Degree project

UNIVERSITY OF SKÖVDE

Ownership in passive and active movements: A systematic review and meta-analysis of the moving rubber hand illusion

Bachelor Degree Project in Cognitive Neuroscience
First Cycle 22.5 credits
Spring term 2021

Student: Joakim Arntz
Supervisor: Andreas Kalckert
Examiner: Oskar MacGregor

Table of Contents

Abstract

The *rubber hand illusion* is an experimental paradigm that induces the illusion of ownership over a fake hand. The illusion was originally induced using visuotactile stimulation but can also be induced using movements. Self-produced movements are *active movements*, and if they are produced by external force, they are *passive movements*. According to the *comparator model*, only active movements produce a *sense of agency*. As both passive and active movements can be used to induce the *sense of ownership* in the rubber hand illusion, but only active induce a sense of agency, they can be compared to determine the effect agency has on bodily ownership. This meta-analysis included nine studies with a total of 359 participants that compared the induced sense of ownership using active and passive movements in the rubber hand illusion to determine these effects. The results show that agency has a small but significant effect on body ownership.

Keywords: rubber hand illusion, passive movements, active movements, comparator model, sense of ownership, sense of agency

Ownership in passive and active movements: A systematic review and meta-analysis of the rubber hand illusion

How do we determine that our body is our own, and how do we determine that we are the ones moving our body? Does the feeling of control over our movements affect the sense that we own our bodies? These questions are of interest for consciousness research, research regarding different neurological or psychiatric disorders, prosthetic research, and virtual reality. It is often taken for granted that we can separate between what is our body and what is not and that we have a *sense of agency* over our movements, but what are the underlying mechanisms of these sensations? The sense of agency refers to the experience of being the agent of the actions or movements of our body, the feeling of controlling our body (David et al., 2008). The *sense of ownership* over our bodies is the sense that we are the ones undergoing an experience (Ehrsson, 2012).

Researchers have manipulated different sensory input to induce the illusion of ownership over a fake limb (e.g., Botvinick & Cohen, 1998) or even an entire fake body (e.g., Petkova & Ehrsson, 2008). The feeling of ownership over a fake limb or an entire body do not necessarily imply a sense of agency. Recent research has started to induce the illusion of ownership over a fake limb using movements (e.g., Dummer et al., 2009; Kalckert & Ehrsson, 2012; Tsakiris et al., 2006). When the movements are self-produced, it induces a sense of agency over the fake limb in addition to a sense of ownership (e.g., Dummer et al., 2009; Kalckert & Ehrsson, 2012). When the movements are produced by an external force, i.e. by the researcher, it does not induce a sense of agency but still induces a sense of ownership over the fake limb (e.g., Dummer et al., 2009; Kalckert & Ehrsson, 2012). How the illusion of ownership is induced and how the sense of ownership is created will be explained in the next section.

The sense of ownership

One of the most famous body illusions is the *rubber hand illusion* (RHI) (Botvinick & Cohen, 1998). Classically it is induced by manipulating visuotactile input to create the illusion of ownership over a fake hand. It is done by hiding the participants' real hand from view while a fake hand is within view and stroking the two hands synchronously. However, when the real hand and fake hand are stroked asynchronously, the illusion is not induced. The illusion is typically measured using subjective questionnaires and *proprioceptive drift* (Botvinick & Cohen, 1998). The questionnaires contain statements regarding whether the participants felt that the fake hand was their own (e.g., "I felt as if the rubber hand were my hand") and are typically answered on a 7-point Likert scale (e.g., Botvinick & Cohen, 1998; Ehrsson, 2012; Tsakiris et al., 2010). Information about where the body is positioned is called proprioception, and it is created by specialized nerve cells that receive information from, e.g., muscle, tendons, and joints (Gazzaniga et al., 2014). Proprioceptive drift is measured by

asking the participants to close their eyes and point where they feel their real hand is (e.g., Ehrsson, 2012; Kalckert & Ehrsson, 2017). The distance between where the participants have pointed before and after the illusion has been induced is measured. If the participants point closer to the fake hand after the illusion has been induced it means that their proprioception has "drifted" away from their real hand.

