79cm ± 6.864 SD, 6 right-handed, 1 left-handed) participated in Experiment 3-2. The apparatus was similar to Experiment 3-1 except that participants actually wore gloves and socks. The body condition and the synchronicity condition were similar to Experiment 3-1.

Participants stood 2.75 m away from Kinect, and observed the white gloves and socks in HMD from the first-person view (Figure 17). They performed the reaching task similar to Experiment 3-1 for 10 min (learning block). Then, the gloves and socks disappeared, and a red ball was presented in the virtual room after 10s of darkness. Participants were asked to point to the ball with their hand. Since there was no visually corresponding hands or gloves, they must point at it by using only proprioception.

The ball was presented at 50, 52, 54, or 56 cm ahead of the participant in a random order. Participants were asked to reach it by using both the left and right hand for each one. Thus, eight pointings were per-formed at a trial.

At the end of each trial, participants rated the 9-item questionnaire in 7 levels.

1. It felt as if the invisible body on the socks I saw when looking down was my body. 2. It felt as if the invisible body between the socks and gloves in the mirror was my body. 3. It felt as if my right arm became longer. 4. It felt as if my left arm became longer. 5. It seemed as if there is a whole body between the socks and gloves in the mirror. 6. It felt like the movement of the white socks and gloves were my movement. 7. It felt like the movement of white socks and gloves was another’s movement. 8. It felt like my body posture tilted more than usual. 9. It felt as if my body became a floor.

Each participant performed a total of eight trials of a combination of two body conditions (normal same-length arms, left/right longer arm), two synchronicity conditions (synchronous, asynchronous) and two repetitions in random orders. Before and after the experiment, only the proprioceptive pointing task was performed as a control trial for calibration.

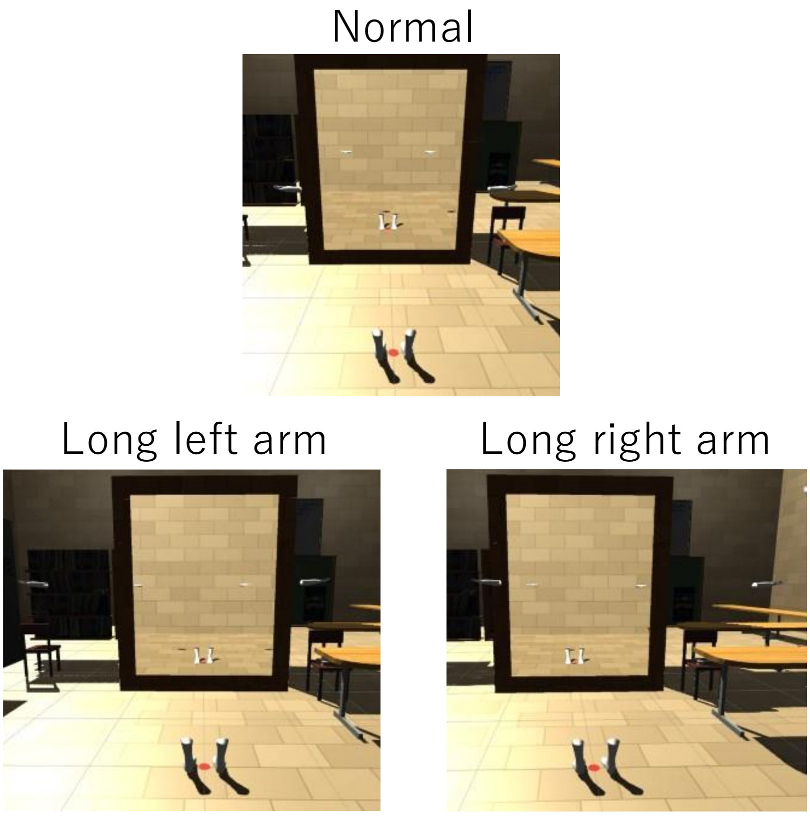


Figure 17: Invisible body of socks and gloves. These images were from the third-person view as schematic. However, actually participants viewed the stimuli from the first-person view in front of a mirror.

5.3.2 Results

One of the eight participants stopped the experiment owing to foot pain, and his data was excluded from the analysis.

Subjective Ratings

Two-way repeated measures ANOVA (Body: normal, long; Synchronicity: synchronous, asynchronous) was performed for each question. The invisible body between socks and gloves was felt as their own body in the synchronous than the asynchronous condition irrespective of arm length (Figure 18; Main effect of synchronicity: Q1 $F(1,6)=22.00$, $p=.0034$, $\eta_p^2 = 0.79$; Q2 $F(1,6)=22.57$, $p=.0032$, $\eta_p^2 = 0.79$; No interaction or main effect of body). Own arm was felt as if it was elongated only when the corresponding arm of the invisible body was elongated and synchronously moved with the participant (Interaction: Q3&Q4 $F(1,12)=21.46$, $p=.0036$, $\eta_p^2 = 0.78$). Whole body between the socks and gloves was perceived when the body with normal arms moved synchronously rather than asynchronously (Interaction: Q5 $F(1, 6)=3.93$, $p=.0948$, $\eta_p^2 = 0.40$; Simple effect of synchronicity in the normal body condition: $F(1,6)=8.00$, $p=.03$, $\eta_p^2 = .57$; No other simple effect). The participants felt as if the white socks and gloves were moved by their selves in the synchronous condition, and moved by others in the asynchronous condition, irrespective of arm length (Main effect of synchronicity: Q6 $F(1,6)=29.98$, $p = .0016$, $\eta_p^2 = 0.83$; Q7 ($F(1,6)=18.63$, $p=.005$, $\eta_p^2 = 0.76$; No interaction or main effect of body). They did not feel their posture tilt more than usual in any conditions (Q8: all were approximately 0). Q9 was a control question to check participants attitude to the questionnaire, and the answers were valid (all were -3).

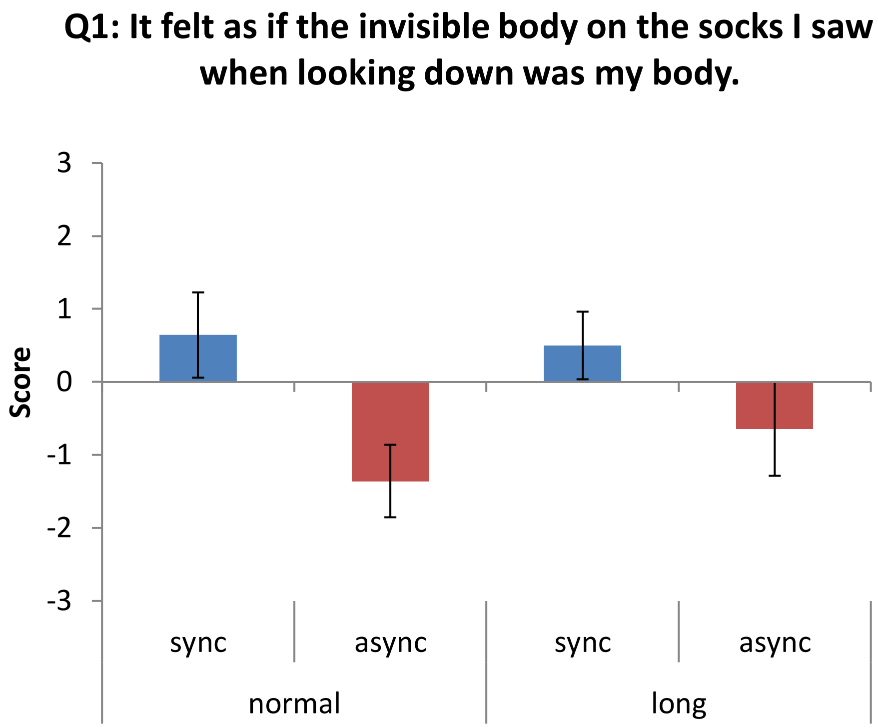


Figure 18: Results of subjective ratings (Q1)

Proprioceptive pointing bias

We predicted that participants point at a nearer point after experiencing the long arm than the normal or short arm. We separated the data into normal, long and short arm conditions; all data in the normal arm condition (normal arm condition), the data of the pointing hand that corresponded to the virtual longer/elongated arm (longer arm condition), and the data of the pointing hand that corresponded to the shorter arm in the long arm condition (short arm condition).

