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Requirements in Multisensory Feedback to Maintain Sense of Self-body

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Abstract

The term “self-like usability” refers to an ultimate usability sensation that is cognitively opaque and does not attract and demand our attention or awareness when we control something. The following questions then arise: What is self-like usability? How can it be scientifically defined and applied to engineering? Along with these questions, this dissertation addresses the requirements for human multisensory processing to maintain a sense of self, namely a sense of ownership and agency. The sense of ownership refers to the sensation that a part of the observable body is “my own.” The sense of agency corresponds to the sensation that “I” caused an action (for it). These two sensations have been discussed as the fundamental basis of the physical self in philosophy, psychology, and rehabilitation. Nowadays, even in engineering, these two sensations are investigated in the context of intuitive controllability or the feeling of control for mechanical systems, such as tele-operation robots, humanoids, and virtual reality techniques including virtual avatars and interactions between a virtual world and an operator.

Introducing the idea of ownership and agency to mechanical system design involves two main problems. One is how to assess ownership and agency. Traditional methods for assessing ownership and agency have mainly depended on questionnaires, resulting in a tendency for evaluation to be retrospective, qualitative, and language dependent. In contrast, for a simple mechanical system design based on human sensation and perception, one option to use the relationship between a physical property of stimulus and the psychological value evoked by it, called a psychometric function, as a design guideline. Thus, the classic agency/ownership measurement method is not suitable for the quantitative estimation of critical distances or time offsets across multisensory information modalities such as vision, proprioception, and touch, which are required for spatio-temporal design of mechanical systems.

The other problem is how to optimize multisensory feedback of action in a mechanical system. The human brain receives a great deal of sensory information in real-time and can distinguish whether the sensory information comes from the self. Namely, this online monitoring process can identify whether

sensory information comes from the environment or body itself. To elicit ownership and agency for manipulation of a mechanical system as though it is a part of the operator's body, it is necessary to know how to optimize the multisensory feedback of action in a manner that matches this online monitoring processing.

To highlight these problems, this dissertation focuses on two main topics. The first is a novel method of evaluating the critical spatial offset between a visual stimulus and human body part in 2D. The second is investigation of the requirements for visual features to maintain a sense of ownership and agency.

In the spatial offset method, the mirror illusion was combined with machine learning analysis to evaluate the critical spatial offset between visual and proprioceptive feedback in 2D space. Mirror illusion uses the mirrored visual feedback, which is an image of left hand reflected by a mirror, as the visual feedback of the obscured right hand. This mirrored visual feedback was often used as a tool for the treatment of removing phantom pain and recovering the motor function of paralyzed limbs in the field of rehabilitation. In the mirror illusion, a mirror image of the left hand visually captures the subjective position of the right hand, which is hidden by a mirror positioned along the midsagittal plane. To test this illusion, participants were required to respond when the mirrored left and hidden right hands were perceived to be at the same position while both hands were moved synchronously. A support vector machine analysis revealed that offsets of up to approximately 10 cm between the mirrored left and hidden right hand, in either height and depth, were compatible with maintenance of the mirror illusion. Questionnaire assessment confirmed that the participants felt ownership and agency for the mirrored left hand within this critical area. These results suggest that the proposed method can reveal the critical offset between visual and proprioceptive feedback required to maintain ownership and agency. Additionally, using this method, an investigation of temporally synchronized visual-proprioceptive-tactile (tri-modal) effects on the visual capture area, ownership, and agency was conducted for further understanding of multisensory processing. The results indicated that visual-proprioceptive synchronization is dominant for ownership and agency over visual-tactile synchronization, and that tri-modal

synchronization had no significant effect.

To investigate the visual features that maintain ownership and agency, an experiment on modified visual search for a self-controlled target was conducted. Related research reported that a self-controlled target is easily found by the operator but not by an observer, and that ease of searching the self-controlled object can be disrupted by adding an operational delay between the object and hand movement. The ease in finding a target can be used as a behavioral index of self-control, or of agency as a non-verbal, behavioral measurement. In the current study, the shapes of targets and distractors were modified to hand-like or scattered dot patterns. The task for the participants was to find the target reflecting their right hand movement and then respond to questions about ownership and agency for the target. Two types of hand movement were tested, waving their hands vigorously and clenching and unclenching their hands repeatedly. Behavioral results showed that accuracy and reaction time were dramatically altered by a delay of 300 ms between the movements of the two hands, but were not affected by the target's shape. The question results showed that ownership and agency elicited regardless of hand shape in the hand-waving condition, but only agency was elicited with hand-like dots in the clenching condition. These scores also decreased with a delay of 300 ms or more. These results suggest that the multisensory process of identifying "global" hand position plays a role in generating ownership, and the process of matching multisensory feedback plays a role in generating agency.

In conclusion, the present results revealed the requirement of the multisensory processing to maintain the self-like usability based on our representation of body movement acquired in the brain. This multisensory processing can tolerate spatio-temporal offsets between visual and proprioceptive feedback of movement. The critical spatial offset is approximately 10 cm. The critical temporal offset seems to be about 300 ms. In addition, the present results indicate that the appearance of the visual stimulus need not resemble the operator's hand itself. Altogether, the present results highlight not only the mechanical design for an intuitive control feeling but also the research to investigate brain process to elicit sense of self.

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1. Introduction

1.1 Background and motivation

This dissertation addresses the minimum requirements for multisensory information delivered to the human brain to generate an intuitive feeling of control, for not only the body itself but also for real-time control systems of the sort that have recently been developed.

Recent technology in mechanical engineering, control science, and informatics has advanced the development of real-time control systems, such as remote-controlled robots and virtual avatars in virtual reality (VR) system. For example, remote surgery systems provide an option to perform surgery via a mechanical system (Guthart & Salisbury, 2000). This type of system provides a real-time video of the surgical field, displaying manipulators, such as endoscopic forceps, that can be controlled by a surgeon. In the video, the manipulators can be observed as if surgeons are looking at their own hands from a first-person perspective. This type of a spatial relationship between a manipulator and an operator's perspective can also be implemented in VR systems, particularly systems using head-mounted displays (HMD) (Rolland & Hua, 2007). Through an HMD, the users of a VR system observe the virtual world in a first-person perspective and interact with virtual objects by moving controllers or their own bodies. Users receive sensory feedback from their movements via multiple senses, including vision, proprioception, and touch, and a part of this sensory feedback may come from a mechanical system such as an HMD.

As mentioned above, in a certain type of real-time control system, the operators moves his or her body as an input for the system and monitors the consequences via multiple senses, such as vision, proprioception, and touch. This process is quite similar to the way the human body controls itself. When one moves one's body, the brain monitors the consequences of movement via multiple senses. For example, when one reaches for an object, one can see the trajectory of hand movement and sense how the body moves based on signals from the body itself. When, for example, the hand touches a book, one can feel a sense of touching the object. These sensory signals of body movement are called multisensory, or visual, proprioceptive, and tactile feedback. Multisensory feedback may be provided to

the brain even when manipulating real-time control systems.

However, compared to controlling the human body itself, multisensory feedback during manipulation of mechanical systems can lack congruence with ordinary sensory feedback. For example, spatial information about the position of a manipulator from visual and proprioceptive feedback modalities can be discordant due to a spatial offset between the display and input devices. In addition, the visual feedback can be delayed relative to the proprioceptive feedback because of signal processing latency inside the system. Moreover, due to system constraints, the shape of a manipulator always differs to some degree from that of a human body part, resulting in further inconsistency between visual and proprioceptive feedback.

Given these differences between mechanical systems and the human body, is it possible to generate an improved user experience and an improved feeling of control of these systems? Specifically, is it possible to make control of a mechanical system feel as smooth and natural as control of the operator's own body?

To shed light on these problems, this dissertation focuses on how the human brain generates the sense of self for parts of the body. This aspect of the self has been explored for decades and is frequently discussed nowadays in the fields of philosophy, psychology, and neuroscience. Recently, a philosopher, Shaun Gallagher, proposed two fundamental components of the sense of self: ownership and agency (Gallagher, 2000). The sense of ownership refers to the sensation that the observable body is "my own." The sense of agency corresponds to the sensation that "I" cause an action. In Gallagher's model, these two sensations are elicited when sensory feedback from an action is congruent with sensory feedback predicted by a forward or internal model of action. Numerous empirical studies have supported this model but also reinforced the importance of multisensory feedback (Haggard, 2005 and 2009; Kalckert & Ehrsson, 2014; and Tsakiris, 2016).

The purpose of this dissertation was to reveal the requirements to keep the sense of ownership and agency with a manner which can be applicable to the design of usability in the real-time controlling system. In other words, it was investigated the requirement to keep the intuitive usability of real-time controlling

systems like one's "self-body". "Self-body" in this dissertation was defined as one's own body which can be controlled obeying one's will or intention. In this dissertation, the representation of self-body already acquired in the brain was focused. Namely, it was focused how the human recognize the one's own body itself. Thus, it was investigated the requirement to keep sense of ownership and agency over human body itself, at first.

If these requirements were obtained and applied to the design for sensory feedback in the real-time controlling system, our brain might recognize the sensory feedback from that system with the manner recognizing one's own body. This could enable the operator to feel as if the manipulator of the real-time controlling system were a part of one's own body, implying the possibility that the operator might control the system intuitively like their own body without learning.

1.2 Issues

To introduce the concepts of ownership and agency for use in the design of intuitive real-time control systems, let us begin by considering two practical issues.

One issue is the assessment method. Traditional assessment methods for ownership and agency depend on questionnaires; consequently, the assessment tends to be qualitative and retrospective. These features make this method unsuitable for use in mechanical design. In mechanical design, quantitative information about multisensory feedback is required. For example, in designing a real-time controlled system such as a remote-controlled robot, it is necessary to consider what the optimal spatial relationship between monitor and input device is and how much temporal latency between input and output is acceptable. In this type of system, the monitor can provide visual feedback on the operator's actions and the input device can provide tactile and proprioceptive feedback about the movements of the operator. To understand which factors determine the sense of ownership and agency, a quantitative method of evaluating the spatio-temporal properties of multisensory feedback is required.

The other issue is how to optimize the generation of multisensory information from the system and the operator. During manipulation of a mechanical system, the operator's voluntary body movement is used as system

input via an input device. This is a totally different situation from those that typically arise in empirical experiments on ownership and agency. In traditional experiments, the participant's free hand movement tends to be restricted due to complex experimental requirements. Thus, it is still unclear exactly what is required for multisensory feedback to maintain the sense of ownership and agency during free hand movement.

1.3 The approach in this work

To address these issues, three behavioral experiments were conducted to investigate requirements for multisensory action feedback to maintain the sense of hand ownership and agency during active hand movement. Experiment 1 involved quantitative estimation of the critical spatial offset between visual and proprioceptive feedback required to maintain the sense of ownership and agency. Experiment 2 was an investigation of the role of synchronized visual-proprioreceptive-tactile feedback in maintaining the sense of ownership and agency. Experiment 3 investigated the visual features that account for maintaining the sense of ownership and agency.

In experiment 1, a quantitative method for analyzing the relationship between the spatial properties of multisensory feedback and the sense of agency was proposed, and then the critical offset between visual and proprioceptive feedback was evaluated in 2D space. The estimation method was developed by combining psychophysical experiments with analysis using machine learning techniques. This combination enabled visualization of human behavior in multiple dimensions, such as height and depth, an approach that has been avoided in traditional psychophysics due to the complex experimental conditions it requires.

In experiment 2, using the newly developed method, the effect of visual-proprioreceptive-tactile congruence on the critical distance between visual and proprioceptive feedback needed to maintain the sense of ownership and agency was investigated. In daily life or in the operation of mechanical systems, tactile feedback is often delivered to the brain in addition to visual and proprioceptive feedback. For further investigation, the effect of visual-proprioreceptive-tactile congruence was focused on. If the human brain prefers stimulation patterns that

match those encountered in real life, tri-modal congruence would be expected to enhance ownership and agency.

Experiments 1 and 2 focused on the relationship between multisensory processing and ownership and agency. To introduce the idea of ownership and agency to the design for real-time control systems, it is necessary to take into account the differences in appearance between human body parts and the manipulators of a control system. In experiment 3, to address this appearance problem, the role of human-like appearance in generating a sense of ownership and agency was examined during viewing of a virtual object reflecting a participant's right-hand movement. If ownership and agency were elicited regardless of the appearance of the object, this would indicate that the appearance of the manipulator might not affect the sense of ownership and agency.

