Psychology, 2018, 9, 2996-3006
http://www.scirp.org/journal/psych
ISSN Online: 2152-7199
ISSN Print: 2152-7180

Inferior Parietal Lobe Activity in Visuo-Motor Integration during the Robot Hand Illusion

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How to cite this paper: Ismail, M. A. F. B., & Shimada, S. (2018). Inferior Parietal Lobe Activity in Visuo-Motor Integration during the Robot Hand Illusion. *Psychology, 9,* 2996-3006.
https://doi.org/10.4236/psych.2018.915174

Received: December 4, 2018
Accepted: December 22, 2018
Published: December 25, 2018

Abstract

The robot hand illusion (RoHI) is the participant's illusion of the self-ownership and the self-agency of a robot hand that appears to be moving consistently with their own hand, and feel as if the robot hand belongs to them. Mismatching between motor and visual information disrupt the effect of RoHI respect to the robot hand. In our previous study, we found that participants felt that the virtual hand was their own when the visual feedback was delayed by less than 200 ms. Moreover, although they did not feel that the virtual hand was their own, the participants felt that they could control the virtual hand even with a visual delay of 300 - 500 ms. Here, we used near-infrared spectroscopy (NIRS) to investigate brain activity associated with the RoHI under different delayed visual feedback conditions (100 ms, 400 ms, and 700 ms). We found significant activation in the supramarginal gyrus and superior temporal gyrus in the 100 ms feedback delay condition. An ANOVA indicated that this activation was significantly different from that in other conditions ($p < 0.01$). These results demonstrate that activity in the inferior parietal cortex was modulated by the delay between the motor command and the visual feedback regarding the movement of the robot hand. We propose that the inferior parietal lobe is essential for integrating motor and visual information that enables one to distinguish their own body from those of others.

Keywords

Robot Hand Illusion, Sense of Ownership, Sense of Agency, Inferior Parietal Lobe

1. Introduction

As humans, we can make a distinction between our own body and those of other people. This sensation of self-body ownership, which happens naturally in our body, can be easily manipulated via the rubber hand illusion (RHI) paradigm. In the RHI, the participant perceives visually presented tactile stimulation of a fake hand (rubber hand) as their own tactile sensation, and sometimes perceives the rubber hand as being part of their own body (Botvinick & Cohen, 1998; Armel & Ramachandran, 2003). This experience indicates that self-body ownership can be established based on the temporal integrity of somatosensory and visual information.

However, a mismatch between tactile stimulation of the rubber hand and that of the real hand can prevent the RHI from occurring. Some studies have addressed this issue by investigating synchronous and asynchronous conditions (Tsakiris & Haggard, 2005; Longo et al., 2008; Lane et al., 2017; Rohde et al., 2011; Kalckert & Ehrsson, 2014). The results indicated that the participants felt the rubber hand as if it was their own in the synchronous but not the asynchronous condition. Further studies comprehensively have been conducted to investigate more accurately of the time binding in the RHI (Shimada et al, 2009, 2014). According to Shimada, the sensation of ownership toward the rubber hand was attenuated for a delay greater than 200 ms between tactile stimulation of the real and rubber hands. Several studies examined brain activity during the RHI in terms of multisensory integration. They found that when participants felt the effects of the RHI, brain activity in the premotor cortex (PMC) and inferior parietal lobe (IPL) was associated with multisensory integration (Ehrsson et al., 2004; Shimada et al., 2005; Petkova et al., 2011; Brozzoli et al., 2012; Limanowski & Blankenburg, 2015, 2016).

Self-body recognition has been extensively investigated in terms of both ownership and agency. Recently, studies have employed robot hands to investigate this subject using a phenomenon known as the robot hand illusion (RoHI) (Ismail & Shimada, 2016; Romano et al., 2015; Alimardani et al., 2013; Caspar et al., 2014; Sato et al., 2017). In the RoHI, participants experience an illusion of self-ownership and self-agency when observing a robot hand that moves consistently with their own hand, and they report feeling as if the robot hand belongs to them. In terms of both ownership and agency, the effect of the RoHI was found to be significantly stronger when the visual feedback was delayed by less than 200 ms (Ismail & Shimada, 2016). Further, the attenuation in the degree of the RoHI was observed for delay between 200 - 300 ms (Ismail & Shimada, 2016). However, previous RoHI studies have not comprehensively addressed the effects of temporal delay between these senses modulate the brain area.