The difference between the hand position and the ball position was calculated for horizontal (x), vertical (y), and depth (z) directions. We calibrated the data by subtracting the average data of control trials. In the x axis, left was plus and right was minus, in the y-axis, up was plus and down was minus, and in the z-axis, near was plus and far was minus while the ball was at (0, 0, 0).

Two-way repeated measures ANOVA (Body: normal, long, short; Synchronicity: synchronous, asynchronous) was performed for each of x, y and z-axis. The pointed position was biased leftward in the long arm condition than the other conditions irrespective of synchronicity (

Figure 19; Main effect of body: $F(2,12)=7.0481$, $p=.0095$, $\eta_p^2 =.54$, No interaction or main effect of synchronicity). There was no significant effect in the y or z-axis.

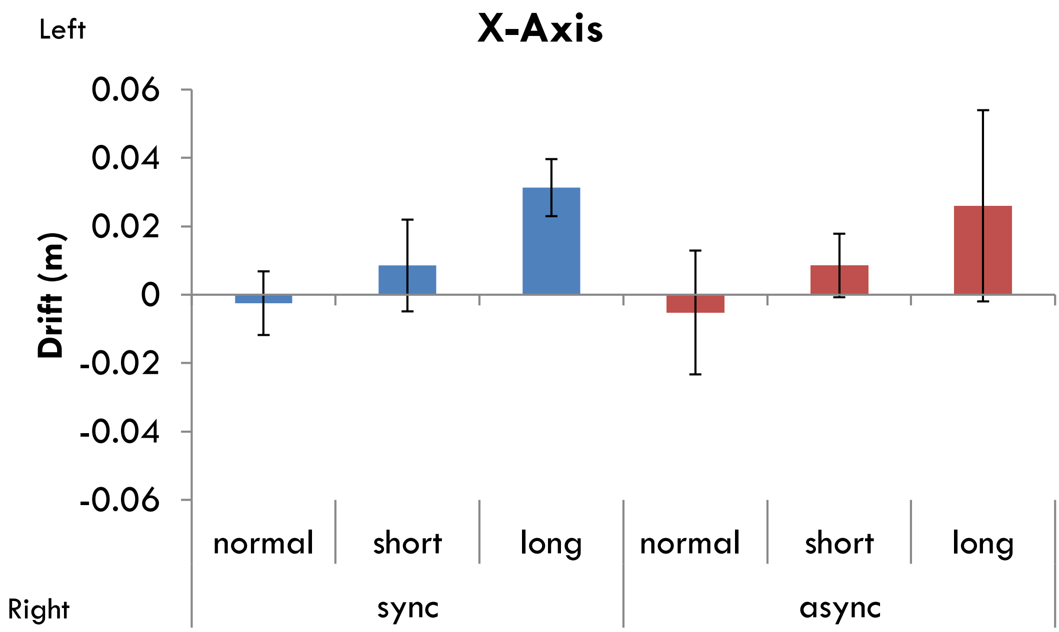


Figure 19: Results of proprioceptive pointing bias (x)

5.4 Experiment 3-3

5.4.1 Methods

We aimed to investigate the learning process of the novel elongated-arm body. We predicted that participants would use the longer arm more gradually than the shorter (normal) arm as they were getting to use the novel elongated-arm body continuously. In Experiment 3-3, we investigated changes in the frequency of use of the longer arm when participants reach their hand to touch balls in a 3D space.

Ten volunteers (all male, mean age 22 years old ± 1.633 SD, mean height 170.66 cm±7.85 SD, 6 right-handed, 1 left-handed) participated. The apparatus was the same as Experiment 3-1. The body condition was the same as Experiment 3-2 and only the synchronous movement was applied.

Participants observed stimuli through the HMD and stood on the center of the force plate. The experiment consisted of two type of blocks: a learning block and 10 test blocks. In the learning block, participants were asked to touch a red ball at their own pace for 10 min similarly to Experiment 3-2. In the test blocks, they were asked to touch the ball as quickly as possible. Another ball appeared 5s after the cur-rent ball was touched. Fifteen balls appeared in one test block for 1 min. The body sway was measured for 15s with-out vision after every test block. Participants kept both their arms open horizontally while measuring body sway. Posture was changed from Experiment 3-1 to increase body sway potentially affected by the elongated arm. One session consisted of one learning block and 10 test blocks. Each participant performed four sessions in a random order of combinations of the two body conditions (normal, long arm) and two repetitions. Long arm was either left or right in random orders. Participants were asked to rate the questionnaire at the end of each session. The questionnaire was the same as in Experiment 3-1 and 3-2.

5.4.2 Results

One participant who fell off the force plate, and one who was continuously out of tracking with Kinect were excluded from the analysis.

Subjective Ratings

Wilcoxon signed-rank test was used for each question. The participants felt as if their own arm was elongated when the corresponding arm of the invisible body was elongated (Figure 20: z(1,7)=-2.54, p=.0078). There was no significant difference in the other questions.

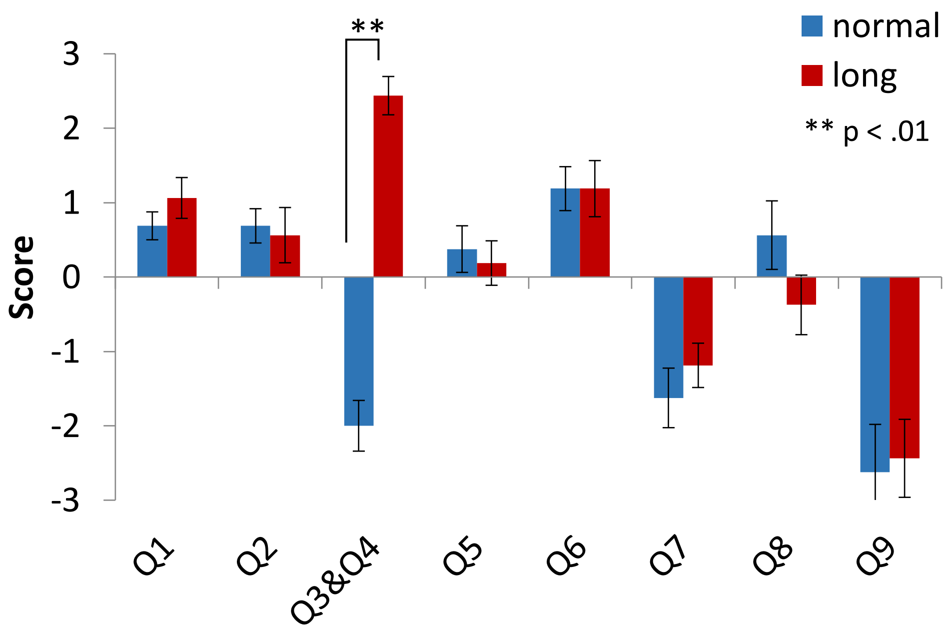


Figure 20: Results of subjective ratings

Reaching Task

The ratios of touching the ball with the right/left hand in the learning block and test blocks were calculated for each condition. The learning block was divided into four periods in time series. We calculated the total number of balls that participants touched in the learning block (10 min), and divided it into four as each period had the same number of balls. Thus, each period was approximately 2.5 min. The test blocks were 10 (1min each). Three participants who touched all balls with only one hand during all trials were excluded from the analysis. Thus, the data of five participants were analyzed in the reaching task.