1.4 Organization of this thesis

This dissertation consists of six chapters. Chapter 2 provides reviews of papers related to the sense of ownership and agency in the fields of psychophysics, neuroscience, and engineering. Chapter 3 describes a new experimental method for assessing the critical spatial offset between visual and proprioceptive feedback. Chapter 4 reports on an investigation of the effect of synchronized tri-modal input on ownership and agency using the proposed method. Chapter 5 reports on an experiment examining the critical visual features of a controlled object required to maintain ownership and agency. Chapter 6 discusses the future of ownership and agency research, remaining issues, and limitations.

2. Literature review

2.1 Ownership and Agency

The existence of a sense of ownership and agency was originally proposed by a philosopher, Shaun Gallagher, in a discussion of “self” (Gallagher, 2000). The sense of ownership is the feeling that a body part is my own. The sense of agency is the feeling that a movement or action is self-caused. According to Gallagher’s model, these two sensations are generated when sensory feedback resulting from action matches with sensory feedback predicted by a forward model of the action. This monitoring system for self-action was considered as a fundamental process in identifying the “self”. In fact, this concept originally came from a neurocognitive model of schizophrenia, which is a brain disorder disrupting the sense of having and controlling one’s body (see Frith et al., 2000).

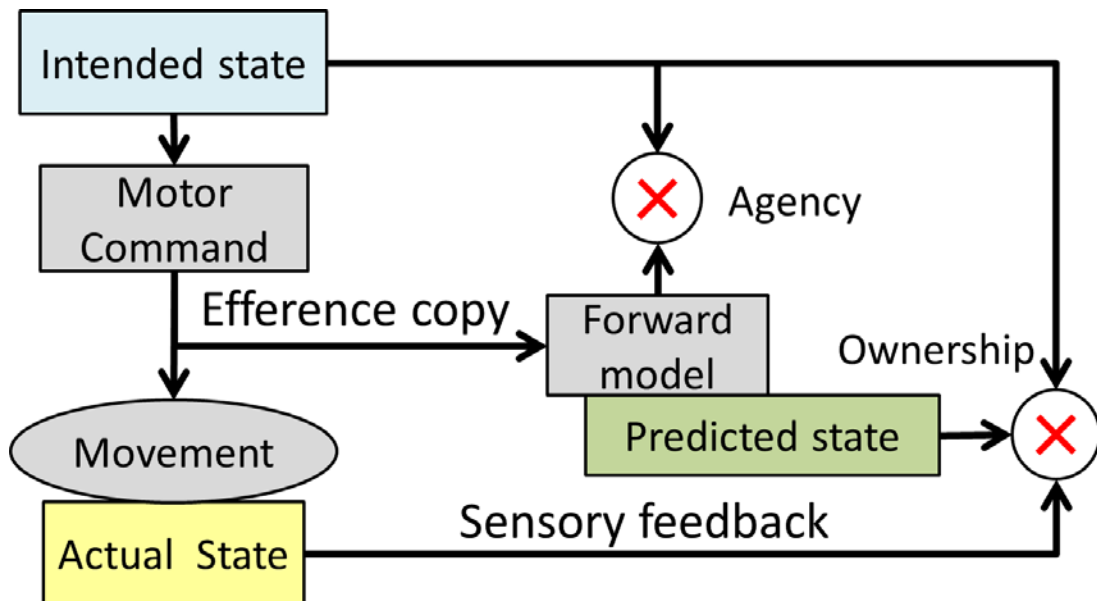


Figure 2-1 Forward and feedback comparators for ownership and agency. This image was modified from Gallagher (2000).

Empirical data in the fields of psychology and neuroscience support the existence of this fundamental sense of self. The “rubber hand illusion” is one of most famous phenomenon related to the sense of ownership (Botvinic et al., 1998, Tsakiris & Haggard, 2005, Rohde et al., 2011, Kalckert & Ehrsson, 2014). In this

illusion, the participant sees a rubber hand positioned in front of him or her while his or her actual hand (e.g., the right hand) is obscured. In this situation, synchronized stroking of the rubber hand and the obscured right hand with a paintbrush makes the participant perceive the rubber hand as a part of his or her body. A possible explanation of this illusion is that temporal synchrony of sensory information between vision and touch elicits illusory ownership over the rubber hand. In other words, matching of actual tactile information with predicted (or expected) tactile information elicits illusory ownership. This means that multisensory congruence can elicit a sense of ownership.

Using the rubber hand illusion, the visual or tactile factors required to generate a sense of ownership have been investigated. The original research on the rubber hand illusion reported that a spatial offset between the rubber hand and the obscured real hand decreases the sense of ownership (Botvinic & Cohen, 1998). Tsakiris & Haggard (2005) demonstrated that a temporal offset of the paintbrush stimulation between the rubber hand and obscured hand eliminated the sense of ownership. They also showed that anatomical congruence of visual feedback with proprioceptive information about body posture is required to keep ownership. Tsakiris et al. (2010) reported that it is necessary for the object to have a hand-like shape. However, the skin color of the rubber hand does not matter (Farmer et al., 2012). These studies generally support the hypothesis that congruent visual-tactile feedback can elicit a sense of ownership.

Although there have been many studies of the sense of ownership, investigation of the sense of agency has been more limited. The main reason is that voluntary body movements are required for investigation of agency. Kalckert & Ehrsson (2012) tried a modified version of the rubber hand illusion involving a voluntary movement condition. In their experiment, the index finger of the rubber hand was connected to the participant's right index finger by a rod. In this paradigm, the timing of finger movement (synchronous or asynchronous), mode of movement (active or passive), and position of the rubber hand (anatomically congruent or incongruent) were examined. They found that synchronization of the rubber hand and real hand elicited both ownership and agency; the mode of movement affected only the sense of agency; and the position of the rubber hand

played a role in ownership. To my knowledge, this is the first research using the rubber hand illusion paradigm to report that visual-proprioceptive synchrony affected ownership and agency.

Another method of investigating the sense of agency is to make use of a simple action such as a button press (Haggard et al., 2002, Farrer et al., 2013, Caspar et al., 2015 and 2016). In this method, the timing difference between a button press and a certain sensory event (e.g., a beep triggered by the button press) is controlled. The participant is asked to assess whether the sensory event was caused by the button press. Using this paradigm, Sato & Yasuda (2005) found that the sense of agency was reduced when a tone was unpredictable due to its timing variability, even if the tone was in fact caused by the participant's button press.

2.2 Explicit and implicit measurements

The traditional method of measurement of ownership and agency is based on questionnaires. Typical statements are "I felt as if the rubber hand was a part of my body," and, "I felt as if I could control the movement of the rubber hand." The former is used for ownership and the latter for agency. In most research related to ownership and agency, participants were required to rate their experience in terms of a given statement using a 7-point Likert rating, ranging from +3 (totally agree) to -3 (totally disagree). This approach directly evaluates ownership and agency based on the participant's subjective experience. Thus, this type of measurement is sometimes called explicit measurement.

However, the explicit measurement approach has some problems. Because the responses to the questions rely on the participant's experience and retrospective judgement, they can easily be biased by context and by instructions from the experimenter, resulting in large individual differences. Moreover, because the method of assessment evaluates the sense of ownership and agency qualitatively, reproducibility and objectivity are difficult to guarantee.

To avoid these problems, behavioral indices of ownership and agency have been explored. A typical behavioral index is proprioceptive drift, which is a perceptual shift of the participant's perception from a hidden real hand to a visible

hand-like object (Tsakiris & Haggard, 2005). This shift is often observed simultaneously with generation of ownership over the rubber hand and can be measured as the spatial offset from the obscured real hand to the rubber hand. Thus, proprioceptive drift is used as a behavioral index of ownership. However, as some researchers claim that proprioceptive drift is not always associated with subjective ownership (Rodhe et al., 2011), careful treatment is required.

Another behavioral index of ownership is the skin conductance response (SCR). The SCR is a physiological measurement of psychological and autonomic arousal (Armel & Ramachandran, 2003). Anticipation of a threat produces autonomic nervous system arousal or excitation, resulting in an increase in skin conductance. This phenomenon can also be observed when a participant is attacked by a fake hand that is perceived as part of the self. As this mechanism is based on the autonomic nervous system, which is activated automatically, the measurement of SCR can be a behavioral index of ownership independent of subjectivity. However, the method has a critical weakness for repetitive use. The SCR only occurs if the event is perceived as threatening (e.g., stabbing the fake hand with a toy knife), but repetition of such an event will result in adaptation, which reduces the SCR. Thus, this measurement is not useful for repetitive measurements, and consequently requires a large number of participants.

The search for a general behavioral index for agency continues. Haggard et al. (2002) reported that intentional binding, which is a shrinkage of perceived time between an action and its effect, can be used as a behavioral index of agency. This index derives from research on the sense of agency using the button press paradigm. To use this index, the perceived times of the participant's action and its effect (e.g., a beep) must be measured. The measurement depends mainly on the participant's subjective estimation of time, so the same sorts of problems that affect questionnaires come into play. However, as the judgement of perceived time depend on the human perception about a certain sensory event, this method can be more reliable than the explicit measurement, which requires the participant to evaluate their subjective experience. A further consideration is that, although it is easy to assign a time to a beep, it may be more difficult for a participant to assign a specific time to a self-generated action.

As the measurements described above are based on quantitative changes in behavior and estimate the sense of ownership and agency only indirectly, they are referred to as implicit measurements. These implicit measurements are useful for examining the mechanisms that generate ownership and agency without involving subjective biases. However, implicit measurement sometimes shows results that are inconsistent with explicit measurement. To understand the mechanisms that underlie this inconsistency, it is important to evaluate ownership and agency using both types of measurement.

2.3 Investigation using virtual reality systems

Recently, several researchers have tried to use VR systems as a tool for investigation of ownership and agency. In VR environments, the participant can see a virtual body via a head-mounted display. Thus, the participant can interact with a virtual object in a virtual environment from a first-person perspective. This paradigm allows investigation of the sense of ownership and agency not only for a body part but also for an entire body. In addition, since the virtual avatar is based on computer graphics and can be formed in any shape, it is possible to project a sense of self onto a virtual avatar that is far from human in body shape.

Sanchez-Vives et al. (2010) found that congruence between the operator's body motion and an avatar's motion can induce a sense of ownership of the virtual avatar. Slater et al. (2010) showed that experiences of first-person perspective using a head-mounted display can generate a sense of ownership of a female virtual avatar even if the participant is male. Kilteni et al. (2012) found that visual-tactile congruence can elicit ownership over an elongated virtual arm extending up to 3 times the length of the participant's real arm. Steptoe & Slater (2013) found that participants could experience ownership and agency for a "human tail" when it moved synchronously with the participant's hip motion. Hoyet et al. (2016) found that participants could feel ownership and agency for an extra finger between the ring and pinky fingers when that extra finger was animated based on the motion of the real ring and pinky fingers.

These findings indicate that the human brain has enough flexibility to adopt a visible non-human-like object or virtual body as part of the self when the virtual

entity and the operator's real body move synchronously. This means that the experience of synchronous sensory feedback about one's own body can artificially generate a subjective sense of self for a fake virtual body, in other word, 'project' our self into an artificial body. If this relationship could be induced for an artificial body formed by a mechanical system, would the subjective sense of self be projected onto the artificial body?

2.4 Linkage between brain science and engineering

Investigations of ownership and agency for a mechanical body have been performed in the fields of rehabilitation and engineering. Rosen et al. (2009) showed that patients lacking a limb can feel a mechanical prosthesis as a part of their body when the rubber hand illusion paradigm is applied, that is, by simultaneously stroking a visible hand-like object and the hidden real hand (or a part of body where one's brain misrecognized as the hand). Romano et al. (2015) found that visuomotor congruence could elicit a sense of ownership of a robotic hand in healthy participants. Caspar et al. (2015) confirmed that synchronous movement of the participant's hand and a robotic hand could induce a sense of ownership and agency over the robotic hand. These findings imply that a robotic hand can be perceived as part of the operator's body when its motion is congruent with the participant's body motion.