In the present study, we investigated temporal binding in the ownership sense and the agency sense during the RoHI under various delayed visual feedback conditions. We also examined the effects of the RoHI on brain activity. Data collected using near-infrared spectroscopy (NIRS) were analyzed to examine how the visual feedback delay modulated activity in different brain areas during the RoHI. We predicted that activity in the parietal lobe would be associated with multisensory integration due to the effect of RoHI toward the robot hand.

2. Material and Methods

2.1. Participants

Seventeen healthy students (all male; aged 21.6 ± 0.5 years) who were naive to the purpose of the study were recruited for the experiment. Fifteen participants were right-handed and two were left-handed, and all had normal or corrected-to-normal vision. All participants provided written informed consent. The experiment was approved by the ethics committee of the School of Science and Technology, Meiji University, and was conducted according to the principles and guidelines of the Declaration of Helsinki.

2.2. Procedure

The participants were asked to sit at a table with their right hand on the table with their palm facing down. The participants were not able to see their own right hand directly (see **Figure 1**). The participants wore a sensor glove on their right hand, and were instructed to make specific hand movements. This enabled us to record the hand movements and transfer them to the arduino. The movement of the robot hand was generated using recorded data through the arduino. We tested three visual feedback delay conditions (100, 400, and 700 ms) and two control conditions (control 1, participants observed the robot hand moving without moving their own hand; control 2, participants moved their hand without observing the robot hand) for opening and closing hand movement for each participant. Each trial lasted 30 s (5 s pre-rest, 10 s task, and 15 s post-rest), and was repeated 6 times. We recorded NIRS data for each delay condition. The order of the delay conditions was pseudo-random and counterbalanced across participants.

Before start the experimental task, each participant was instructed to mark the position of the index finger of their hidden right hand from under the table. This served as the origin from which to measure proprioceptive drift. After completing each trial, the participant was instructed to mark the felt position of their right index finger again from under the table (post-task). Proprioceptive drift was measured from the origin to the post-task mark position of the right index finger. A positive drift value indicated that the participant sensed their hand position toward the robot hand.

After completing each condition, participants (except for those in the control 2 condition because no robot hand was presented) completed a 16-item questionnaire identical to that used in previous studies (Kalckert & Ehrsson, 2012; Ismail & Shimada, 2016). The questionnaire was conducted in either the original English or in Japanese (see **Figure 1**). Participants rated their subjective experience on a 7-point Likert-like scale ranging from −3 (totally disagree) to +3 (totally agree), with 0 indicating neither agreement nor disagreement (uncertain). Four statements referred to the feeling of ownership (e.g., "I felt as if I was looking at my own hand"), and four statements described sensations related to agency (e.g., "I felt as if I was causing the movement I saw"). The remaining

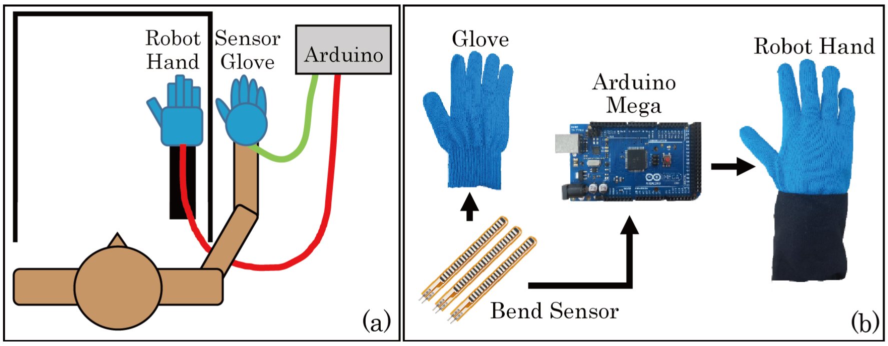

Figure 1. The experimental setting (a) and the composition of the sensor glove used to record the hand movement and transfer it to the robot hand through arduino (b).

eight statements were control statements which is describe the fake question of the senses; four describing ownership and the other four describing agency (e.g., "I felt as if I had more than one right hand" and "It seemed as if the hand image had a will of its own").