The ratios of touching the ball with the right hand were plotted against time (serial blocks) in Figure 21. We performed two-way repeated measures ANOVA (Body: normal (left=right) arms, longer right arm, and longer left arm; Time series: 1st-4th periods). The right (left) hand was used more when the virtual right (left) arm was longer than the normal arms (Figure 21; Main effect of body F(2,8)=15.18, p=.002, η_p^2 =0.79; Multiple comparisons with Shaffer's method: *p*s<.05). The main effect of time series and the interaction were not significant, but marginal (Main effect of time F(3,12)=2.76, p=.0882, η_p^2 =0.41; Interaction F(6,24)=2.41, p=.0579, η_p^2 =0.38). The effect of the size of arm length gradually increased as time series up to 4th period (Simple effect of the body at 1st (F(2,8)=8.37, p=.0109, η_p^2 =0.68), 2nd (F(2,8)=8.81, p=.0095, η_p^2 =0.69, 3rd (F(2,8)=16.81, p=.0014, η_p^2 =0.81), 4th (F(2,8)=11.97, p=.0039, η_p^2 =0.75) periods).

Two-way repeated measures ANOVA (Body: normal, longer right, and longer left arm; Time series: 1st -10th block) was performed for the test blocks similarly to the previous analysis. Similarly to the learning block, the right (left) hand was used more when the virtual right (left) arm was longer than the normal arms (Main effect of body F(2,8)=13.85, p=.0025, η_p^2 =0.78; Multiple comparisons with Shaffer's method: *p*s<.05). However, the main effect of the time series and the interaction were never significant (Main effect of time F(9,36)=0.70, p=.71, η_p^2 =0.15; Interaction F(18,72)=1.30, p=.2168, η_p^2 =0.24).

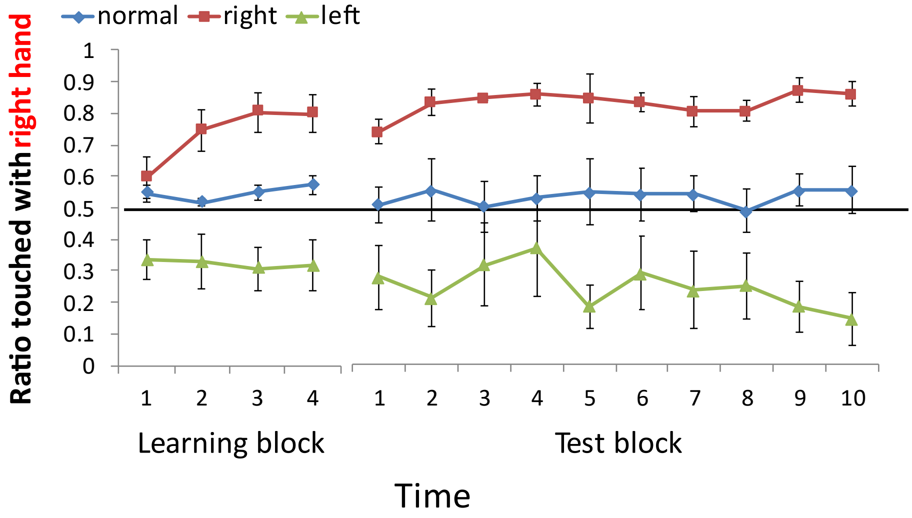


Figure 21: Time series data of ratio touched with right hand in learning block and test blocks

Body sway

Two-way repeated measures ANOVA (Body: normal, longer left, and longer right arms; Time series: 1st – 10th periods) was performed for the center of gravity averaged for 15s. We did not find any significant effects (Main effect of body F(2,14)=1.48, p=.2617, η_p^2 =0.17; Main effect of time F(9,63)=0.44, p=.9100, η_p^2 =0.06; Interaction F(18,72)=0.54, p=.9347, η_p^2 =0.07).

We performed the same analysis using the total-path length, and found that the total-path length gradually increased as the time series (Figure 22; Main effect of time F(9,63)=2.24, p=.0308, η_p^2 =0.24). However, the main effect of the time series and the interaction were never significant (Main effect of body F(2,14)=1.57, p=.2432, η_p^2 =0.18; Interaction F (18, 126) = 0.64, p = .8623, η_p^2 =0.08).

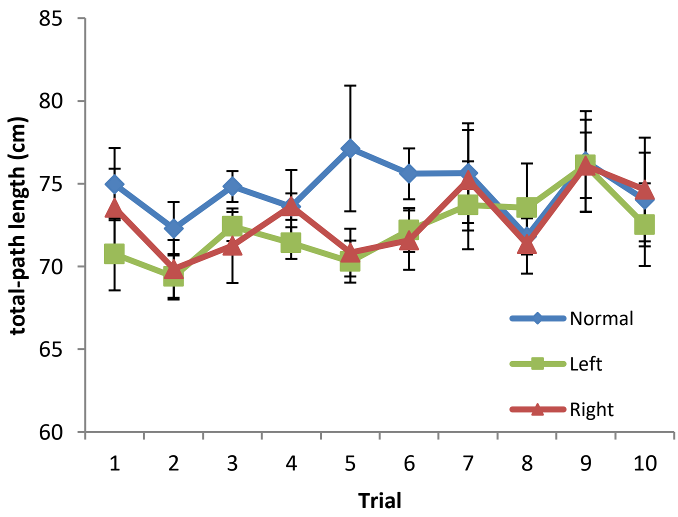


Figure 22: Time series data of total-path length

5.5 Discussion

We found that the illusory body ownership could be induced to the whole visible body that had a long left/right arm and a normal right/left arm when the avatar was synchronized with participants' movement (Experiment 3-1). The similar illusory body ownership to the body with a long arm was induced to an invisible body by synchronizing only gloves and socks with participants' movement (Experiment 3-1 and 3-2). The behaviors of using the long arm and the normal arm to touch an object changed gradually as learning the invisible body up to 7.5 min (Experiment 3-3). However, the results of postural sway and proprioceptive pointing were not consistent with our prediction (Experiment 3-1, 3-2, and 3-3).

Subjective ratings showed that participants felt as if their arm was elongated when the virtual long arm was synchronous with their movement, and the degree of ownership to the long-arm body was not significantly different from that to the normal-arm body (Experiment 3-1 and 3-2). These results suggest that we can acquire a new body with different-length arms similar to our physical body that usually has two same-length arms.

In the proprioceptive pointing task in Experiment 3-2, the participants' hand position drifted leftward in the long arm condition. This is not consistent with our prediction, and might be caused by some artifacts. We need to collect measurements using a more accurate motion capture system than Kinect to further investigate this issue.

In Experiment 3-3, we showed than reaching behaviors gradually changed as the learning advanced up to 7.5 min. After 10 min, the reaching behaviors was constant, and participants used the longer arm more than the shorter or normal arm. This would reflect the acquirement of the new transformed body. However, one may argue that the change of behaviors is just caused by the learning of a new tool like that when using a toy arm grabber. To investigate the relationship between body ownership and tool use, we need a further study to compare them in a future.

Illusory body ownership was induced to the long-arm whole body (Experiment 3-1) and long-arm invisible body with only hands and feet (Experiment 3-2 and 3-3). However, it is unclear whether the degree of body ownership was the same or different between the visible body and the invisible body. It is necessary to compare them in the future.

The center of gravity was biased rightward in the synchronous condition than the asynchronous condition regardless of the length of the arm (Experiment 3-1). It is inconsistent with our prediction, and might be caused by the participants' laterality bias that all participants were right-handed. The total-path length increased gradually in the test blocks (Experiment 3-3). We speculated that physical fatigue caused the unstable posture in the later blocks. Imaizumi et al. (2016) reports that participants who frequently use an artificial limb show less body sway while their artificial limb was attached than while it was excluded. Thus, stabilization of posture was expected as the learning advanced. However, our results did not support it. We speculate that the learning of the longer arm body was already completed in the learning block, so that there was no effect in the test blocks. There was no effect of body transformation on the postural sway in either Experiment 3-1 and 3-3. We predicted that participants who have a transformed body with a longer arm and a normal (shorter) arm would tilt toward the normal arm to maintain body posture. However, if the participants have already acquired the transformed body as their own body and felt ownership of it, the posture should be rather stabilized with referring an artificial-limb study (Imaizumi et al., 2016). In our experiments, the measurements of postural sway were conducted after learning to the transformed body for 5 min (Experiment 3-1) or 10 min (Experiment 3-3). Thus, we need to study the postural sway during learning the transformed body in a future study.