Studies of the projection of the sense of self have extended not only to body parts such as a hand-like prosthesis, but also to a whole humanoid body. Alimandani et al. (2013) showed that observation of a humanlike robot controlled by the operator's brain signals could induce illusory ownership of that robot. In that study, each participant viewed the hand of a humanlike robot from a first-person perspective via a head-mounted display. The participant's task was to imagine clenching and unclenching hand motions while the real hands were fixed. Electroencephalography (EEG) recording was conducted during the task and its results were used to drive the humanlike robot's hand movements. Synchrony of the robot's hand movements with the participant's motor imagery induced a sense of ownership over the humanlike robot. This result implies that consistency between an operator's intentions and a humanlike robot's actions can induce a

sense of ownership even for an artificial body, and even if the operator's body does not itself move.

In summary, there is abundant evidence that the human brain has flexibility that allows it to project a subjective sense of self into an artificial or mechanical body. However, there have been a few studies showing that consistent multisensory feedback of body movement may be required to maintain a sense of self for a mechanical system. For example, a critical temporal offset between visual and proprioceptive feedback was revealed using both button press and rubber hand illusion paradigms (button press paradigm: Farrer et al., 2013, rubber hand illusion paradigm: Ismail et al., 2016). According to these studies, a delay of roughly 300 ms is the critical value for maintaining a sense of ownership and agency.

In addition to the temporal offset, critical values for the spatial offset between visual and proprioceptive feedback are also crucial aspects of mechanical design, constraining the spatial relationship between the monitor and input devices. However, because spatial design involves three-dimensional offsets (in height, depth, and length), knowledge of the critical spatial offset in a single dimension is not sufficient. To address this problem, this dissertation proposes a novel quantitative estimation method for the critical spatial offset in 2D space between visual and proprioceptive feedback that is needed to maintain a sense of ownership and agency for the human body itself (Experiment 1).

Additionally, in daily life as well as in the operation of mechanical systems, tactile information is often generated as a consequence of body motion. As mentioned in Chap. 2.1, visual-tactile synchrony can elicit a sense of ownership and agency for the face or hand. A question therefore arises: Does visual-tactile synchrony affect the critical spatial offset between visual and proprioceptive feedback? To examine this interaction of multisensory feedback modalities, the effect of visual-proprioceptive-tactile synchrony on the critical spatial offset and sense of ownership and agency was tested (Experiment 2).

Furthermore, the appearance of the manipulator in a mechanical system (e.g., endoscopic forceps in a teleoperation system) does not always resemble the shape of the corresponding human body part (e.g., the hand). According to

Tsakiris et al. (2010), only a hand-like shape elicits a sense of ownership in the rubber hand illusion paradigm. However, recent studies using VR techniques showed that even a non-human-like object could elicit a sense of ownership and agency when the motion of the object and the operator's body movements were congruent (Slater et al., 2010; Hoyet et al., 2016). This implies that either visual-motor or visual-proprioceptive congruence can generate a sense of ownership and agency over the non-human-like object controlled by the operator. However, little is known what types of visual features play critical roles in generating ownership and agency in these paradigms. To clarify this critical issue, the aspects of appearance and motion required to generate ownership and agency over a controllable object were examined (Experiment 3).

3. Spatial constraints on visual-proprioceptive feedback

3.1 Introduction

In the real-time controlling system, the position of visual feedback and proprioceptive feedback tend to be spatially offset (Figure 3-1). In order to obtain the critical spatial property of multisensory feedback to keep ownership and agency, a novel estimation method was proposed to evaluate the spatial offset between visual and proprioceptive feedback in 2D space. As this method was based on the spatial property of multisensory feedback of body movement, which is already acquired in the brain, it was necessary to discuss how our brain knows one's body position.

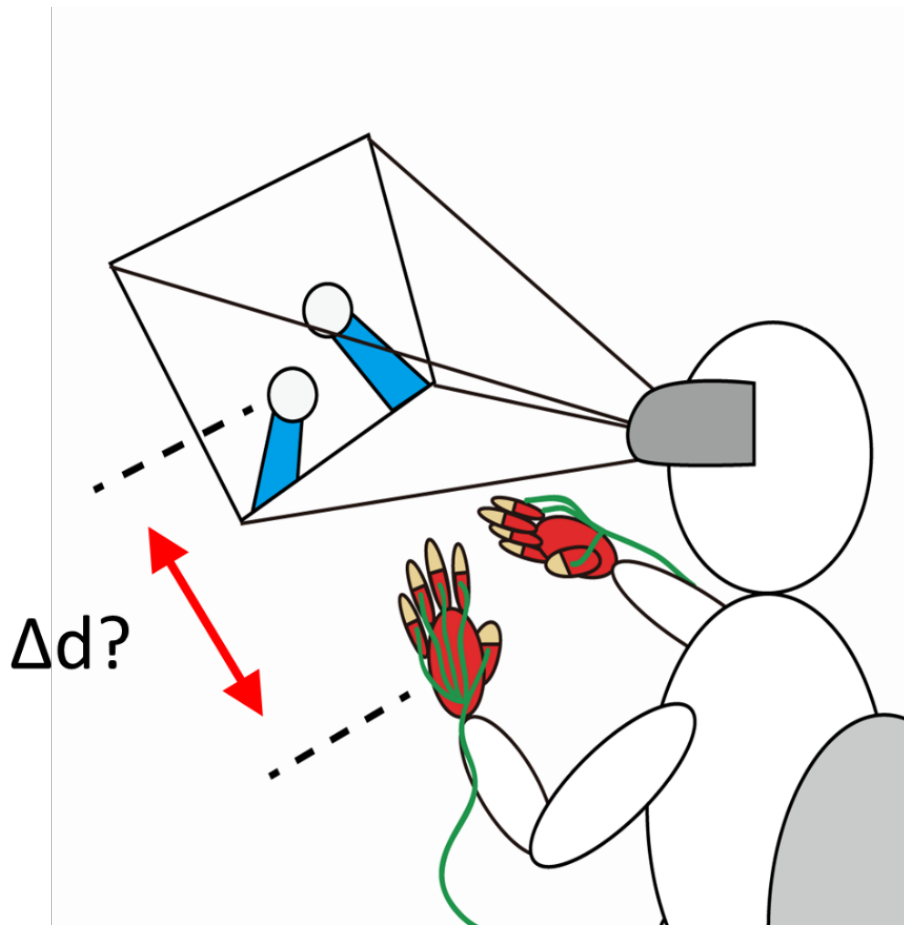


Figure 3-1 A schematic representation of the spatial property of visual and proprioceptive feedback in the real-time controlling system.

In our daily lives, humans rely on multiple cues from multisensory channels, such as vision, proprioception and the vestibular system, to determine body position. However, in some situations one channel can dominate the others. When participants viewed their left hands in a mirror positioned along the midsagittal axis while moving both hands synchronously (e.g., repeatedly opening and closing left and right hands simultaneously), they hardly noticed the spatial offset between the hand in the mirror and the obscured real right hand (Holmes et al., 2004). This is termed the mirror illusion. This illusion encompasses a shift in perceived body-part position from proprioceptive-driven to visual-driven, called proprioceptive drift.

Only a few papers have reported on the spatial properties that the brain uses to detect the discrepancy between visual and proprioceptive feedback in the mirror illusion. For example, Snijders et al. (2007) tested the discrepancy with horizontal and vertical lines on a table top during a reaching task, and their results showed a maximal space of 5 cm for which participants did not notice the discrepancy between the real hand and the mirror image. However, there are some problems with the methodology in studies of that type. Since hands can move freely in 2D and 3D space, analysis along only one dimension is insufficient to reveal the precise details of the spatial properties of the illusion, especially the details of the relationship between visual and kinematic information. Another issue is how to investigate this illusion in 2D or 3D with a robust, statistically valid psychophysics method. The statistical methods for psychophysics in past mirror illusion papers were optimized for experimentally controlled and limited conditions, not for natural conditions in which participants can move their hands at will.

Here, a novel proprioceptive drift evaluation method is proposed to visualize the spatial discrepancy between visual and proprioceptive feedback in a 2D paradigm, by combining psychophysical procedures with machine learning using a support vector machine (SVM). To replicate previous findings regarding the mirror illusion, subjective body position was investigated using this method, both with and without visual feedback (i.e., mirror condition and a blackboard control), to clarify the effects of participant body movement on perception of an

image of the body in a mirror.

In addition to proprioceptive drift, the mirror illusion is known to evoke sensations of ownership and agency (Holmes et al., 2004, Gallagher, 2000). According to Gallagher's model, these two sensations are generated when actual sensory feedback from body movement matches sensory feedback predicted by a forward model of body movement. As feedback can be multisensory, the model could in principle include multisensory components, such as visual, tactile, and proprioceptive feedback. However, Gallagher's model did not include this multimodal feature. As a result, it is unclear whether ownership and agency should be generated when different sources of feedback are inconsistent. In the mirror illusion, proprioceptive feedback from the real hand is spatially inconsistent with visual feedback. Even in this situation, the participant often feels clear ownership and agency. In addition, some research has demonstrated the generation of ownership and agency despite temporal discrepancies between vision and other modalities (ownership: Shimada et al., 2009; agency: Farrer et al., 2008). This implies the potential maintenance of ownership and agency despite spatiotemporal discrepancies in multisensory feedbacks. This gives rise to the following questions: To what extent do proprioceptive drift and ownership and agency overlap? Do they go hand in hand? Are they merely different aspects of the same process of self-perception? A principal component analysis of multiple body-sensation test batteries found that they belong to the same cluster, suggesting that they can share the same processing mechanisms to some extent (Jared Medina, personal communication, December 27, 2013). In contrast, a recent paper suggested that proprioceptive drift, ownership, and agency can be attributed to separate brain information processes (Rohde et al., 2011).

To answer these questions, the spatial aspects of ownership and agency were investigated using questionnaires (common in the testing of these sensations) tailored for use with the mirror illusion in the midsagittal plane. The overlap between the spatial distributions of proprioceptive drift and feelings of ownership and agency was investigated by comparing results. The aim of these experiments was to clarify whether proprioceptive drift goes hand in hand with other body sensations, such as ownership and agency. In addition, the potential

applications of the results for the mechanical design of real-time control systems will be discussed, along with possible applications for objective, quantitative assessment of body sensations, especially assessment of patients' self-perception changes during rehabilitation.

3.2 Materials and methods¹

3.2.1 Participant

Ten graduate and undergraduate students from the Tokyo Institute of Technology were recruited as paid participants (all male, aged 19–28 years, mean age = 22.1, SD = 2.42). They all had normal or corrected-to-normal vision and were right-handed. All participants were naïve to the purposes of the study. The study was approved by the Ethical Committee of Tokyo Institute of Technology and all participants provided written informed consent prior to each experiment.

3.2.2 Equipment

A schematic representation of the setting is shown in Figure 3-2. A 100 × 100 cm acrylic mirror was positioned vertically 60 cm above the floor, oriented parallel to the participants' sagittal axes with the reflective surface facing toward the participants' left. In the blackboard condition, a 100 × 90 cm matte acrylic blackboard was positioned in place of the mirror. To record the positions of the participants' right hands, a position sensor (CyVerse, SLC-C02) was placed 1.0 m to the right of and facing the mirror. Spatial resolution of the motion capture software was approximately 1.5 mm and its sampling rate was 30Hz. A custom-made retroreflective marker was attached to the participants' right index fingertips to relay their hand positions to the sensor. An infrared LED was attached at the top left of the reverse side of the mirror to record the relative positions between the fingertip marker and the edge of the mirror. A foot pedal (P.I. Engineering, Classic X-keys USB, and PS/2 Foot Pedals) was placed to the left of the mirror to collect the participants' responses. Noise-cancelling

¹ The material and methods were explained by a video.

<http://www.jove.com/video/53970>.

headphones (Bose, Quiet Comfort 3) were used to reduce the possibility that participants would get information about hand position from sound cues.