2.3. NIRS Recording and Data Analysis

The NIRS data were recorded using a multichannel NIRS unit operating at 780-nm, 805-nm, and 830-nm wavelengths (OMM-3000, Shimadzu, Japan) with a sampling frequency of 10 Hz. Oxy-hemoglobin (oxyHb), deoxy-hemoglobin (deoxyHb), and total hemoglobin (total Hb) concentrations were recorded in the temporal, parietal, and occipital lobes (see Figure 2). The optode locations were recorded using a 3D magnetic space digitizer (Fastrak, Polhemus, USA) to estimate the anatomical brain region beneath the NIRS channels. To determine the correspondence between the measured position data and the NIRS channels, we used the probabilistic spatial registration method (Singh et al., 2005) to generate probabilistic mapping between each NIRS channel and its corresponding anatomical brain region. This was then used to interpret the NIRS-activation data. The change in oxyHb is considered to be the main parameter that changes with regional cerebral blood flow. We applied a 2-Hz low-pass filter and a 0.2-Hz high-pass filter to the NIRS data. To compare the degree to which cortical activity was correlated among the conditions, we took the sum of the averaged correlations for each participant and each experimental condition (known as ISC). We used general linear model (GLM) which is an analysis method for statistically examining how much fitting observed signal data can be fitted with a model called design matrix. Comparisons across conditions were performed using an analysis of variance (ANOVA).

3. Result

3.1. Questionnaire Results

The averaged responses to the questionnaire items related to the ownership sense (item 1 - 4) and those related to the agency sense (item 9 - 12) for all

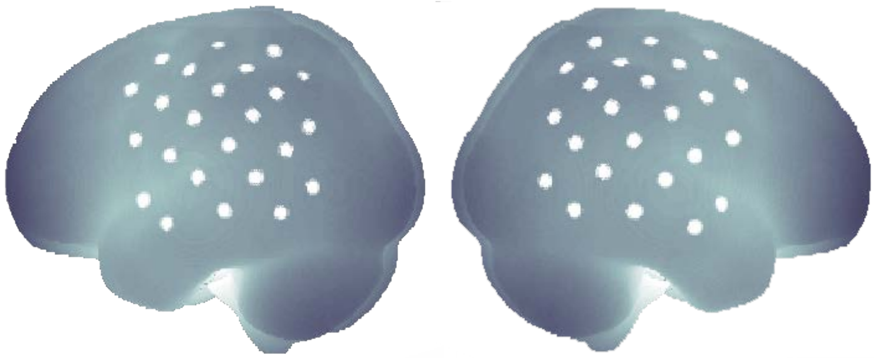

Figure 2. Location of the optodes placed in both hemispheres.

participants are shown in **Figure 3**. The participant questionnaire scores in the 100-ms visual feedback delay condition were significantly different than 0 (neutral) in terms of both ownership and agency. Scores for both ownership and agency decreased as the length of the visual feedback delay increased, and scores were lowest in the control condition.

The one-way (delay) ANOVA was applied separately to the ownership sense and the agency sense related questionnaire. The results showed significant main effects of delay (ownership, $F(3, 64) = 12.764$, $p < 0.01$; agency, $F(3, 64) = 98.416$, $p < 0.01$, Tukey's honestly significant difference (HSD)). For both the ownership sense and the agency sense, subsequent analyses showed that the questionnaire scores in the 100-ms delay condition were significantly greater than the other conditions, and those in the 400-ms delay condition were significantly greater than those in the 700 ms delay and control 1 conditions ($p < 0.01$). In addition, there was significantly greater between 700 ms delayed conditions and control 1 condition in agency sense ($p < 0.01$).

The subjective ratings for the sense of ownership control and the agency control are depicted in **Figure 4**. The one-way ANOVA indicated no significant main effect of delay among conditions for both senses (ownership control, $F(3, 64) = 1.811$, $p > 0.1$; agency control, $F(3, 64) = 0.440$, $p > 0.1$).