Chapter 6

Study IV: Re-association of Body Parts

Abstract

Illusory ownership can be induced in a virtual body by visuo-motor synchrony. Our aim was to test the possibility of a re-association of the right thumb with a virtual left arm and express the illusory body ownership of the re-associated arm through a synchronous or asynchronous movement of the body parts through action and vision. Participants felt that their right thumb was the virtual left arm more strongly in the synchronous condition than in the asynchronous one, and the feeling of ownership of the virtual arm was also stronger in the synchronous condition. We did not find a significant difference in the startle responses to a sudden knife appearance to the virtual arm between the two synchrony conditions, as there was no proprioceptive drift of the thumb. These results suggest that a re-association of the right thumb with the virtual left arm could be induced by visuo-motor synchronization; however, it may be weaker than the natural association.

6.1 Introduction

Body ownership can be induced not only in real or realistic bodies but also in fake or virtual bodies. Examples of such illusory body ownership include the rubber hand illusion (Botvinick & Cohen, 1998; Longo et al., 2008). In this illusion, body ownership was induced for a rubber hand by stroking a rubber hand and the observer's hand simultaneously. The observer felt that the rubber hand belonged to his own body. In this example, a visuo-tactile integration induced the illusory body ownership. In other cases, visuo-motor synchrony has been used to induce an illusory body ownership (Gonzalez-Franco et al., 2010; Sanchez-Vives et al., 2010). For example, when a virtual avatar's movement is synchronized with an observer's movement, the observer feels as if the avatar is his own body. The illusory body ownership is stronger in the visuo-motor synchrony method than in the passive visuo-tactile integration method (Kokkinara & Slater, 2014).

Induction of the rubber hand illusion needs many pre-conditions: the rubber hand and the observer's hand must be in the same posture (H Henrik Ehrsson et al., 2004; Manos Tsakiris & Haggard, 2005), and synchronous stimuli need to be provided for approximately 23 s (Kalckert & Ehrsson, 2017). The illusory ownership can also be induced with a bright light from a laser pointer without any touch stimulus, and the tactile and thermal sensations can be provided simultaneously (Durgin et al., 2007). The illusion has been expanded to two rubber hands (H. Henrik Ehrsson, 2009), and further to a third arm illusion, with a rubber hand and the visible own hands by visuo-tactile integration (Guterstam et al., 2011).

Illusory body ownership may be induced for a body in a different color to decrease implicit racial bias (Maister et al., 2013; Peck et al., 2013). Similarly, it may be induced as a child avatar for adult observers, then the illusion can modulate implicit attitudes and object-size perception (Banakou et al., 2013). The ownership can be induced to an empty space like an invisible body (Guterstam et al., 2013, 2015; Kondo et al., 2018; van der Hoort & Ehrsson, 2016). Thus, an illusory body ownership can be induced, even for a different age, race, or visibility, through visuo-tactile integration or visuo-motor synchrony. These studies focused only on body appearance, shape, posture, and position. The studies have hardly reported on the difference in correspondence between the actual and virtual/illusory body parts—the correspondence has been mostly of natural association. For example, only the right hands of the rubber and the observer are stroked by a brush simultaneously in the rubber hand illusion. In an active method, when observers move their right arm, the avatars' right arm moves.

On the other hand, Sasaki et al. (2017) created a four-arm interaction by adding two robot arms to a body and synchronized them with left and right foot movements. However, the sense of ownership has not been investigated with the robotic system. In Won et al.(2015), participants controlled avatar's arms using their legs in the virtual environment, and they could quickly learn to control the avatar.

As a related work, Petkova and Ehrsson (2009) indicated that an illusory touch can be induced in the right rubber hand when it is brushed simultaneously and synchronously with the observer's left hand. However, the illusion occurred only when a homologous pair of hands was brushed. In contrast, the rubber hand illusion was eliminated when an experimenter touched different fingers between participants' hand and the rubber hand (Kammers et al., 2009). Although these studies manipulated the correspondence between body parts, it has not been clarified whether the illusory body ownership can be induced by body-part re-association at different levels of the human body hierarchy.

In phantom limb studies, a reorganization of the primary somatosensory area (S1) has been reported (Ramachandran et al., 1992; Ramachandran & Altschuler, 2009; Yang et al., 1994). Patients feel touch in the amputated arm when the face is touched (Ramachandran et al., 1992). This result suggests that the map of S1 was rewritten, because there was no signal on the hand region owing to amputation. Therefore, the face region sensations seem to have spread to the hand region. In a study with magnetoencephalography, the hand area was activated when the face was touched (Yang et al., 1994), thus demonstrating that S1 remapping occurs for amputee patients.

In this study, we aimed to see whether a body-part re-association is induced by visuo-motor synchrony in healthy adults. We focused on the re-association of the real right thumb and a virtual left arm because although the right thumb and the left arm are at different levels of the human body hierarchy, the directions of their movements are similar.

6.2 Methods

Participants

Twenty volunteers participated in the experiment (all male and right-handed, mean 23.2 years old ± 2.1 standard deviation (SD)). They had healthy vision and exercise capacity. All participants gave written informed consent before the experiment. All the experiments were approved by the Ethical Committee for Human-Subject Research at Toyohashi University of Technology and were performed in accordance with this committee's guidelines and regulations. The participants were paid for the experiment.

Apparatus

The participants received stimuli through a head-mounted display (Oculus Rift DK2, 960 (width) x 1080 (height) pixel, 90 x 110 deg, refresh at 75 Hz). A motion capture system (Noitom Perception Neuron, 120 Hz) detected the observers' right thumb movement. A computer (OS: Windows 10, RAM: 16.0 GB, CPU: Intel(R) Core(TM) i5-6400 CPU @2.70 GHz (4 CPUs), GPU: GeForce GTX 1080) controlled the stimuli. BIOPAC Systems MP150 measured the observers' skin conductance response (SCR) for a threatening stimulus. Two electrodes (EL507) were attached to the distal phalanges of the middle and ring fingers of the participants' left hand. A wireless transmitter (BN-PPGED) was attached to the participants' left wrist and two lead wires (BN-EDA-LEAD2) were connected from the transmitter to the electrodes. The data were acquired by manufacturer's software AcqKnowledge 4.4 for Windows at a sample rate of 1000 Hz. The computer sent a trigger signal to an interface module (UIM 100c) connected to the MP150 via Arduino Uno. The trigger was set 10 seconds before the threatening stimulus, and the data were acquired for 20s. The participants' right hand was put on a wrist rest so that they could move the thumb freely with the hand facing down (Figure 23). They put their real left arm down at their side.

Figure 23: **Apparatus.**

Stimuli and conditions

We presented a virtual left arm that moved synchronously or asynchronously with the observers' right thumb action. The tip and joints of the thumb were associated with the joints of the arm in the synchronous condition; their positions were used to move the virtual arm (Figure 24). The tip of the right thumb was associated with the wrist of the virtual left arm, the proximal interphalangeal joint of the right thumb was associated with elbow joint of the virtual left arm, and the metacarpophalangeal joint of the right thumb was associated with the shoulder of the virtual left arm. We used an inverse kinetics library (Rootmotion Final IK) to generate the movement of the virtual arm from positions of the wrist and the elbow. The postures of the virtual hand and fingers were constant. The participants could see the entire virtual body from a first-person perspective, but they were instructed to observe the virtual left arm. The virtual right hand was not yoked with the actual right hand; it was actually out of sight. One out of two pre-recorded motions was selected randomly and presented in the asynchronous condition. A virtual knife appeared to threaten the participants for measuring SCR at the end of each trial (Figure 25).