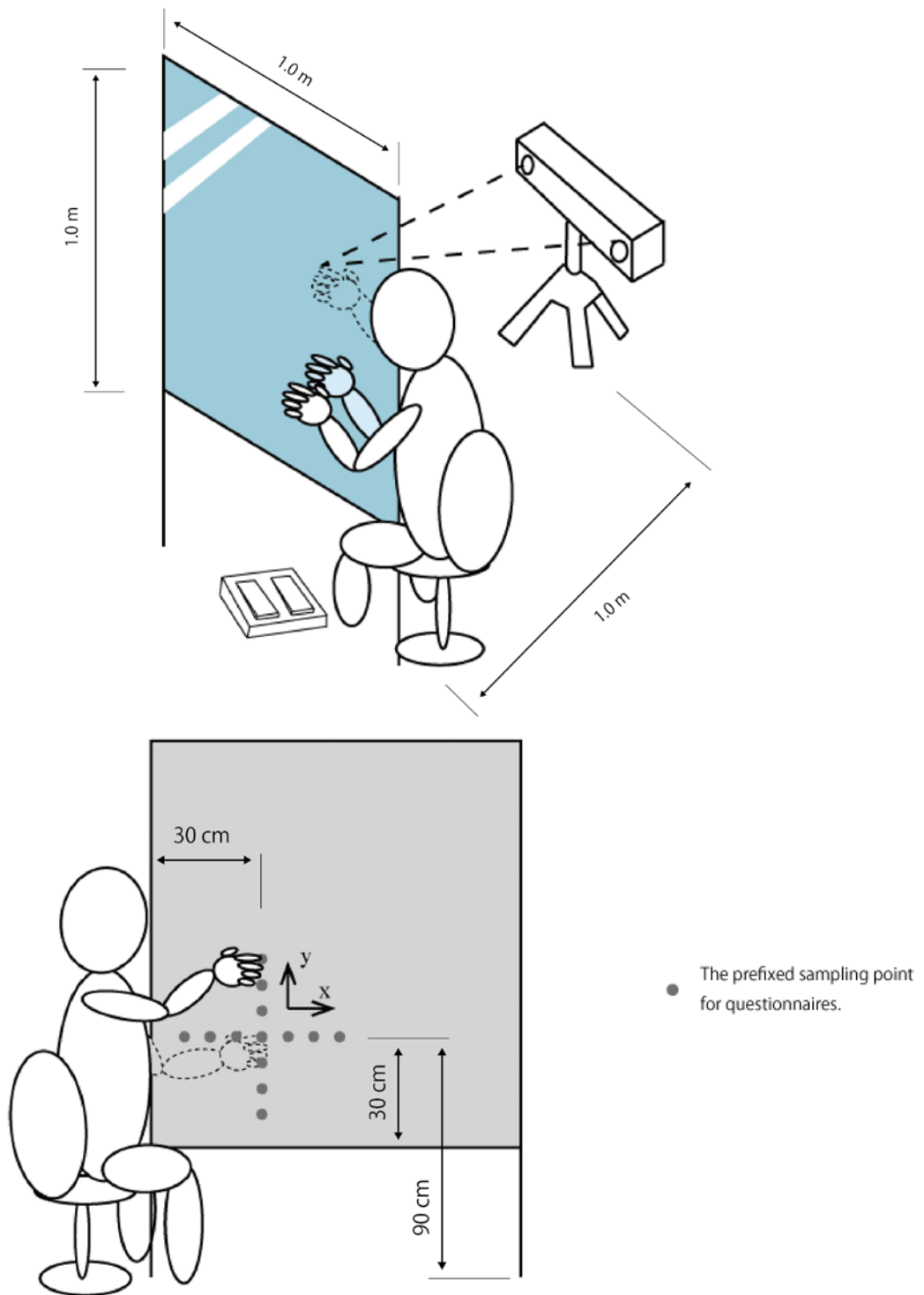


Figure 3-2 Schematic representation of the experimental setup.

3.2.3 Experimental design and procedure

Two conditions were tested. In the mirror condition, participants saw their reflected left hand images in the mirror and could perceive the position of their right hands using at least two possible cues: 1) proprioception and 2) the position of the image of the right hand in the mirror. The control condition used the blackboard instead of the mirror, and the participants perceived the position of their right hands using proprioception alone. The order of the conditions was counterbalanced across participants.

Prior to initiation of the experiment, the participants were trained to tap both hands synchronously on the mirror or blackboard at roughly one cycle per sec (approximately 1 Hz), which was slow enough for the participants to observe the mirror image, and to prevent them from executing this task in a feed-forward mode while ignoring the visual feedback. During the experiment, the experimenter monitored the timing of the participants' tapping and instructed them to reset their timing if it differed considerably from 1 Hz.

In the mirror condition, the participants were seated very near the mirror, so that their bodies almost touched it. They turned their heads slightly to the left to look into the mirror. The participants' left hands were placed such that they could be viewed both directly and in the mirror. Their left index fingertips were approximately 30 cm vertically and 30 cm horizontally from the lower right corner of the mirror and 90 cm above the floor. The participant was instructed to fix the position of his or her left hands were fixed during the experiment. In contrast, the participant was allowed to place their right hands in a preferred position on the reverse side of the mirror. They could change the position of their right hands at will at the beginning of every trial. The participants were instructed to maintain the same angles of both wrists, and to look at the reflection of the left hand in the mirror. After placing their right hands in new positions, the participants pressed the middle button of the foot pedal and started to tap with both hands synchronously at 1 Hz. They were instructed to tap at least six times. A previous paper reported that it requires at least 6 sec of visual stimulation to induce the mirror illusion (Holmes et al., 2004), which is equivalent to six times tapping at 1 Hz. Therefore, it was concluded that six or more taps would suffice for the

purposes of the experiment. After at least six taps, the participants were asked to answer a two-alternative forced choice question (2AFC) by pressing the right or left button on the foot pedal. The question was, “Do you feel that both hands are in the same position?” When the foot pedal was pressed, the participants’ responses and the positions of their right hands were recorded, and a beeping sound served as a sign to change the position of their right hands for the next trial. This process was repeated for a maximum of 200 trials per condition.

In the blackboard condition, the procedure was almost the same as that of the mirror condition, except that the participants were instructed to look at the spot where they had seen the reflection of the left hand during the preceding mirror trials.

In a separate experimental session, the sense of ownership and agency for the hand in the mirror were measured using a 16-statement questionnaire, to replicate previous findings and compare results to proprioceptive drift data. The first four statements referred to ownership (e.g., “I felt as if I was looking at my own right hand.”), and four described sensations related to agency (e.g., “I felt as if I was causing the movement I saw as my right hand”). The remaining eight statements were control statements, with four for ownership and four for agency (e.g., “It seemed as if I had more than one right hand” and “I felt as if the hand in the mirror was controlling my will”). These questionnaires were adapted and translated into Japanese from questionnaires previously used in a rubber-hand illusion experiment (Botvinick & Cohen, 1998, Kalckert & Ehrsson, 2012). Full statements are provided in appendix A.

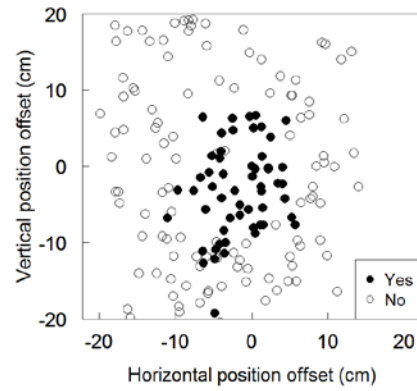
In the experiment measuring proprioceptive drift, the participants could choose the positions of their right hands freely. In contrast, to measure feeling of ownership and agency, 13 prespecified right-hand positions were examined (Figure 3-2). These points were arranged every 7 cm up to ± 21 cm from the original position, both vertically and horizontally. The participants were required to respond to the questionnaires after tapping both hands synchronously six times at the assigned positions. They were not required to press the foot pedal in this session. The participants responded to questionnaire items using a 7-point Likert scale with ratings ranging from -3 (totally disagree) to +3 (totally agree), with 0

indicating neither agreement nor disagreement.

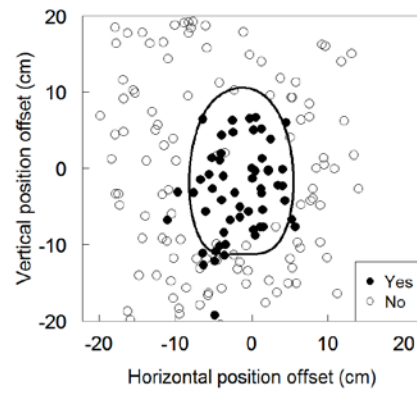
3.3 Data analysis

Figure 3-3 illustrates the flow of the data analysis for the first part of the experiment. Panel A is a raw plot of one participant's data, panel B shows the border between Yes and No positions determined by a support vector machine (SVM) analysis, and panel C is the average border across participants. The analysis was two staged; the first stage was within participants and the second was between participants. The first stage involved subjective position sensation for the right hand, with within-participant analysis conducted to determine the area in which participants did not notice the spatial gap between their visual and physical bodies. The between-participants analysis was conducted to obtain an average of the spatial areas provided by participants' "Yes" responses.

A



B



C

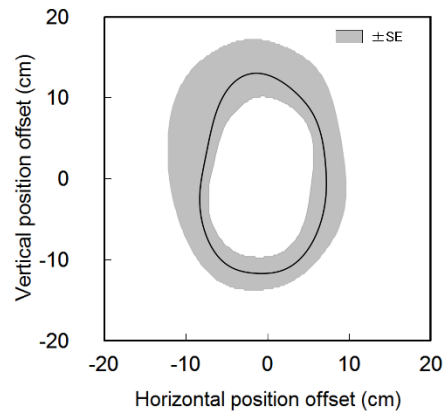


Figure 3-3 Data analysis flow for the first part of Experiment 1.

In the within-participant analysis, an SVM was used as a classifier (Karatzoglou et al., 2004) to extract the borders between the positions that elicited Yes and No responses from each participant. The SVM provided a probabilistic model of each participant's response in 2D space, trained using their response data and the position of the right hand at the time of response. Bishop (2006) provided a description of the algorithms of the classifier (see Chapter 7 in Bishop, 2006). The area in which the p-value of a Yes response was estimated to be over 0.5 was defined as the area in which the participant did not notice the spatial gap between body image in the mirror and proprioception of the right hand. The kernel used for the SVM was the commonly used radial basis function. To build a stable model, virtual responses were added to this analysis. The virtual responses were all No responses, and the positions used are listed in Table 3-1, showing that the participants could not reach their right hands. These data were used to teach the probabilistic model that the probability of the participant's 'yes' response should be zero where the participant could not reach.

Table 3-1 Positions of the virtual response in the SVM analysis.

No	Position	
	X (cm)	Y(cm)
1	30	30
2	15	30
3	0	30
4	-15	30
5	-30	30
6	30	15
7	-30	15
8	30	0
9	-30	0
10	30	-15
11	-30	-15
12	30	-30
13	15	-30
14	0	-30
15	-15	-30
16	-30	-30

After running the analysis described above for each participant's data, the results were averaged across participants. Two averaging methods were attempted to visualize the results of analysis. One method was to average the p-values for the participants' responses across 2D space. The degree of variation of the area was calculated as the average plus or minus standard error of the probability for each right-hand position and is shown as the masked area in each graph. The other method was to average the area sizes, which were calculated after estimating the individual borders.

All data were assessed for normality of distribution using the Shapiro-Wilk test ($p > 0.05$), and appropriate non-parametric tests were applied when one or more of the corresponding data sets failed to meet the criteria for normality. The area size data were not normally distributed due to participant variance; therefore, a Wilcoxon signed-rank test was used for pairwise comparisons. The questionnaire data were not normally distributed; however, a two-way repeated-measures analysis of variance (ANOVA) was performed to analyze these data, as there is no non-parametric equivalent. The results of Mauchly's sphericity test were not significant ($p > 0.05$) for the questionnaire data. Therefore, Greenhouse-Geisser corrections were not used.

The analyses comparing area size and questionnaire data were conducted using SPSS (version 21, IBM Corp., Armonk, NY, USA). Asterisks in plots indicate statistical significance: * $p < 0.05$.

3.4 Results

Figure 3-4 shows a comparison of area shape between the mirror and blackboard conditions. The origin represents the position of the left index fingertip, or the position of the visual feedback in the mirror condition. The vertical and horizontal spatial offsets between the left and right hands form the axes. In both conditions, as their right hands approached the origin, the participants tended not to notice the spatial gap between their left and right hands. However, the shape and size of the area clearly differed between the mirror and blackboard conditions (Wilcoxon signed-rank test: $Z = -2.803$, $p = 0.005$). This result is consistent with previous findings regarding the mirror illusion (Holmes et al., 2004), suggesting that

current method showed the visual capture effect successfully. Based on current results, offsets between visual and proprioceptive feedback of up to approximately 10 cm are compatible with proprioceptive drift.