It is suggested that the sense of ownership depend on *multisensory integration* (Ehrsson, 2012). The human brain has different cortical convergence zones in the parietal, temporal, and frontal lobes, where information from different sensory modalities converge. The different senses have different subjective impressions, and multisensory integration creates a unitary perceptual experience from all the impressions (Stein & Stanford, 2008). Spatial congruence is important for multisensory integration. Spatially congruent stimuli reinforce each other, but when incongruent, one can suppress the other. These inputs must also be connected in time, and the window for the integration can last up to several hundred milliseconds.

Both spatial and temporal congruence is important for multisensory integration and the sense of bodily ownership (Ehrsson, 2012). Studies that have measured delayed tactile stimulation in the classical RHI have found that the illusion of ownership is not induced when there is temporal incongruency (Botvinick & Cohen, 1998; Kalckert & Ehrsson, 2014a). Nor is the illusion induced when there is too large a spatial incongruence between the fake hand and the real hand (Kalckert & Ehrsson, 2014b). The classical illusion is suggested to depend on a three-way interaction between vision, touch, and proprioception (Ehrsson, 2012). The premotor cortex and intraparietal areas have been found to be important for integrating visual and somatosensory stimuli, and the illusion depends on this integration. The ventral premotor cortex is connected to both visual and somatosensory areas in both posterior parietal cortex (PPC) and frontal motor areas and has been observed to reflect the matching of visual and somatosensory input (Ehrsson et al., 2004). A correlation between the sense of ownership and activation in frontal motor areas, the PPC, and bilateral premotor cortex has been observed. The intraparietal cortex is connected with visual and somatosensory input and the integration of these senses, and this integration has been found to be important for the sense of ownership. It has been suggested that visual and tactile stimuli are likely to evoke multisensory reinforcement or suppression (Stein & Stanford, 2008). Visual input has been suggested to be dominant over proprioceptive input (Ehrsson et al., 2004), and that is why the illusion of ownership is generated in the RHI.

As demonstrated above, the sense of ownership is dependent on multisensory integration (Ehrsson, 2012), and the illusion of ownership over a fake hand is induced by manipulation visual and somatosensory input (Botvinick & Cohen, 1998). However, the classical RHI does not induce a sense of agency over the fake hand (e.g., Kalckert & Ehrsson,

2014a). How the RHI experimental paradigm can be changed to induce a sense of agency over a fake hand and how the sense of agency is created will be presented in the next section.

The sense of agency

The RHI is not limited to visuotactile stimulation and can also be induced using movements (e.g., Dummer et al., 2009; Kalckert & Ehrsson, 2012, 2014a). When the RHI is induced with different movements, it is typically referred to as the *moving RHI* or active RHI and will be referred to as the moving RHI in this thesis (e.g., Kalckert & Ehrsson, 2014a; Pyasik et al., 2019). The setup is often similar to the classical RHI, but instead of stroking the hand, the illusion is induced by moving the hand. Movements caused by self-produced actions are *active movements,* and movements caused by external force are *passive movements* (Cullen, 2004). The illusion can be induced by both active movements (the participants move their hands) and passive movements (experimenter move the hands of the participants) *(*e.g., Dummer et al., 2009). Both types of movements induce a sense of ownership over the fake hand, but only active movements induce a sense of agency (e.g., Dummer et al., 2009; Kalckert & Ehrsson, 2012, 2014a). The sense of agency in the moving RHI is typically measured using subjective questionnaires answered on a 7-point Likert scale similar to the questionnaires measuring ownership. However, it instead contains statements regarding agency over the fake hand (e.g.," I felt as if I was causing the movement I saw") (Kalckert & Ehrsson, 2012). The questionnaires regarding both ownership and agency are most commonly rated on a -3 to +3 scale, and scores over +1 are interpreted as that the illusion was induced. Control statements are often included in the questionnaires to control for suggestibility, compliance, and expectancy effects.

The sensory systems need to differentiate between passive and active movements to maintain accurate motor control and perceptual stability. One of the most prominent motor control theories is *the comparator model*, and it suggests that motor control is essential for the sense of agency (David et al., 2008). The transduction of sensory signals to the central nervous system is not instant, which delays sensory input by around 100ms (Wolpert & Ghahramani, 2000). The delay creates a need to use predictions to determine the actions and properties of the external world. These predictions are about the sensory feedback a movement will generate and the new state of the body the movement will create. Motor output sends efferent signals when a movement is made, and these movements, in turn, produces new sensory information (Cullen, 2004). A theory proposed by von Holst and Mittelstaedt in 1950 suggested that intentional movements produce an *efference copy* of the motor command. The efference copy is then subtracted from the sensory input the movement produces. The efference copy is used to predict the new sensory information the movement will produce. If the predicted sensory input and the actual sensory input is congruent, it can be determined that the movement was self-produced. If they are not, it can be determined

that an external force caused the movement. The comparator model further suggests different steps of this determination and that the efference copy has an essential role in our sense of agency (David et al., 2008).