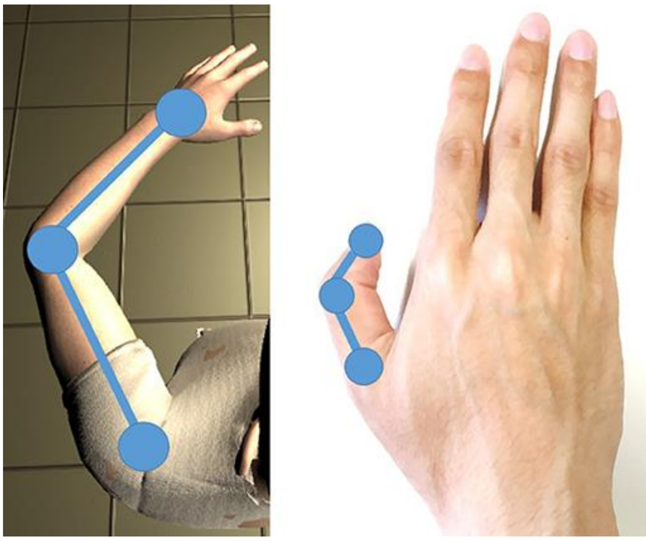


Figure 24: **Joint correspondence of the thumb and the virtual arm**

Figure 25: **A virtual left arm and a virtual knife.**

Procedure

Participants observed the virtual left arm while they moved their right thumb freely for 5 min (re-association). Then, a virtual knife appeared on the left arm for measuring SCR as a startle response. Under the table, the participants pointed with their left index finger where they felt the tip of their right thumb (self-localization task, Figure 26). During the localization task, they had the head-mounted display attached and were in the dark. Then, the participants were asked to answer a questionnaire about embodiment on a seven-level Likert scale from 1 (I did not feel it at all) to 7 (I felt it extremely strongly).

1. It felt as if my right thumb became the left arm that I saw.
2. It felt as if the left arm I saw was my left arm.
3. It felt as if my right thumb drifted towards the left arm that I saw.
4. It felt as if my right thumb became longer.
5. It felt as if my left arm increased to two.
6. It felt as if my right thumb became my left thumb.
7. It felt as if the movements of the left arm I saw were my own movements.
8. It felt as if the movements of the left arm I saw were another's movements.

Each participant performed four experimental trials (2 conditions x 2 repetitions) in SAAS (S: Synchronous condition, A: Asynchronous condition) and ASSA order. Two control trials were performed (no re-association period) before the first and after the final trial. In the control trials, the participants were asked to move their right thumb without the virtual body for 5 min, and then they perform the self-localization task (pointing the location of their right thumb with their left index finger without vision) without re-association period. This allowed to calibrate the self-localization measurements of each participant. We subtracted the mean of both control trials from the measured data of the test trials.

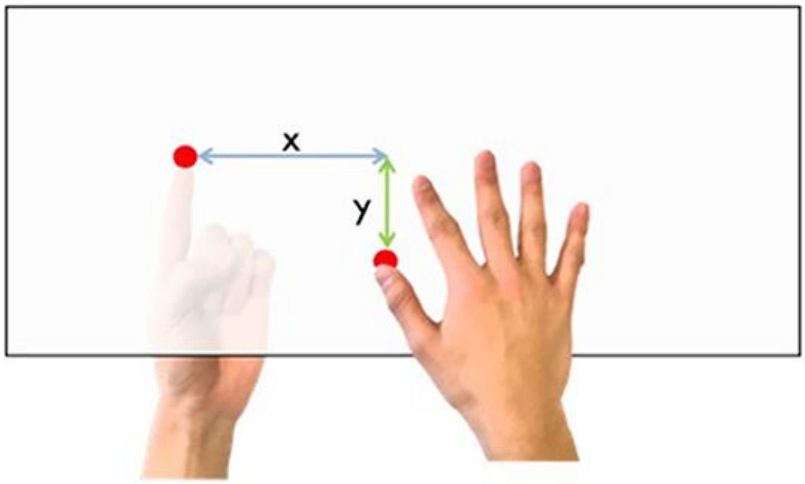


Figure 26: Self-localization task.

6.3 Results

Wilcoxon signed-rank test was used for a statistical test of the results of the questionnaire. The probability of superiority of dependent measurements (PS_{dep}) showed the effect size. Paired t-tests were applied to test the difference between the synchronous and asynchronous conditions using the SCR data from the startle response, the data of self-localization drift, and the length of the finger the participants perceived. Cohen's d showed the effect size. We hypothesized that the illusory re-associated body ownership of the virtual left arm should occur more in the synchronous condition than in the asynchronous one.

Questionnaire

The results of the questionnaire are shown in Figure 27. Participants felt that their right thumb was the left arm (Q1) more strongly in the synchronous condition than in the asynchronous condition ($z(19) = 3.63$, $p < 0.01$, $PS_{dep} = 0.85$). They also felt that the virtual left arm was their left arm (Q2) more strongly in the synchronous condition ($z(19) = 2.16$, $p = 0.031$, $PS_{dep} = 0.70$). They felt that their right thumb drifted towards the left arm (Q3) more strongly in the synchronous condition than the asynchronous condition ($z(19) = 2.40$, $p = 0.014$, PSdep = 0.60). The feeling of their right thumb growing longer (Q4) was also more prevalent in the synchronous condition than in the asynchronous one ($z(19) = 2.78$, $p < 0.01$, $PS_{dep} = 0.60$). Furthermore, the participants felt the movement of their left arm as their own (Q7) more strongly in the synchronous condition ($z(19) = 3.84$, $p < 0.01$, $PS_{dep} = 0.95$).

By contrast, they felt the movements of their left arm as another's movements (Q8) more strongly in the asynchronous condition than in the synchronous condition ($z(19) = -3.93$; $p < 0.01$, $PS_{dep} = 1.00$). There was no significant difference in the other items (Q5: $z(19) = 0.56$, $p = 0.63$, $PS_{dep} = 0.35$; Q6: $z(19) = 1.33$, $p = 0.25$, $PS_{dep} = 0.3$). They did not feel the left arm increasing to two (two left arms), suggesting that the virtual left arm did not become the second left arm or the third arm (Q5). Additionally, the participants did not feel that the right thumb became the left thumb (Q6). Actually, Q6 was a control question to check possible participants' random (unreliable) responses.

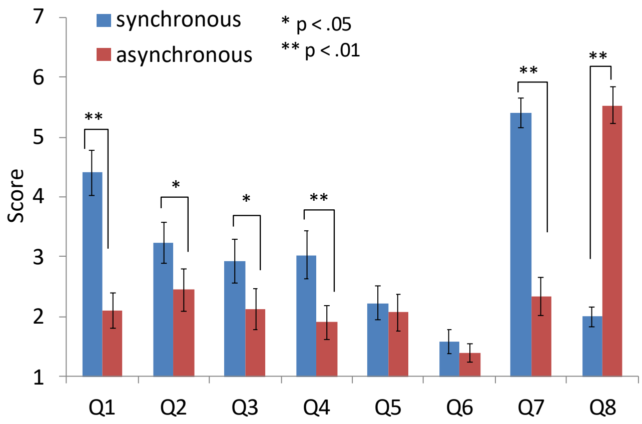


Figure 27: **Results of the questionnaire. The error bars indicate standard errors (SE). *, ** indicate statistical significance at the 0.05 (*p* < 0.05) and 0.01 (*p* < 0.01) levels with Wilcoxon signed-rank test, respectively.**

3.2 Startle response

The amplitude of SCR was calculated as the difference between the maximum and minimum level of skin conductance in the period of 0–5s after the knife appearance. It was based on previous studies (Petkova and Ehrsson, 2008; Guterstam et al., 2011, 2013, 2015; Petkova et al., 2011; Guterstam and Ehrsson, 2012). We did not find a significant difference in SCRs between the synchronous and asynchronous conditions (Figure 28, $t(19) = 0.62$, $p = 0.54$, $d = 0.09$).