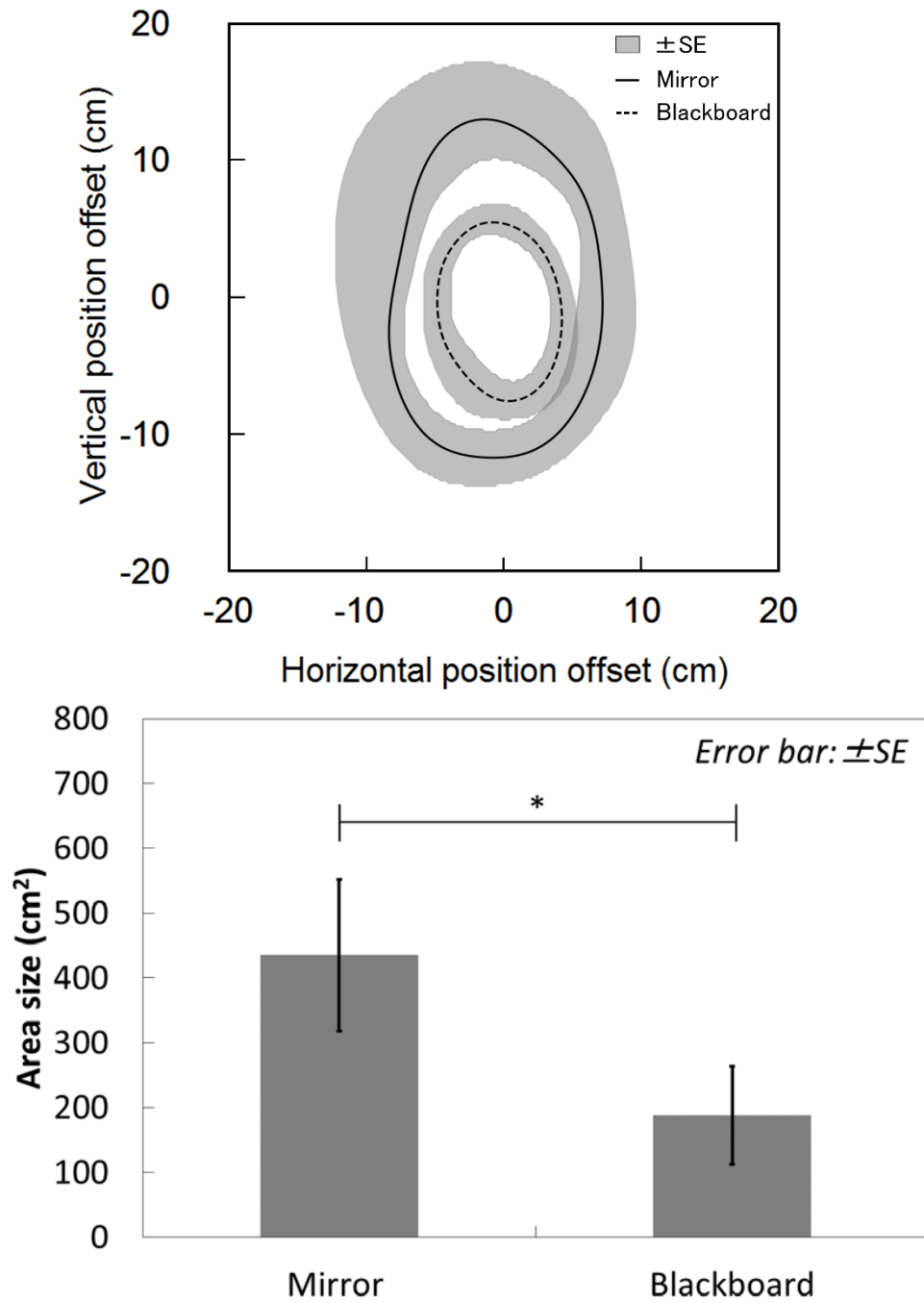


Figure 3-4 Comparison of area shape and size between the mirror and blackboard conditions. N = 10.

Figure 3-5 shows the questionnaire results about ownership and agency at each sampling point. The axes show vertical and horizontal spatial offset between the hand in the mirror and the obscured real hand. The plots and lines represent differences between questionnaire categories; the black squares, white squares, black circles and white circles represent ownership, ownership control, agency, and agency control, respectively. The ownership and agency scores are highest at the origin and decrease with distance in the vertical and horizontal directions. The scores for the control statements show little difference between positions. A two-way repeated-measures ANOVA revealed significant main effects of category and position (Horizontal: Category: $F(3,27) = 11.12$, $p < 0.001$; Position: $F(6,54) = 10.27$, $p < 0.001$; Vertical: Category: $F(3,27) = 24.21$, $p < 0.001$, Position: $F(6,54) = 7.298$, $p < 0.001$). The interactions between category and position were also significant (Horizontal: $F(18,162) = 9.42$, $p < 0.001$; Vertical: $F(18,162) = 8.00$, $p < 0.001$). These results indicate that a smaller discrepancy between the mirrored hand and the real obscured right hand was associated with a greater feeling of ownership and agency for the hand in the mirror. The data show that ownership and agency were evoked at distances of up to ± 10 cm vertically and ± 15 cm horizontally from the origin.

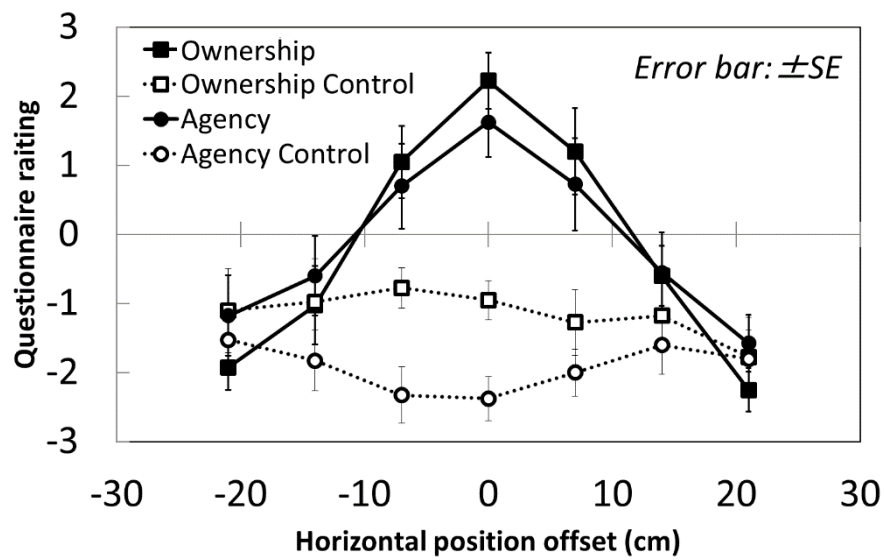
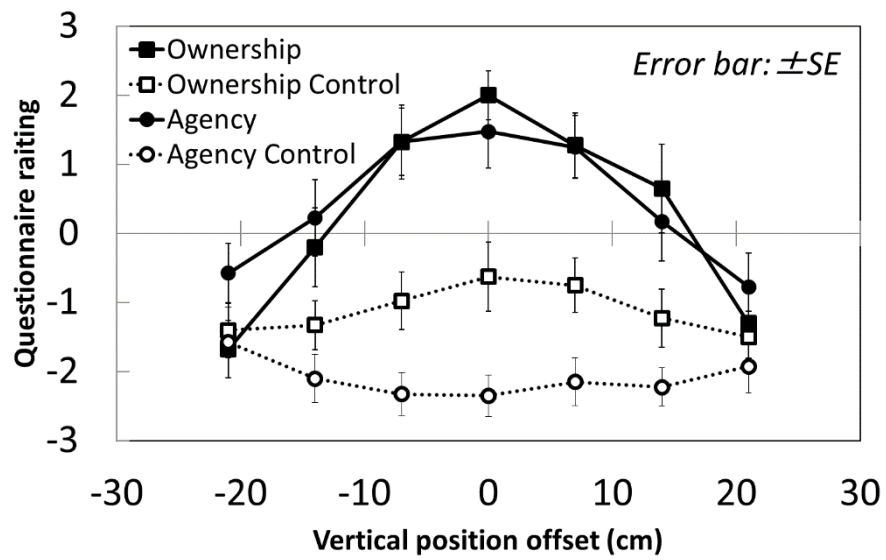


Figure 3-5 Questionnaire results. N = 10.

Figure 3-6 shows comparisons between the 2AFC data and the questionnaire results. The highest questionnaire scores for sense of agency and ownership came from almost the same positions in the center of the area for which the participants did not notice the spatial gap between the mirrored hand and the obscured real hand. The zero-crossing points of the scores for agency and ownership were in almost the same positions as the borders of the area in the horizontal direction; however, in the vertical direction, they differed slightly. These results suggest that the offsets between visual and proprioceptive feedback compatible with proprioceptive drift overlapped almost perfectly with the offsets evoking feelings of ownership and agency.

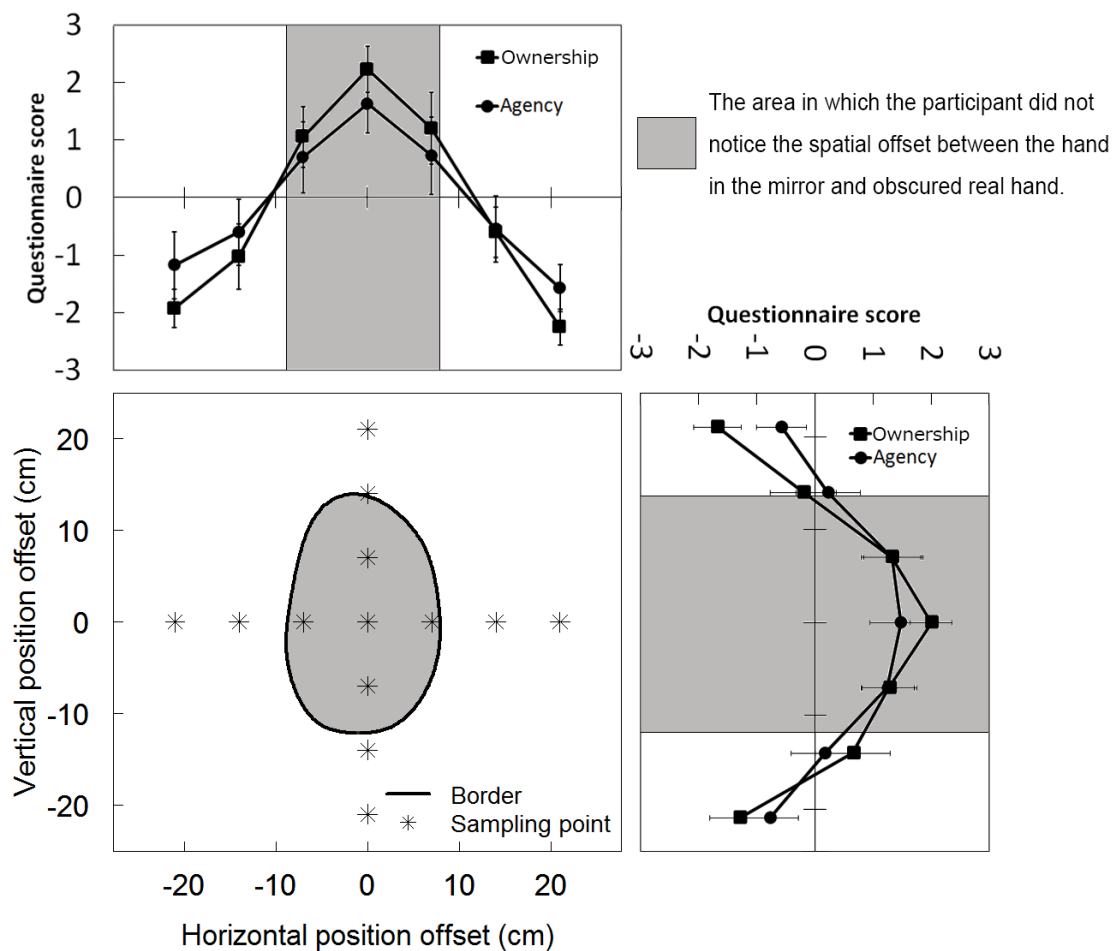


Figure 3-6 Comparison between the classification and questionnaire.