The first step of a movement is the intention to move, followed by the motor planning of said movement (David et al., 2008). The next step is sending efferent signals for the movement, which is joined by the efference copy that contains the predicted sensory consequences of the movement. After the movement has been executed, the actual sensory input is compared with the prediction. When the predicted sensory outcome and the actual sensory feedback is congruent, it gives rise to a sense of agency over that movement. If they are incongruent, it can be determined that the movement must be caused or perturbed by an external force, and consequently, there is no sense of agency.

According to the comparator model, sensory information caused by external force and self-produced actions must be processed differently in the brain, which is crucial for our sense of agency (David et al., 2008). Single brain areas are yet to be discovered directly connected to the sense of agency (David et al., 2008). However, the PPC and extrastriate body area (EBA) have been suggested to be important for the comparator model. The PPC is involved in self-produced actions and visual consequences, and the EBA is involved in self-generated movements. These areas are heavily connected to each other and have a similar response activation, which would indicate a close functional relationship (David et al., 2008).

Nevertheless, this retrospective comparison of predicted sensory outcome and actual sensory feedback is not enough to explain agency (Haggard, 2017). The intention and planning of the movement are also important for the sense of agency, and consequently, there is no sense of agency without intention and planning. Hence, both the selection and intention of movements are as important as the congruency of predicted sensory outcome and actual sensory feedback to create a sense of agency.

Frontal and prefrontal areas are important to the selection and initiation of actions (Haggard, 2017). These areas send information to the parietal lobe, which matches the actual sensory feedback of a movement with the predicted sensory outcome. The dorsolateral prefrontal cortex (DLPFC) has also been suggested to represent the possible movement responses and choose the most optimal motor response. DLPFC and rostral supplementary motor area (SMA) are involved in the planning, timing, and direction of movements (Jenkins et al., 2000). Active movements recruit the brain areas underlying motor control. In contrast, passive movements are independent of motor control and caused by external force, and are not compared to an efference copy and no sense of agency can be produced (David et al., 2008). Consequently, passive movements do not elicit a sense of agency, while active movements elicit a sense of agency (David et al., 2008; Wolpert & Ghahramani, 2000).

In essence, agency is created by three components, the comparison of sensory outcome and actual sensory feedback, the intention of the movement, and the planning of the movement (Haggard, 2017). The illusion of agency over a fake hand is induced by manipulating visual and afferent signals (e.g., Kalckert & Ehrsson, 2012, 2014a). Both passive and active movements induce a sense of ownership over a fake hand in the RHI, but only active movements induce a sense of agency. Therefore, the movement conditions can be compared to investigate if the sense of agency has an effect on the sense of ownership. The next section will examine the relationship between ownership and agency.

Agency and ownership

Moving RHI studies that have used an incongruent position of the fake hand have found a dissociation between the sense of ownership and the sense of agency (e.g., Kalckert & Ehrsson, 2012, 2014a). When the illusion is induced using active movements with a fake hand in an incongruent position, the participants get a sense of agency over the fake hand, but not a sense of ownership (e.g., Kalckert & Ehrsson, 2012; Shibuya et al., 2017). The classical version of RHI and RHI using passive movements have found that there can be a sense of ownership over a fake hand without a sense of agency (Botvinick & Cohen, 1998; Caspar, De Beir et al., 2015; Kalckert & Ehrsson, 2012). The dissociation between agency and ownership means there can be a sense of one without the other, but it is still unclear if agency affects ownership.

The role agency has in body ownership has been tested by comparing passive and active movements in the moving RHI (e.g., Caspar, De Beir et al., 2015; Jenkinson & Preston, 2015; Kalckert & Ehrsson, 2012; Marotta et al., 2017; Tsakiris et al., 2010). The comparison of passive and active movements would also test the efferent copy's role in the sense of ownership, as it has a crucial role in the sense of agency according to the comparator model (David et al., 2008).