3.2. Proprioceptive Drift

One sample t-tests indicated that proprioceptive drift was significantly higher than 0 in the 100-ms, 400-ms, and control 1 conditions (100-ms, $t(16) = 6.530$; 400-ms, $t(16) = 3.192$; control 1, $t(16) = 3.143$) (see **Figure 5**). We used a one-way ANOVA to more closely inspect the proprioceptive drift data with respect to the RoHI. The results showed a significant main effect of experimental condition ($F(3, 64) = 7.974$, $p < 0.01$). Subsequent analyses showed that the proprioceptive drift for the 100-ms delay condition was significantly greater than the other conditions ($p < 0.01$).

3.3. NIRS Results

NIRS measurements revealed that the length of the delay modulated parietal activity. In the right hemisphere, the supramarginal gyrus (Ch. 33, 36, 40) was

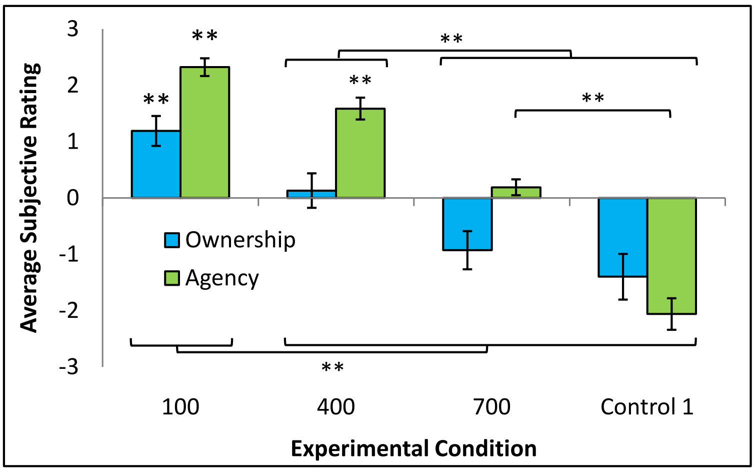

Figure 3. Average subjective ratings of ownership and agency (**$p < 0.01$).

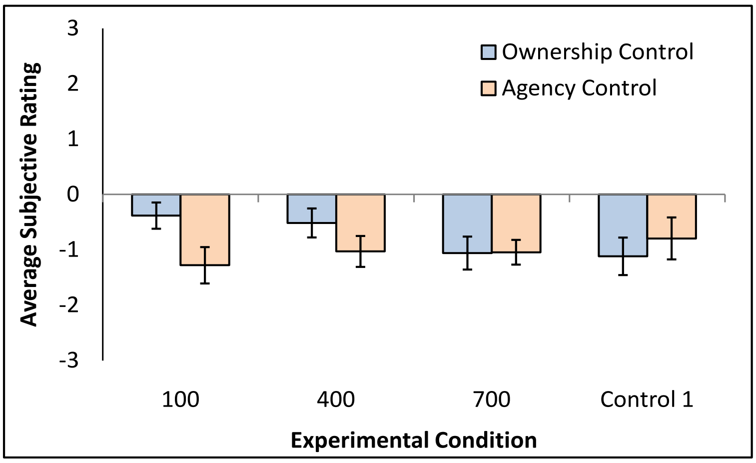

Figure 4. Average subjective ratings of ownership control and agency control.

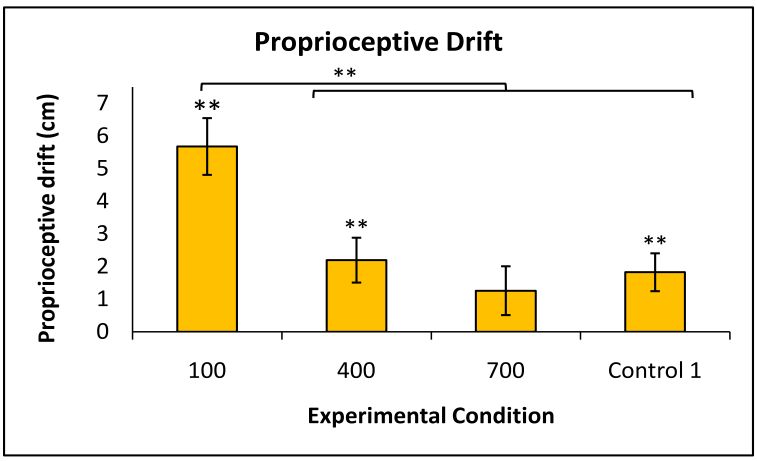

Figure 5. Proprioceptive drift (**$p < 0.01$).