3.5 Discussion

The visualization method developed here revealed that the maximum offset compatible with proprioceptive drift was approximately 10 cm. This distance was larger than the value measured in previous research using the rubber-hand illusion paradigm (Kalckert & Ehrsson, 2010; Tsakiris et al., 2010; Rohde et al., 2011). Two factors may have accounted for the difference. The first was the reality of the hand's visual feedback. According to the study conducted by Tsakiris et al. (2010), the appearance of a hand image plays an important role in evoking feelings of ownership and proprioceptive drift. Compared to the rubber hand, the hand image in the mirror matched the real appearance of a hand almost perfectly. This may have increased the level of visual capture, thereby increasing the maximum offset value.

The second factor was the hand movement. In the rubber-hand illusion paradigm, the participant's hand and rubber hand receive synchronous strokes of a paintbrush. These stimuli provide visual and tactile feedback from the hand to evoke ownership of the rubber hand. In contrast, under the paradigm used in this research, the participant moved both hands synchronously while viewing the hand in the mirror, positioned along the midsagittal plane. The main difference between the rubber hand illusion and the mirror illusion is whether the participants receive feedback from their voluntary body movements. It has been speculated that the difference between voluntary and involuntary body movement can be attributed to a difference in the ability of "attention" to enhance the salience of controlled objects in the visual field. Kobayashi & Yoshida (2014) found that moving objects or visual feedback that matched ongoing action or hand movement can be found faster, as in the "pop-out" phenomenon in visual search for higher-order visual features, suggesting the involvement of attentive processes in the perception of self-controlled objects. If the same principle can be applied to moving hand images in the visual field, then the hand image in the mirror would attract the participant's attention relatively quickly with minimum effort. In contrast, in the rubber hand illusion paradigm, the rubber hand does not attract the participants' attention—rather, the participants must voluntarily pay attention to the rubber hand. Such differences in the participants' attentive states may

contribute to the time course and enhancement of visual capture for voluntary control.

In the mirror condition, the maximum vertical offset between visual and proprioceptive feedback appeared larger than the maximum horizontal offset. This result supports the existence of direction-dependent differences in visual-proprioceptive integration (Van Beers et al., 1999, 2002). Snijders et al. (2007) discussed similar differences. They investigated the effect of visual capture by measuring reaching error when participants viewed a hand in a mirror as a substitute for a real hand. Their results showed that azimuthal (directional) errors were significantly larger than radial (distance) errors. This result also supports direction-dependent differences. The current results showed that the radial (depth) offset between visual and proprioceptive feedback was smaller than the attitude (height) ones. This implies that radial information about the hand position was handled more precisely than altitude information. One possible reason for the ellipse-shaped proprioceptive drift area is differences in the proprioceptive sensitivity of the elbow and shoulder joints. When the hand is moved in a horizontal direction, the elbow joint angle increases relative to that of the shoulder joint. In contrast, when the hand is moved vertically, the shoulder joint angle increases relative to that of the elbow joint. This difference may generate direction-dependent differences in proprioception. In this study, joint angles were not measured, nor were other potentially correlated factors such as the force exerted by muscles connected to the joint or joint sensations such as pain. Further research is required to explore these factors.

The results of this study showed that the spatial offset between visual and proprioceptive feedback evoking proprioceptive drift was similar to the offset required to maintain ownership and agency. This result suggests that the same integration or matching processes for visual and proprioceptive feedback could be used to evoke proprioceptive drift, feeling of ownership, and agency. However, some parts of the literature do not support such an association. For example, Rohde et al. (2011) provided evidence of a dissociation between the feeling of ownership and proprioceptive drift in the rubber-hand illusion paradigm. They found that proprioceptive drift could be observed between the rubber hand and

the real hand even in conditions that did not generate a feeling of ownership. The differences between the brain mechanisms underlying proprioceptive drift, ownership, and agency are an important issue in neuroscience research.

The initial motivation for this line of research was to apply it to mechanical design. In our daily lives, humans scarcely pay attention to the spatial discrepancy between modalities. In contrast, spatial discrepancies arise in the design and manipulation of many real-time control systems, including remote control systems, robotic surgical systems, and VR systems. Robotic surgical systems, for example, apply the user's hand movements as commands for operating a robotic arm. The system then provides the user with the consequences of the robotic arm movement, displayed on a monitor. Thus, the normal visual feedback of the user's body is substituted with feedback from the robotic arm. In VR systems, visual feedback is substituted using the virtual body depicted on a monitor. In these systems, distance between the user's body and the perceived source of the visual feedback is often unavoidable due to physical constraints of the mechanical design. For example, the position of a virtual hand on a monitor does not share the same space as the user's real hand or the input device (such as a joystick). Therefore, without some appropriate calibration between the user's hand and the monitor, the locations of the visual and proprioceptive feedbacks are physically distinct. Despite this separation, if the user is unable to detect the spatial discrepancy between visual and proprioceptive feedback and feels that his real hand position is at the visual feedback position, his experience during operation of the system would not be so different from the experience of using his or her own arm and hand. The precise details of this type of real time control system design are still under debate (e.g., Rosén et al., 2009). VR researchers do not always carry out this type of calibration between visual and haptic information, because they know that users do not notice a small spatial offset between modalities. Not all visuo-haptic VR systems and real-time control systems are intended to generate the feelings of self-tested here. However, the current results and the assessment method developed here can be a first step toward showing mechanical designers how to maintain natural sensations without enforcing perfect correspondence between visual and haptic inputs.

According to some researchers, the sense that a part of the body is part of oneself is dependent on the relationship between action and feedback, not on the physical link between the brain and body. Some clinical phenomena and psychological findings support this proposal. In clinical cases, phantom limb sensations and the alien hand syndrome are powerful evidence that the physical linkage between brain and body is not the basis of the sense of self. The former phenomenon occurs when a patient without a limb still feels the missing limb (Ramachandran et al., 1995). The latter is a phenomenon in which patients feel as if one of their hands is actually that of another person (Bank et al., 1989). In psychology, the mirror and rubber hand illusions provide further support for the proposal. The current findings are limited to situations where the visual feedback is highly similar to that of a human body, with almost zero temporal delay and a high-resolution image. Compared to the human body, the visual feedback in artificial systems usually involves various transformations, such as shape, color, position, and time lag. Therefore, whether the current findings can be generalized to these cases may be an interesting topic for future research.

The current finding may also provide an important contribution to the field of rehabilitation. In rehabilitation, treatments to improve motor function and pain are often carried out for patients with missing or paralyzed limbs. Although these treatments can help patients recover functions needed for the usual activities of daily living, they do not guarantee recovery of feelings of ownership and agency for these limbs. Treatments that attempt to accomplish this have just been initiated in recent years, and the most effective methods are still under discussion. Unlike physical treatment with surgery, the treatment of ownership and agency means treatment of the patient's subjective experience. In general, subjective experience differs across patients. Moreover, since the assessment of subjective experience relies almost solely on qualitative methods (such as questionnaires), it is often difficult to determine the reasons why patients lack the sense of ownership and agency for their limbs. To help us understand why this happens, an objective and quantitative method is needed. The current finding could help to provide psychophysical data that might be useful.

3.6 Conclusion

There were two main findings in this study. First, it was possible to analyze precisely the maximum spatial offset between visual and proprioceptive feedback compatible with maintaining proprioceptive drift in the midsagittal plane. The maximum offset was approximately 10 cm. Second, despite the differences in measurement, a strong spatial relationship between proprioceptive drift and feelings of ownership and agency was demonstrated. This is the first report providing evidence that the spatial overlap between these two phenomena is almost perfect. It will be interesting to learn whether this finding can be replicated with real-time control systems, where the offset between visual and proprioceptive feedback is within the range that maintains proprioceptive drift and own-body-like usability. These types of study would help to understand the human brain mechanisms that produce the experience of self and allow us to better understand the action-feedback relationship required to maintain the sense of self, whether for an artificial body or the natural body.

4. Spatio-temporal relationship of visual, proprioceptive, and tactile feedback.

4.1 Abstract

Our previous experiment revealed the critical spatial offset between the visual and proprioceptive feedback of the body that is required during movement, in order to maintain a sense of ownership and agency. A particular combination of visual and proprioceptive feedback was essential to assess the action-feedback of body movement. Additionally, during human activity, tactile feedback occurs, alongside visual and proprioceptive feedback (Figure 4-1). For further investigation of the human multisensory processing that is required to maintain ownership and agency, this study focused on the effect of visual-proprioceptive-tactile congruency. If the human brain indeed preferred a daily life situation with sufficient multisensory action feedback to maintain ownership and agency, the tri-modal congruency paradigm would enhance ownership and agency.

By combining the mirror illusion paradigm and a vibrating device, the synchrony of the voluntary movement (VM condition) of a participant's hidden right index finger and the vibration (Vib condition) of the right index fingertip with mirrored left-hand movement were manipulated. In order to measure proprioceptive drift, and as a behavioral index of ownership, the initial experiment involved participants observing a critical area containing an unnoticeable physical gap between a mirrored left-hand image and the hidden real right-hand. In a subsequent experiment, the questionnaire scores for ownership and agency were measured directly. Behavioral results indicated that the area measured in the initial experiment did not significantly vary across the experimental conditions. The questionnaire assessment in the subsequent experiment showed that only the VM condition significantly affected ownership and agency scores. Additionally, ownership and agency scores were not altered in response to synchronization of the mirrored left-hand image, hidden right-hand movement, or the vibration of the hidden right index fingertip, compared with other synchronized VM

conditions. These results indicated that visual-proprioceptive congruence could be dominant with respect to proprioceptive drift, sense of ownership, or agency, for the mirrored-hand image compared with the visual-tactile image, resulting in a lack of enhancement by tri-model synchrony.

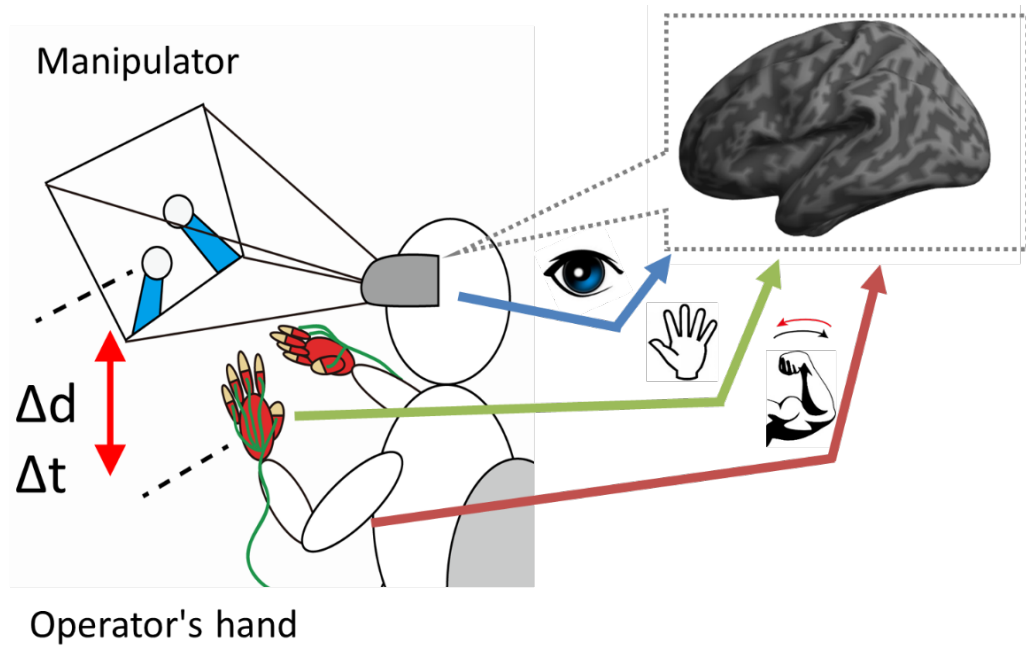


Figure 4-1 A schematic representation of the multisensory feedback of body movement via the real-time controlling system.