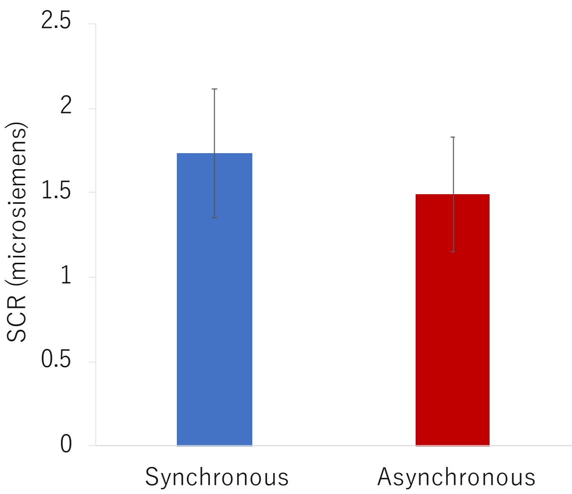


Figure 28: **Result of startle response (mean). The error bars indicate SE.**

3.3 Self-localization task

We hypothesized that if the observers felt that the right thumb became the left arm, then the proprioceptive location of the right thumb would drift toward the left arm, and the thumb would be perceived as being longer than its actual length. We defined the position in the *x* (horizontal) direction as the self-localization drift and the position in *y* (vertical) direction as the length of the finger perceived by them. The average of the control trials was subtracted from that of the experimental trials to control the participants' individual differences.

There was no significant difference between the synchronous and asynchronous conditions for the self-localization drift (x) (Figure 29A, $t(19) = -0.39$, $p = 0.70$, $d = 0.10$) as well as for the length of the finger perceived (y) (Figure 29B, $t(19) = -1.37$, $p = 0.19$, $d = 0.27$).

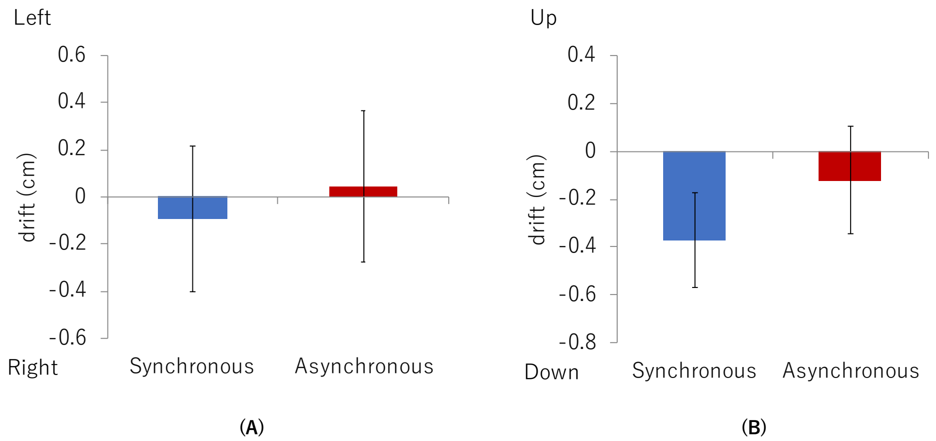


Figure 29: **Results of self-localization drift** (A) **and perceived length of the finger** (B)**.**

6.4 Discussion

We found that participants felt as if their own right thumb had become the left arm and illusory body ownership of the virtual left arm was induced more in the visuo-motor synchronous condition than in the asynchronous one (illusory re-associated ownership). The SCR for the threatening stimulus to the left arm did not show a significant difference between the synchronous and asynchronous conditions. The self-localization drift or the elongation of the right thumb by the illusory re-associated ownership of the left arm did not occur in the behavioral task.

The results of the questionnaire suggest that the synchrony of the real right thumb action and the movement of the virtual left arm could induce an illusory re-associated ownership of the left arm. However, the scores of re-association and ownership are not high (Q1: mean 4.4; Q2: mean 3.2 (1-to-7 Likert scale); both in the synchronous condition). The SCR (startle response) and the behavioral data of the self-localization task did not support our hypothesis. Thus, the illusory re-associated ownership can definitely be induced in the current method, but only weakly. We speculate that the natural association (such as the real left arm and the virtual left arm) conflicts with the virtual re-association, and it diminishes the effect of the visuo-motor synchrony. In previous studies of brain remapping by neural plasticity, patients have lost their natural associations with amputation (S. Aglioti et al., 1994; Salvatore Aglioti et al., 1997; Ramachandran et al., 1992; Yang et al., 1994) or brain damage (Clarke et al., 1996; Turton & Butler, 2001). It is an open question whether the re-association or dual association of body parts in the brain could be induced with the natural association intact. Our method might become a good tool for investigating such neural plasticity.

Kilteni et al. (2012) defined the sense of embodiment as the sense that emerges when one's own body's properties are processed as if they were the properties of one's own biological body, and they proposed that it comprises three subcomponents: the senses of self-location, agency, and body ownership. In our results, the subjective measures corresponding to these three subcomponents were significantly higher in the synchronous condition than in the asynchronous condition. From the questionnaire, we found significant differences between the synchronous and asynchronous conditions in terms of feelings of illusory body ownership, body-part re-association, the finger's subjective drift and elongation, and a sense of agency, although we did not observe differences in terms of SCR or self-localization tasks. On the other hand, Blanke and Metzinger (2009) proposed the minimal phenomenal selfhood (MPS), which is related to the concept of embodiment and the conscious experience of being a self; it is also characterized by the ownership of a whole body, self-location, and the first-person perspective. In contrast to MPS, our re-association body ownership is limited to body-part ownership, and hardly disturbs MPS in terms of global body ownership (especially of the trunk and head), global self-location, and the first-person perspective.

However, participants' responses on body ownership might be affected by the perceived sense of agency. The sense of body ownership and the sense of agency mutually strengthen each other unless the experimental method prevents their concomitant emergence (Kalckert and Ehrsson, 2012; Braun et al., 2018); Zopf et al. (2018) demonstrated that the motion congruency of the participant's hand and an object (sphere) increased the sense of ownership as well as the sense of agency. In the present study, the participants moved their right thumb voluntarily and the virtual left arm moved congruently so that the sense of ownership could not be dissociated from the sense of agency and might be enhanced by the voluntary motion congruency.

The scores from the questionnaire of illusory body ownership (like "I felt as if the rubber hand was my hand") for the visuo-motor rubber hand illusion are usually around 2 (-3 to +3 Likert scale) in previous studies (e.g., Kalckert and Ehrsson, 2014a; 2014b; 2017). Thus, our score (4.4 in 1-to-7 Likert scale) is much lower than that of natural association in the previous studies, although there is a significant difference between the synchronous and asynchronous conditions. This is a limitation of our study that should be addressed in the future. We would like to add tactile stimuli to the re-association setup to increase the sense of body ownership in a future study.

In the present study, participants moved their right thumb freely and observed the virtual left arm for 5 min in the experiment, similar to previous studies. For example, the studies on the illusory ownership of a hand (Sanchez-Vives et al., 2010) and a full-body (Gonzalez-Franco et al., 2010) exposed participants to stimuli for 3 min, whereas the study of the rubber hand illusion on the contralateral hand had 5 min as the exposure time (Petkova & Ehrsson, 2009). However, a longer exposure time might improve the illusory ownership of the re-associated body parts.

In heautoscopy, patients often experience two different bodies at two distinct spatial locations (Brugger, et al., 2006). However, out-of-body illusion studies have shown that body ownership cannot be induced with two full bodies of the physical body and the illusory body simultaneously (H. H. Ehrsson, 2007; Guterstam & Ehrsson, 2012). In an experiment, a participant observed video camera images of his or her back through an HMD, and illusory body ownership was induced in a space in front of a camera by touching simultaneously the participant's actual chest and a space in front of the camera. Additionally, the body ownership of their actual body decreased (Guterstam & Ehrsson, 2012). On the contrary, when the participants observed two fake hands (two right rubber hands (H. Henrik Ehrsson, 2009) or a right rubber hand and observer's right hand in sight (Guterstam et al., 2011), they assumed an illusory ownership of the two hands by visuo-tactile stimulation. For full-body illusion, we have self-identification with two virtual bodies or two physical (video-image) bodies when two virtual bodies are presented side by side in front of us and their backs as well as our physical back are stroked synchronously (Heydrich, et al., 2013). Hence, illusory ownership can be induced in two similar fake body parts and two similar virtual/pictorial full bodies. These suggest that there is a limitation or rule of illusory body change or editing. Our aim was to induce re-association of different body parts at different hierarchies, such as the finger and the arm. We speculate that an analogous structure and movement are necessary for the re-association to elicit the appropriate sense of agency, and hence contribute to the illusory ownership. Therefore, the joints of the thumb were mapped to the joints of the arm, which can be done because the structure and movement between the finger and the arm are similar. Additionally, we used both the right thumb and the virtual left arm (contralateral combination) in a hand-face-down posture and set their motion directions similarly. However, the question is still open as to how much two body parts must be analogous for re-association. It must be further investigated in a future study.