strongly activated in the 100-ms visual feedback delay condition (Ch. 33, t (16) = 2.618; Ch. 36, t (16) = 2.454; Ch. 40, t (16) = 4.882; $p < 0.05$, False discovery rate

(FDR) corrected), but not in the other conditions. In addition, the superior temporal gyrus was strongly activated in the 100-ms visual feedback delay condition (Ch. 43) (t (16) = 3.299, $p < 0.05$, FDR corrected). We applied a one-way (experimental conditions) ANOVA separately to each NIRS channel. The results showed that there were significant effects of delay in all channel (Ch. 33, F (4, 80) = 3.461, $p < 0.05$; Ch. 36, F (4, 80) = 3.844, $p < 0.01$; Ch. 40, F (4, 80) = 4.056, $p < 0.01$; Ch. 43, F (4, 80) = 3.659, $p < 0.01$) (see **Figure 6**). Subsequent analyses showed that the activation in the supramarginal gyrus and the superior temporal gyrus during conditions with a 100 ms delay was significantly greater than other conditions ($p < 0.01$).

4. Discussion

In this study, we investigated changes in the sense of ownership and agency that occurred during the robot hand illusion. As expected, participants experienced a significantly stronger RoHI in 100-ms visual delay condition both in terms of ownership and agency. Our questionnaire results were consistent with the findings of our previous study. Specifically, the participants were more likely to feel that the virtual hand belonged to them and to experience a stronger sense of agency when the visual feedback delay was less than 200 ms (Ismail & Shimada, 2016).

To measure the sense of ownership toward the robot hand, we measured proprioceptive drift after the task in each experimental condition. These data indicated that the sensation of ownership was stronger in the 100-ms delay condition compared with the other conditions. Thus, the participants had a stronger sensation that the robot hand was their own hand in the 100-ms visual feedback delay condition. Other studies have reported that participants felt a stronger sense of ownership in synchronous experimental conditions, and that there was a significant difference in proprioceptive drift between synchronous and asynchronous (500 ms delay) conditions (Caspar et al., 2015). Additionally, Kalckert and Ehrsson identified significant differences in proprioceptive drift between active synchronous and asynchronous conditions, and found that proprioceptive drift was significantly correlated with perception of ownership (Kalckert & Ehrsson, 2014). Our results indicate that when proprioceptive drift is high, the sensation of ownership toward the robot hand is likely to be stronger.

We observed RoHI-induced activation in the inferior parietal lobule (IPL) during the experimental task. The right supramarginal gyrus and superior temporal gyrus were activated in the 100-ms delay condition only. The experience of illusory hand ownership has been associated with the premotor cortex (PMC) (Ehrsson et al., 2004; Petkova et al., 2011; Brozzoli et al., 2012; Gentile et al., 2013; Bekrater-Bodmann et al., 2014) and intraparietal sulcus (IPS) (Ehrsson et al., 2004; Petkova & Ehrsson, 2008; Makin et al., 2008; Brozzoli et al., 2012; Gentile et al., 2013). When their real hand and a fake hand were stroked synchronously, participants exhibited activation in the PMC and IPS that was stronger