5. Critical visual feature of self-control object

5.1 Abstract

Our previous experiments focused on the multisensory processing that is required for the human body to maintain ownership of, and agency for, itself. To introduce the idea of ownership and agency within the usability design of a real-time controlling system, it is necessary to ignore differences in appearance between the human body and the manipulator of a controlling system. To address this appearance problem, the effect of hand-like appearance was investigated for generation of ownership and agency in this experiment (Figure 5-1). Thus, the investigation focused on the mechanism that allows the human brain to recognize one's own body among a grouping of objects seen from one's own perspective. This investigation determined whether the existing representation of body movement (i.e., a previously acquired representation that is stored within the brain) relies on the shape information of the human body.

To investigate the visual features that contribute to the maintenance of ownership and agency, an experiment was conducted that involved a modified visual search for a self-controlled target. The ease in finding a target was employed as a behavioral index of self-control, or as a non-verbal measurement of behavioral agency. Shapes of visual stimuli were modified to hand-like or scattered dot patterns. The participants' task was to find the target reflecting their right-hand movement and then respond to questions regarding sense of ownership and agency for the target. Two types of hand movement were examined: 1) waving their hands vigorously; 2) clenching and unclenching their hands repeatedly. Behavioral results showed that accuracy and reaction time were dramatically altered by a delay of 300 ms between the movements of the two hands, but were not affected by the target's shape. Ownership and agency were elicited, regardless of hand shape, in the hand-waving condition; however, agency, but not ownership, was elicited with hand-like dots in the clenching condition. These scores also decreased with a delay of 300 ms or more. These results suggest that the multisensory process of identifying "global" hand position plays a role in

generating ownership, whereas the process of matching multisensory feedback plays a role in generating agency.

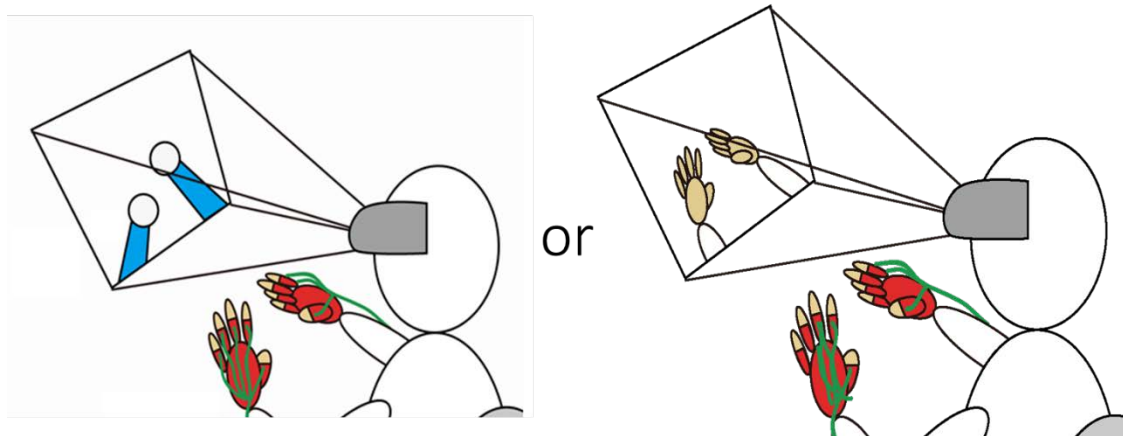


Figure 5-1 A schematic representation of the non-hand-like or hand-like manipulators in real-time controlling system.

6. Conclusion

Based on the three experiments on the generation of the subjective senses of the “self-body,” four requirements for multisensory feedback to generate a sense of ownership and agency can be stated as follows:

1. The spatial offset between visual and proprioceptive feedback must be less than approximately 10 cm (Experiment 1).
2. Visual-proprioceptive congruence is much more important than visual-tactile congruence (Experiment 2).
3. The delay between visual and proprioceptive feedback can be allowed up to 300 ms (Experiment 3).
4. An appearance and motion should be consistent with the goal of the action but a human-like appearance is not always required for the visual feedback of body movement (Experiment 3).

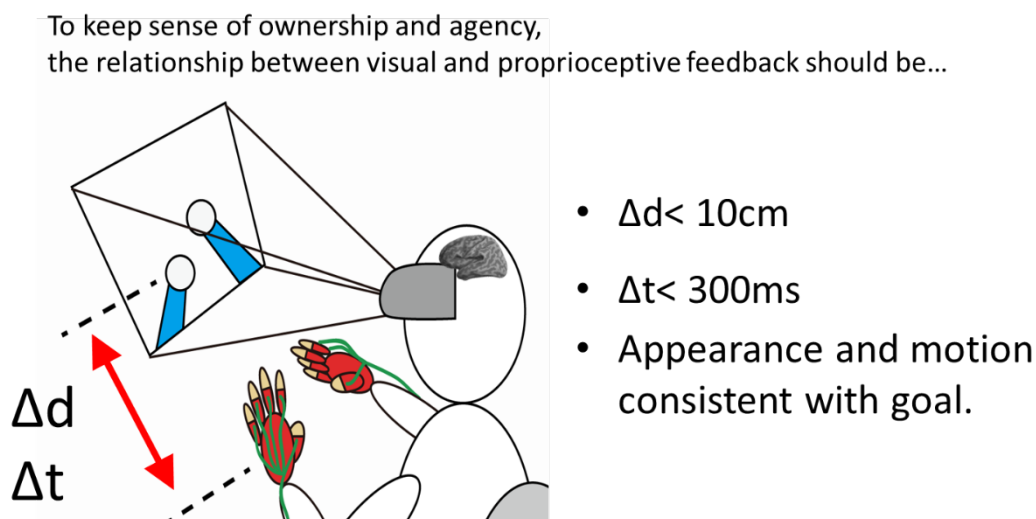


Figure 6-1 A schematic representation summarizing the current findings.

6.1 Contribution

In this dissertation, the requirements to keep sense of ownership and agency in the multisensory processing about body movements were examined. Originally, this sense of ownership and agency were investigated in the field of psychology and rehabilitation, where treat the human perception or sensation about the one's own body. Through these kinds of investigation, the model of the ownership and agency were already proposed in the field of philosopher. In this chapter, implications of the current results for this model of ownership and agency were argued.

Before touching the model of ownership and agency, it was necessary to explain how this model was developed from the model of the body movement. As mentioned at chapter 2.1, the model of ownership and agency were proposed by Gallagher (2000). According to this model, the sense of ownership and agency could elicit if the actual sensory feedback of body movement were matched with the predicted sensory feedback by the forward model of body movement. This forward model could be defined as some kinds of database or template holding the information of the relationship between the efferent copy of the motor command and its consequence of the sensory feedback of the body movement. Thus, in Gallagher's model, our brain can rely on it to predict the incoming sensory information by the efferent copy using the forward model of the body movement.

Interestingly, this forward model idea was repeatedly called the in different terms in different research field, such as internal (or invert) model of body movement, body schema, and the representation of body movement (Blakemore et al., 2000; Wolpert & Ghahramani, 2000; Longo et al., 2008; Salomon et al., 2012). One of the influential paper, Wolpert & Ghahramani (2000) used the term invert model of the body movement as the explanation of motor prediction such as those described as inner model in typical feed-forward human body controlling theory. According to their theory, human brain monitors the motor error, which is the difference between actual and predicted sensory feedback, and used its error as the source of updating forward model. As learning proceed, this motor error gradually decreases. This kind feedforward-feedback loop between body movement and its sensory feedback can enrich the forward

model of the body movements described in the model of sense of ownership and agency.

Based on this type of internal model-based human body controlling idea, the current results can enrich models of the brain mechanisms that generate ownership and agency. Figure 6-2 is a proposed extended model of the brain mechanisms that identify self-caused movement. In this model, predicted sensory feedback is compared to actual multisensory feedback. If the predicted and actual sensory feedback are temporally consistent, the received sensory feedback can be judged as self-caused, resulting in eliciting sense of agency. If consistent with body representation, the received sensory feedback can be judged from one's own body, resulting in eliciting sense of ownership. If inconsistent with either, the received sensory feedback can be judged as caused by another agent. The findings of experiments 1 and 2 and related studies (Ferrer et al., 2013, Ismail et al., 2016) imply the existence of a spatio-temporal window for binding the visual, proprioceptive, and tactile events into a single event in the comparator. The critical spatial offset is around 10 cm, and the critical temporal offset around 300 ms. In addition, the findings of experiment 3 indicated that the type of motion is more important than the shape of the thing that moves.

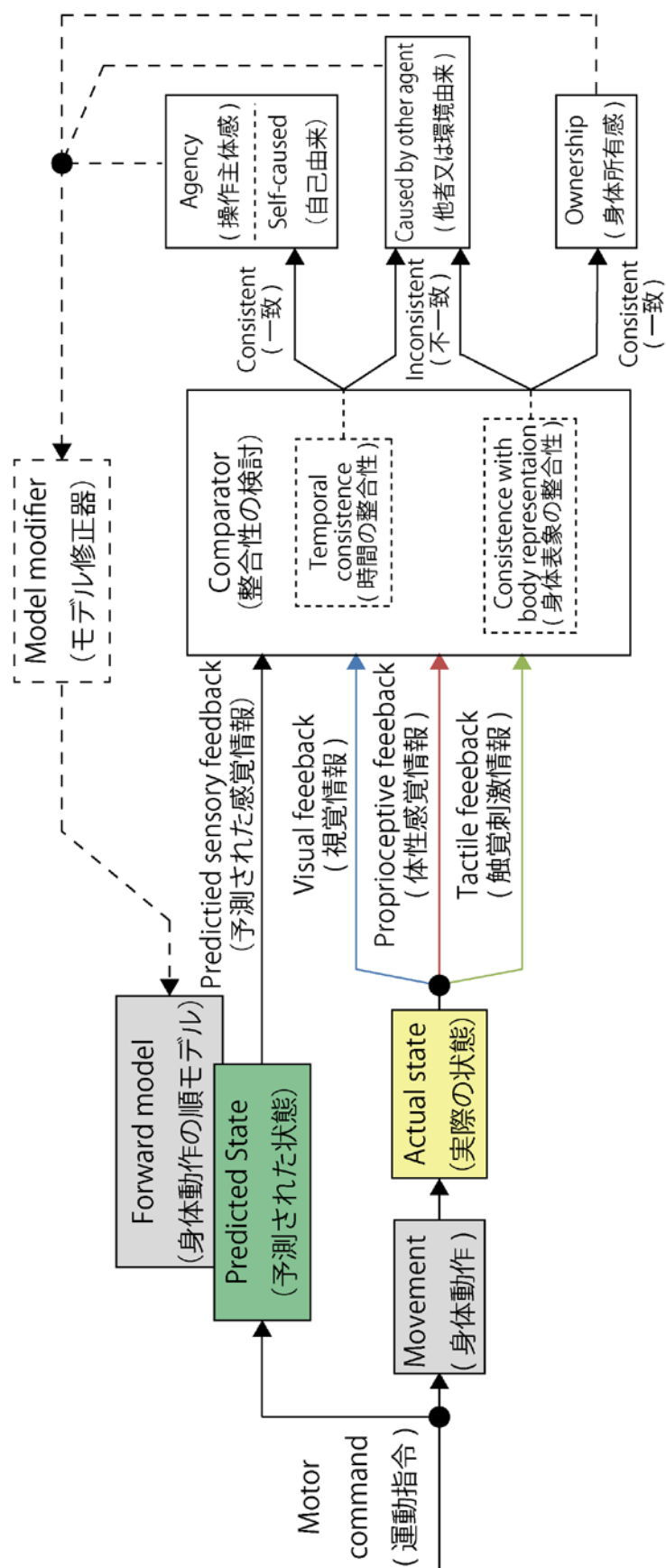
What does these kind of findings mean from the perspective of brain science? Possible account of the current finding was that spatio-temporal window to integrate (or bind) the visual and proprioceptive feedback of body motion in the comparison processing for the multisensory feedback. Although what kind of brain processing generate this window is unknown yet, this window might be a criterion to judge that sensory information from different modality was derived from certain one event. The other possible account was that the requirements in the multisensory feedback to keep sense of ownership and agency might reflect the spatio-temporal property of the forward model of the body movement. However, these possibilities does not go beyond the hypothesis obtained from the current findings. To clarify this, the further research is required with combining the finding in the field of physiology.