A common assumption made in studies that examine active and passive movements with the RHI is that active movements will induce a stronger illusion, as it induces both a sense of agency and ownership (e.g., Kalckert & Ehrsson, 2012). According to the comparator model, the sense of agency induced by active movements requires motor control. It thus recruits more brain areas than passive movements, as the movements need to be attributed to ourselves (David et al., 2008). Studies that have examined passive versus active movements with the RHI have found mixed results. Some studies have found that active movements induce a stronger illusion (e.g., Dummer et al., 2009; Kalckert & Ehrsson, 2012), whereas other studies have found no significant difference (e.g., Kammers et al., 2009; Shibuya et al., 2017).

The present study aims to address the question: does the sense of agency affect the sense of ownership? The question will be answered by quantifying the results of studies

examining and comparing active and passive movements with the moving RHI. Answering this question will have further implications for different neurological or psychiatric disorders that affect both the sense of ownership and the sense of agency (e.g., schizophrenia and functional movement disorder), prosthetics research, and research in virtual reality. In addition, it will also benefit self-awareness and consciousness research, as the sense of agency and ownership are topics of interest in these fields.

Methods

The author has compiled the studies with the guidance of Andreas Kalckert. The initial literature search was conducted on the 2nd of February 2021, and the literature search concluded on the 3rd of March 2021.

Search strategy

Three electronic databases were used to conduct the literature search, Scopus, PubMed, and Web of Science. In addition to these databases, DiVA Skövde was used to examine previous theses on the subject and identify more studies. The search string used to conduct the literature search was ("Active rubber hand illusion" OR "Moving rubber hand illusion") AND "Active movement" AND "Passive movement".

Inclusion and exclusion criteria

The inclusion criteria for this thesis were (1) studies that have used the moving rubber hand illusion as the experimental paradigm. (2) Studies that have used both passive and active movements. (3) Studies that have measured ownership ratings using questionnaires. (4) Studies that have used within-subject comparisons (5) Studies on the general public or healthy participants over 18 years of age.

Studies that met the inclusion criteria were included regardless of the method used to induce the illusion, e.g., virtual reality, robotic hand, or rubber hand/fake hand. Which method used was documented. Questionnaires are the most common way of measuring the sense of ownership in RHI and, based on this, the subjective ratings of ownership from the questionnaires were chosen as the dependent variable. Only studies that included and compared both a passive and active movement condition were included. Only studies that used the same participants for both conditions were included to make within-subject effect size comparisons possible. Participants with neurological or psychiatric disorders that might affect the sense of ownership were excluded as the present study aimed to examine how agency affects ownership in the healthy population and not in the clinical population. Only published and peer-reviewed studies in English were included.