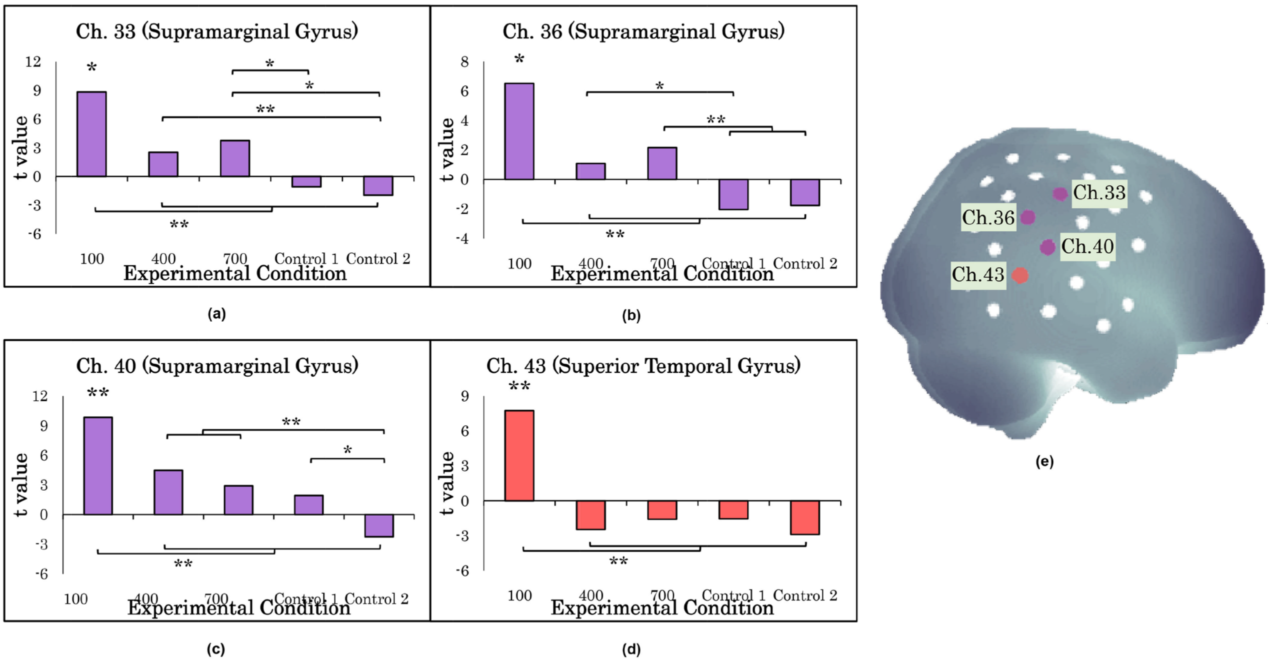

Figure 6. Activity patterns in NIRS channels for each condition (a)-(d) and channel locations on right hemisphere (e). The position with red marker indicates the position of the superior temporal gyrus and with purple markers indicate the position of the supramarginal gyrus. (**$p < 0.01$, *$p < 0.05$).

and more frequent compared with that in other conditions (Makin et al., 2008). Limanowski and Blankenburg identified activity within the temporal gyrus that was associated with a sense of ownership toward a fake hand, indicating that this region might also play a role in the multisensory integration of stimuli with respect to the hand (Limanowski & Blankenburg, 2016). Furthermore, neuroimaging studies have shown that participants felt a greater sense of agency during activation of the IPL and posterior parietal cortex (PPC) (Blakemore et al., 1998; Fink et al., 1999; Chaminade & Decety, 2002; Farrer & Frith, 2002; Farrer et al., 2008; Schnell et al., 2007). These findings are consistent with our results, particularly that activation in the IPL area was associated with a feeling of ownership and agency toward a robot hand. Thus, we suggest that these areas might be engaged in multisensory integration between visual and motor information.

5. Conclusion

In this study, we investigated brain activity associated with the RoHI under different visual feedback delay conditions. Our results indicate that the participants felt the effect of the RoHI with respect to the robot hand. Specifically, they appeared to experience higher levels of ownership and agency in the 100-ms delay condition. We used proprioceptive drift to measure perception of ownership, and found that participants felt more ownership toward the robot hand in the 100-ms delay condition. We suggest that activation in the inferior parietal lobe is essential for integrating motor and visual information necessary to distinguish one's own body from those of others.

Acknowledgements

This work was supported by Grants-in-Aid for Scientific Research (16H02839 and 17H05915) from the Japan Society for the Promotion of Science (https://www.jsps.go.jp/english/e-grants/). The funders had no role in study design, data collection and analysis, decision to publish, or preparation of the manuscript.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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