The concept of re-association of body parts may contribute to developing functional prostheses. Body-powered prostheses are more durable and require less training, but their appearance attracts attention and their functions are limited; myoelectric prostheses are more expensive and require more training, but their appearance is natural and their functions can be improved by signal processing of EMG and training (Antfolk et al., 2013; Carey, et al., 2015). Based on our study, we propose a modified system of body-powered prosthesis with electrical power controlled by body movements. If an upper-limb prosthesis is controlled by a different body part such as the finger of an undamaged hand, people can use it with less training and control it more naturally than conventional prostheses. In the present experiment with healthy participants, the sense of the actual left arm might be conflicted with the illusory ownership of the virtual left arm. For amputees, this conflict is irrelevant, and we speculate that learning will require less time and body ownership will occur more for them than for the healthy participants. This speculation is partly supported by the following neurological findings in amputee patients, as discussed in previous literature. Reorganization of the primary somatosensory area occurs in phantom limb patients (Ramachandran et al., 1992; Ramachandran & Altschuler, 2009; Yang et al., 1994). The use of a myoelectric prosthesis prevents cortical reorganization and phantom limb pain (M. Lotze et al., 1999), and the upper limb amputees exhibit significantly higher activation in the contralateral primary motor and somatosensory cortices while imagining moving the phantom hand, compared with the imagination of hand movements in the healthy participants (Martin Lotze et al., 2001). The rubber hand illusion can be induced in upper limb amputees and is associated with activity in the premotor and the intraparietal cortices (Schmalzl et al., 2014). These suggest that the cortical area corresponding to the amputated limb has the potential to control and sense the re-associated body part if it represents the amputated body part. Thus, it is important to further study the sense of body ownership and agency of re-associated body parts for potential future application to prostheses.

Chapter 7

General Discussion

7.1 Summary of Results

Study I: Dynamic invisible body illusion

We tested whether body ownership could be induced to an invisible body using virtual socks and gloves synchronized with a participant's movement. We evaluated body ownership by subjective ratings and the self-localization task. We found that in the body ownership induced by only socks and gloves, observers perceived a complete body between socks and gloves, and the proprioceptive self-localization drift toward the invisible body was similar to the one observed in the full-body ownership illusion (Lenggenhager et al., 2007).

Study II: Scrambled body illusion

In this study, we developed techniques to investigate the scrambled body and compared body part ownership and the FBI. We found that participants felt as if the space between the gloves and socks was their bodies only when the normal layout stimuli were synchronous with their movements both in the third- and first-person perspective (Experiment 2-1 Q1, Experiment 2-2 Q1, Q2: FBI). They felt as if the gloves or socks were part of their bodies in both body conditions (Experiment 2-1 Q2, Q3; Experiment 2-2 Q3, Q4, Q5, Q6: body part ownership), and the feeling was stronger in the normal layout condition than in the scrambled body condition. The invisible whole body was more likely to be perceived by interpolating the hands and feet when the body parts were normally presented than when they were scrambled, and the stimuli were more synchronous than asynchronous with the participants' actions (Experiment 2-1 Q4: Experiment 2-2 Q7, Q8: invisible body). We did not find a self-localization drift in the questionnaire (Experiment 2-1 Q5) or the behavioral task. We did not find significant SCR differences between any conditions by a threatening event in either Experiment 2-2 or 2-3.

Study III: Invisible long arm illusion

We found that the illusory body ownership could be induced to the whole visible body that had a long left/right arm and a normal right/left arm when the avatar was synchronized with the participants' movement (Experiment 3-1). The similar illusory body ownership to the body with a long arm was induced to an invisible body by synchronizing only gloves and socks with participants' movement (Experiment 3-2). The behaviors of using the long arm and the normal arm to touch an object changed gradually as learning the invisible body up to 7.5 min (Experiment 3-3). However, the results of postural sway and proprioceptive pointing were not consistent with our prediction (Experiment 3-1, 3-2, and 3-3).

Study IV: Re-association of body parts

We found that participants felt as if their right thumb had become the left arm and illusory body ownership of the virtual left arm was induced more in the visual-motor synchronous condition than in the asynchronous one (illusory re-associated ownership). The SCR for the threatening stimulus to the left arm did not show a significant difference between the synchronous and asynchronous conditions. The self-localization drift or the elongation of the right thumb by the illusory re-associated ownership of the left arm did not occur in the behavioral task.

7.2 Minimal condition to induce the illusory body ownership by visual-motor method

Static invisible body studies indicated the minimal condition in BPO and FBI by the visual-tactile synchronization (Guterstam et al., 2013, 2015), and our studies investigated the minimal condition by the visual-motor method (Figure 30). **Study I** and **III** investigated the minimal condition in the FBI, **Study IV** investigated the minimal condition in the BPO, and **Study II** investigated the difference between the FBI and BPO. We consider the minimal condition in each illusion based on our results.

Results of **Study I** showed that the FBI was induced by the synchronous movement of hands and feet. In **Study II**, the FBI was not induced to the scrambled body, only BPO was induced. This result indicates that the spatial relationship contributes to induce the FBI. From the result of **Study I** and **II**, a minimal condition in the FBI is considered to be a spatial relationship and synchronous movements of hands and feet. In **Study III**, the FBI was induced to the invisible body even when the position of the hand was shifted. The minimum condition on the FBI can be adapted to the elongated-limb body. This result implies a spatial relationship is important, not a distance between the participant’s hand and the virtual hand. In **Study IV**, we tested whether the BPO is induced by synchronous movement of different body parts (right thumb and left arm), and the illusion occurred. Our results suggest that the BPO can be induced by a similar movement between the participant's body and the virtual body regardless of laterality. To summarize a minimal condition to induce body ownership by the visual-motor method, the FBI needs a spatial relationship and the synchronous movement of the hands and feet, and the BPO needs a similar synchronous movement of the body part.