Data extraction

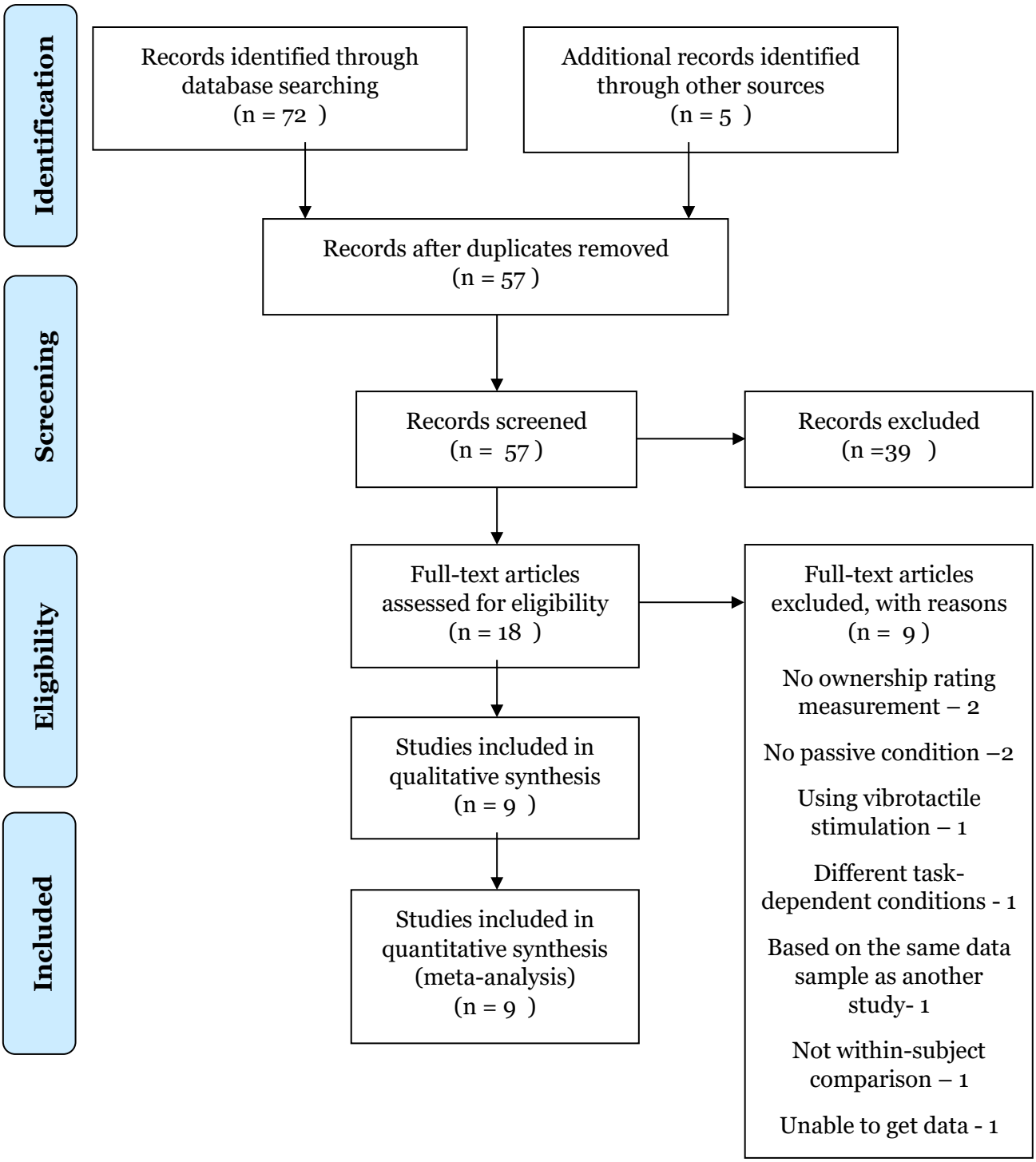
The main analysis focused on the ownership ratings for both active and passive movement conditions in the moving RHI. The mean scores and standard deviations for ownership ratings of the studies were analyzed. A few studies did not include means or standard deviations in text or used median and interquartile range instead. The authors of these studies were asked to provide the data of their study. Alternatively, quantile estimation was to be used to infer the mean and standard deviation from median and quartiles (McGrath et al., 2020).

Statistical analysis

A random-effects meta-analysis was used as these studies were not all conducted in the same manner, e.g. using different methods to induce the illusion (Siddaway et al., 2019). The standardized mean difference was used as the effect size.

Figure 1.

PRISMA 2009 Flow Diagram. Standard flow diagram used to document the literature search process (Moher et al., 2009).



Results

52 studies were identified using different databases after duplicates were removed. Five additional studies were identified from a Master thesis made by Malin Brundin (2020) and two of these were included in the qualitative and quantitative synthesizes (Longo & Haggard, 2009; Tsakiris et al., 2010). The identified studies were screened by title and abstract, and 39 studies were excluded. The full texts of the remaining 18 studies were assessed. The assessment resulted in nine studies in qualitative and quantitative synthesis (see Figure 1). The literature search resulted in 10 experiments and 359 participants to be synthesized in the meta-analysis. One additional study with two experiments that fit the inclusion criteria was identified, but the author was unable to acquire the data of this study (Caspar, Cleeremans et al., 2015). The included studies and experiments are listed in Table 1.