6.2 Future direction

As mentioned at the previous chapter, human brain is hypothesized to use the forward model or representation of body movements already acquired as the source of the prediction of the body movement. In current dissertation, how this representation of body movement was obtained and updated was not investigated since the current motivation was to investigate the representation of body movement already acquired in the brain. In fact, this motivation came from the question what kind of design would be suitable to obtain intuitive usability even for the real-time controlling system that the user used for the first time. This dissertation tried to answer this question from the perspective of brain science and psychophysics using the idea of usability of one's own body. Thus, the current findings was intended to adapt for the real-time controlling system or body itself which can be use the representation of the body movement already acquired in the brain as the source of the prediction of its sensory outcome. In contrast, the lacked (or damaged) body or the real-time controlling system, where patients or operators were required to learn new relationship between the action and its sensory outcome, can be out of range of the current findings. This was because the representation of body movements could not be used as the source of prediction of sensory outcome as our brain did not learn that relationship between action and sensory outcome yet.

However, the usability after getting used to the systems can be a large interest for the strategically design of real-time controlling systems as well. Human brain can gradually learn the new relationship between the body movement and its consequence sensory feedback though the repetitive training. For example, when riding a bicycle for the first time most of us could not ride very well, but once it has gotten used to riding we could ride the bicycle without thinking how to ride the bicycle. In other words, our brain can obtain or update the forward or inner model about relationship between body movement and its sensory consequence. This kind of usability can be a matter for the s strategically design of real-time controlling systems. To investigate this matter, it is necessary to touch the how the brain get used to the usage of tool or one's own body itself. Namely, how the brain generates and updates the representation of body

movement with learning is required to investigate. In this point, the several researches in the field of motor prediction already tried to argue how brain updated the invert model (or forward model) of body movement using prediction error of the body movement (e.g., Wolpert & Ghahramani, 2000). For example, when reaching the hand to a certain position, we sometimes miss approaching. In this time, our brain can rectify next approaching by comparing previous actual sensory consequence about hand movement with the desired ones. This can help to understand the how the brain obtain and update the forward model of body movement. However, it required the careful treatment to combine the model of motor prediction including Wolpert & Ghahramani (2000) and the model of the sense ownership and agency discussed in this paper. Interestingly, the schematic representation of the model of motor prediction (Figure 6-3) and model of sense of ownership and agency (Figure 6-2) could appear almost the same feed forward-based self/other discrimination model at the glance. However, the final output and background discussion was totally different in each models. Former model referred to how body moves, namely, the position or trajectory of body movement in physics, but latter model corresponds to how one feel about the body movement, namely, the feeling or sense about the one's own body movement even without actual body in physical world but in our mind and thought. To fill this gap in, the further research is required on the human subjective issue when we learn new inner model or bodily representation as well as the issue on the relationship between the computational brain science and psychophysics.



Modified from Gallagher (2000)' s model

Figure 6-2 Comparator model to distinguish self-caused action from multisensory feedback of action, modified from Gallagher's model.

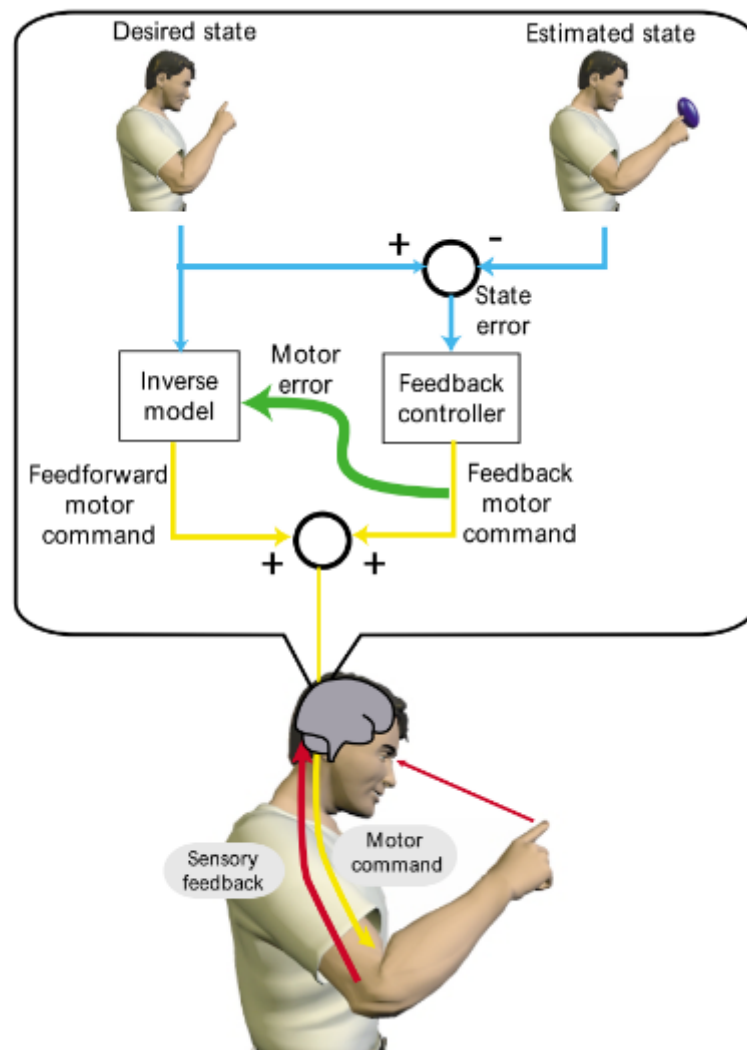


Figure 6-3 schematic model of motor prediction. From Wolpert & Ghahramani, 2000

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8. Achievement List

Reviewed articles

1. Tajima, D., Mizuno, T., Kume, Y., & Yoshida, T. (2017). Synchronized Tri-modal Feedback does not Enhance Proprioceptive Drift, Sense of Ownership, or Agency in a Modified Mirror Illusion Paradigm. (Submitted) (chapter 4.)
2. Tajima, D., Mizuno, T., Kume, Y., & Yoshida, T. (2016). Visualization Method for Proprioceptive Drift on a 2D Plane Using Support Vector Machine. Journal of Visualized Experiments, (116). doi.org/10.3791/53970 (the method of chapter 3.)
3. Tajima, D., Mizuno, T., Kume, Y., & Yoshida, T. (2015). The mirror illusion: does proprioceptive drift go hand in hand with sense of agency? Frontiers in Psychology. doi: 10.3389/fpsyg.2015.00200 (chapter 3.)

Other journal articles

1. 葭田 貴子, 神谷 聖耶, 田島 大輔 (2016) 「自分の身体の使い心地」の心理学的・脳科学的計測, 計測と制御, 55, 3, 252-258.
2. Tajima, D., Mizuno, T., Kume, Y., & Yoshida, T. (2013). The contribution of the vibrotactile stimulation to our self-body position perception: The mirror illusion study. The Virtual Reality Society Report, Vol. 18, No. VRpsy01, 11-14.
3. 田島大輔, 水野統太, 久米祐一郎, 葭田貴子, "Mirror Illusion の生起に遠心性コピーは必要か", 『学会誌 VISION』, Vol.24, Number.2, page 86-89, 2014

International conference presentations

1. Tajima, D., & Yoshida, T., Limb or arm? A local body movement elicits a sense of agency but not a sense of ownership, European Conference on Visual Perception, Berlin, Germany. (August, 2017)
2. Tajima, D., & Yoshida, T. Visual search for self-controlled biological hand motion stimuli, 24th Annual Workshop on Object Perception, Attention, and Memory, Boston, US. (November, 2016)

3. Tajima, D., Mizuno, T., Kume, Y., and Yoshida, T., Does the sense of agency occur when tactile feedback is substituted for proprioceptive feedback? European Conference on Visual Perception, Liverpool, UK. (August, 2015)
4. Tajima D, Mizuno T, Kume Y, Yoshida T, “The Mirror Illusion: Does Proprioceptive Drift Go Hand in Hand with the Sense of Agency?”, Asia-Pacific Conference on Vision, Kagawa, Japan, (July, 2014).
5. Tajima D, Mizuno T, Kume Y, Yoshida T, “The contribution of the vibrotactile stimulation to our Self-body Position Perception: The Mirror Illusion Study”, The 22nd Virtual Reality Psychology International Conference, Fukuoka, Japan, (October,2013).
6. Tajima D, Mizuno T, Kume Y, Yoshida T, "The Contribution of Efferent Copy to a Mirror Illusion." Psychonomic Society, 2002, Toronto, Canada,(November, 2013)
7. Tajima D, Mizuno T, Kume Y, Yoshida T, "The contribution of the vibrotactile stimulation to the mirror illusion", European Conference on Visual Perception, P17-23, Bremen, Germany, (August, 2013)

Domestic conference presentations

1. 田島大輔, 葭田貴子, 操作対象の見た目と動作は身体所有感・操作主体感の生起に関連するか, 日本視覚学会, 島根, 2017 年 9 月
2. 田島大輔, 葭田貴子, 自分の手に対する身体所有感・運動主体感はどの視覚手掛かりによるものか, 日本視覚学会, 東京, 2017 年 1 月
3. 田島大輔, 葭田貴子, 手指の biological motion 刺激への視覚探索, 日本視覚学会, 新潟, 2016 年 8 月
4. 田島大輔, 葭田貴子, 操作主体感覚は, 体性感覚情報の代替として振動触覚刺激が提示された場合でも発生するか?, 日本視覚学会, 東京, 2015 年 8 月.
5. 田島大輔, 水野統太, 久米祐一郎, 葭田貴子, “Mirror illusion の生起に遠心性コピーは必要か”, 日本視覚学会, 札幌, 2013 年 7 月

Awards

1. 2012 年 3 月 平成 24 年度 東京工業大学優秀学生賞

Appendix A: Full questionnaire statements for mirror illusion.

Table A-1. Questionnaires consisted of 16 statements classified into four categories in Japanese and English.

Category	
Ownership	1.まるで自分の右手を見ているように感じた。 (I felt as if I was looking at my own right hand.)
	2.鏡に映る手が私の体の一部のように感じた。 (I felt as if the hand in the mirror was part of my body.)
	3.あたかも私自身の右手が、鏡に映る手が動いている場所と同じ場所で動いているような感じがした。 (It seemed as if I was sensing the movement of my right hand in the location in which the hand in the mirror moved.)
	4.私は、鏡に映る手が自分の右手であるように感じた。 (I felt as if the hand in the mirror was my hand.)
Ownership control	5.私は、自分の本当の右手がだんだん鏡に映る手であるように感じた。 (I felt as if my real right hand was turning into the hand in the mirror.)
	6.あたかも、もう一つの右手があるような感じがした。 (It seemed as if I had more than one right hand.)
	7.鏡に映る手が自分の本当の右手の位置に移動していくような感じがした。 (It appeared as if the hand in the mirror was drifting toward my real hand.)
	8.あたかも自分の右手が以前から消滅しているかのように、以後ずっと右手がなくなるような感じがした。 (It felt as if I had no longer a right hand, as if my right hand had disappeared.)

Table A-1 Questionnaires consisted of 16 statements classified into four categories in Japanese and English

Category	
Agency	9.鏡に映る手が、右手として思うように動き、まるで自分の意思に従っているようだった。 (The hand in the mirror moved just like I wanted my right hand to, as if it was obeying my will.)
	10. 私は自分自身が鏡の中の手の動きを右手として操作しているように感じた。 (I felt as if I was controlling the movement of the hand in the mirror like I would control that of my right hand.)
	11. 私は、自分で見ている動きを、右手の動きとして自分自身が引き起こしているように感じた。 (I felt as if I was causing the movement created by the hand that I saw as my right hand.)
	12. 私は自分の右手を動かしたときは常に、同じように鏡に映る手が動くことを期待した。 (Whenever I moved my right hand, I expected the hand in the mirror to move in the same way.)
	13. 私は鏡に映る手が私自身の意思を操作しているように感じた。 (I felt as if the hand in the mirror was controlling my will.)
	14. 鏡に映る手が自分の動きを操作しているように感じました。 (I felt as if the hand in the mirror was controlling my movements.)
Agency Control	15. 実際の右手と鏡に映った手の間のどこかに、何かが動く感じがした。 (I could sense the movement from somewhere between my real right hand and the hand in the mirror.)
	16. 鏡に映る手がそれ自体に意志があるようでした。 (It seemed as if the hand in the mirror had a will of its own.)