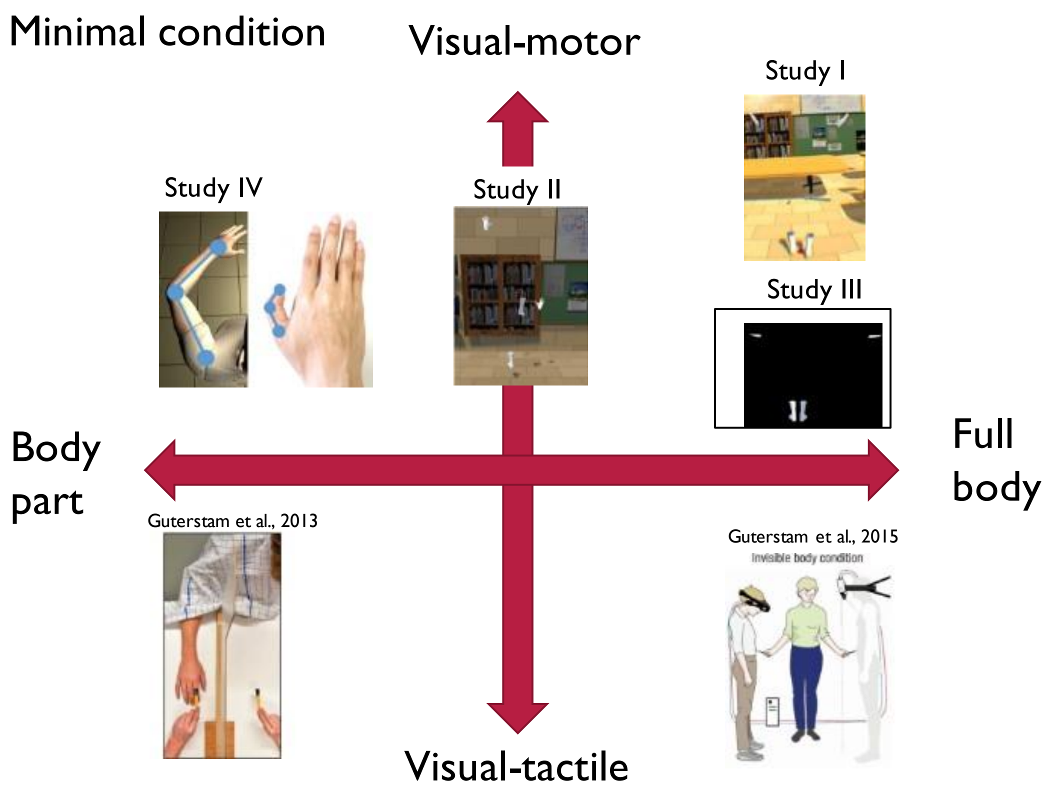


Figure 30: Relationships between our studies and invisible body studies

7.3 Static invisible body vs. Dynamic invisible body: semantic constraints and perception of the invisible body

Static Invisible body studies (M. D'Angelo et al., 2020; Mariano D'Angelo et al., 2017; Guterstam et al., 2013, 2015; van der Hoort & Ehrsson, 2016) suggest that semantic factors are not important for inducing illusory body ownership. In this illusion, objects that do not resemble the human body prevent body ownership. It is thought that the top-down process eliminates the possibility that the body is there. In the case of an active invisible body such as **Study I**, **II**, **III**, semantic constraints seem to be involved in the dynamic invisible body because visual stimuli that follow the participant's body movement are required. However, Giroux et al. (2019) showed that BPO is generated by moving some point lights in synchronization with the subject's motion, such as biological motion (Johansson, 1973) instead of arms. It is thought that the movement of the point light complements and perceives the invisible arm, which contributes to the occurrence of BPO. Therefore, if the whole body could be perceived by something other than the limbs, we can generate the FBI. **Study I** and **II** imply the importance of complemented full-body perception, where the full-body is perceived only under synchronous conditions where the FBI occurs. Thus, full-body perception would be important to the FBI, and in the static invisible body illusion, the synchronized stimulation of the participant's body and the empty space was the condition for the full-body perception (Guterstam et al., 2015). Our results suggest that the conditions for the perception of the full-body in the dynamic invisible body are synchronized movements of the hands and feet and spatial relationship, but other body parts or objects may also be able to induce the FBI.

7.4 Limitations

In this thesis, we investigated a minimal condition to induce illusory body ownership in visual-motor synchronization. Our results suggest a minimal condition to induce body ownership by the visual-motor method, the FBI needs a spatial relationship and the synchronous movement of the hands and feet, and the BPO needs a similar synchronous movement of the body part. However, whether hands and feet are minimal body condition in the FBI is still unclear, hands or feet might be enough to induce the FBI. Also, other body parts may contribute to the FBI such as a face. In **Study III**, the FBI was induced to the hand-shifted body. Long arm illusion (Kilteni, Normand, et al., 2012) showed that a virtual arm can be elonged up to three times. A limit of distance and spatial relationships is still unclear in the invisible long arm illusion.

In **Study I** and **II**, participants perceived a full-body between the gloves and socks when the gloves and socks moved synchronously with the participants' movement and are presented in a normal-layout. The perception of an invisible body occurred under synchronous conditions, possibly related to the FBI, but the mechanism is unknown. The layout of gloves and socks seems to be related because the invisible long arm illusion (**Study III**) and the scrambled body (**Study II**) does not induce the phenomenon.

As a minimal condition of the BPO, our results imply synchronous movement similar to the real body is important, laterality and body size are not important. However, no comparison between the remapped body and a normal body in **Study IV**. The body ownership of the remapped body may be weaker than the normal body one. Also, the visual presentation area of the body for BPO might be reduced such as fingertip only presentation.

7.5 To update the narrative self

The final goal of this thesis is to update the narrative self by accumulating the minimal self, and for this purpose, we investigated the minimal condition to induce the minimal self. How long does it take to update the minimal self and the narrative self? We discuss the learning process separately for the minimal self and the narrative self.

Study I suggest that the learning time for updating the minimal self is less than five minutes. Also, the Onset time of the RHI is 23s (Kalckert & Ehrsson, 2017) and the onset time of the FBI is 5s (Keenaghan et al., 2020). This suggests that the learning process for updating the minimal self is very short. On the other hand, the update of the narrative self is unclear, with only some results suggesting that the update of the minimal self temporarily affects the narrative self (Banakou et al., 2013; Rosenberg et al., 2013; Tacikowski et al., 2020). In many cases, the minimal self is updated by presenting a new body, and behavioral and cognitive tasks are performed after that, therefore it is not clear how long this effect lasts. If a changing body has a long-term effect on the narrative self, it will have some effect on daily life even after the experiment is over. First of all, it is necessary to investigate the relationship between the learning time for updating the minimal self and the duration of the effects on the narrative self for the update of the permanent narrative self.

We live in an age where we can change our bodies freely in cyberspace, and mechanical human augmentation is expected to become widespread with the development of robotic technology. Until now, it was natural to live in the same body from birth to death, but from now on, we will live in an age where we have multiple bodies and selves in a single life. These multiple bodies and multiple selves are not independent, but the narrative self connects the self before and after the change and creating a coherence there. This will maintain the coherence of the self before and after the change, and allow us to go on with our lives with the feeling that we have become whom we want to be.

Chapter 8

Conclusions

The general aim of this thesis was to investigate a minimal condition to induce illusory body ownership by the visual-motor synchronization. The aim of **Study I** was to test whether the illusory ownership of an invisible body could be induced by the method of visual-motor synchronicity and if the illusory invisible body could be experienced in front of the observer similar to the full-body ownership illusion. We found that in the body ownership induced by only socks and gloves, observers perceived a complete body between socks and gloves, and the proprioceptive self-localization drift toward the invisible body was similar to the one observed in the full-body ownership illusion. **Study II** aimed to develop a method to separate the FBI and BPO. Scrambled stimuli that disrupt the spatial relationship by randomizing the positions of body parts from the original/normal body part layout stimulus to induce only BPO. We found that participants felt as if the space between the gloves and socks was their bodies only when the normal layout stimuli were synchronous with their movements both in the third- and 1PP. They felt as if the gloves or socks were part of their bodies in both body conditions, and the feeling was stronger in the normal layout condition than in the scrambled body condition. **Study III** aimed to investigate whether we can have illusory ownership of the invisible body with an elongated arm by presenting only hands and feet with modifying the position of the hands. We found that the illusory body ownership could be induced to the whole visible body that had a long left/right arm and a normal right/left arm when the avatar was synchronized with the participants' movement (Experiment 3-1). Similar illusory body ownership to the body with a long arm was induced to an invisible body by synchronizing only gloves and socks with participants' movement (Experiment 3-1 and 3-2). The behaviors of using the long arm and the normal arm to touch an object changed gradually as learning the invisible body up to 7.5 min. **Study IV** aimed to see whether a body-part re-association is induced by visual-motor synchrony in healthy adults. We focused on the re-association of the real right thumb and a virtual left arm because although the right thumb and the left arm are at different laterality and size, the directions of their movements are similar. We found that participants felt as if their right thumb had become the left arm and illusory body ownership of the virtual left arm was induced more in the visual-motor synchronous condition than in the asynchronous one.

To summarize a minimal condition to induce body ownership by the visual-motor method, the FBI needs a spatial relationship and the synchronous movement of the hands and feet, and the BPO needs a similar synchronous movement of the body part.

Acknowledgments

I am grateful to my supervisor professor Michiteru Kitazaki for providing insightful comments and discussions. I would also like to express my gratitude to Professor Henrik Ehrsson for allowing me to work at Karolinska Institutet for six months.

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