Study designs

Five studies examined the difference between active and passive movements with the moving RHI (Caspar, De Beir et al., 2015; Jenkinson & Preston, 2015; Kalckert & Ehrsson, 2012; Marotta et al., 2017; Tsakiris et al., 2010). Kalckert and Ehrsson (2012) used incongruent and congruent positioning of the fake hand in both movement conditions. Marotta et al. (2017) only used the different positions in the active movement condition with both asynchronous and synchronous movements. The study by Marotta et al. (2017) was mainly focused on the difference between a group of healthy participants and a group of participants with functional movement disorders. Only the group of healthy participants was included in this study. The study by Tsakiris et al. (2010) used synchronous and asynchronous movements in both movement conditions. During the experiment, the participants' brain activity was scanned in an fMRI, and the focus of the study was on the fMRI results. Jenkinson and Preston (2015) also used synchronous and asynchronous movements in both movement conditions in addition to different viewing conditions (mirror, direct, rotated 180˚). Only the direct viewing condition was of interest for this thesis. The experiment by Caspar, De Beir et al. (2015) did not use asynchronous movements, incongruent positions, nor any different viewing condition.

Two of the included studies examined the difference in ownership between passive movements, active movements, and visuotactile stimulation with the RHI (Kalckert & Ehrsson, 2014a; Pyasik et al., 2019). The study by Pyasik et al. (2019) investigated two different groups, one group with non-musicians and one group with musicians (pianists). The study focused mainly on the difference in ownership ratings between these groups. Both groups were included as both groups only contained healthy adults. The studies by Kalckert and Ehrsson (2014a) and Pyasik et al. (2019) used synchronous and asynchronous stimulation in all three variants of the illusion.

Two of the studies examined the difference in ownership ratings in sub-analyses and were mainly focused on other aspects, e.g., reaction time, and timing of the induced illusion (Kalckert & Ehrsson, 2017; Longo & Haggard, 2009).

Induction method

Six of the studies induced the illusion by placing a physical fake hand on top of a wooden box with the real hand obstructed from view inside the box (Jenkinson & Preston, 2015; Kalckert & Ehrsson, 2012, 2014a, 2017; Marotta et al., 2017; Pyasik et al., 2019). Two of the studies were induced using video-image projection of the participants' hand (Longo & Haggard, 2009; Tsakiris et al., 2010). In one of the studies, the real hand was hidden underneath the table the participants were seated. A robotic hand was placed on top of the table above their real hand, and the robotic hand was controlled by a sensor glove (Caspar, De Beir et al., 2015). The induction type for each study is presented in Table 1.

Questionnaires

The questionnaires from the different studies contained a variety of statements, with a majority of the studies including control statements regarding the sense of ownership. Two of the nine studies did not include any agency statements and did not measure agency explicitly. The total number of statements for each study and the number of statements regarding ownership and agency is presented in Table 1. All of the studies that did measure agency found that active movements did induce a sense of agency and passive movements did not. Those studies that used incongruent positions found that agency was induced with active movements regardless of position. However, when the fake hand was in an incongruent position, it did not induce a sense of ownership for passive or active movements in any of the studies. The studies that examined asynchronous and synchronous movements found that neither agency nor ownership was induced using asynchronous movements regardless of whether passive or active movements were used to induce the illusion.

Data acquisition

Three of the nine studies included mean scores and standard deviations (Caspar, De Beir et al., 2015; Kalckert & Ehrsson, 2012; Marotta et al., 2017). The authors of three studies provided the raw data of their experiments (Jenkinson & Preston, 2015; Kalckert & Ehrsson, 2014a, 2017;), and one study provided the raw data in supplementary materials (Pyasik et al., 2019). Two studies provided the mean and standard deviation for each ownership statement, and the total scores of these statements were summed up by the author of this thesis (Longo & Haggard, 2009; Tsakiris et al., 2010). Only conditions that used synchronous stimulation and congruent positions of the fake hand was of interest, and data was only extracted from these conditions for both active and passive movements. The mean, standard deviation, number of participants, and effect size from each study are presented in Table 1.

Table 1.

Information about included studies. The included studies are listed with the authors, year of publication, and which experiments were included in the table's left column. The second and third column shows the mean and standard deviation of ownership ratings for each study for passive and active movement. The column labelled statement is the total number of statements the studies used in their questionnaire. The columns labelled Agency and Ownership are how many statements regarded agency and ownership, respectively. The column labelled induction is the induction method used in the different studies. Box means that the experiment hid the participants' real hand in a box with a fake hand on top, robotic meaning that a robotic hand was placed on the table with the real hand below the table, and video meaning video-projected image of the hand. The column labelled n is the number of participants in each study, and the column labelled Hedge's g is the effect size for each study.

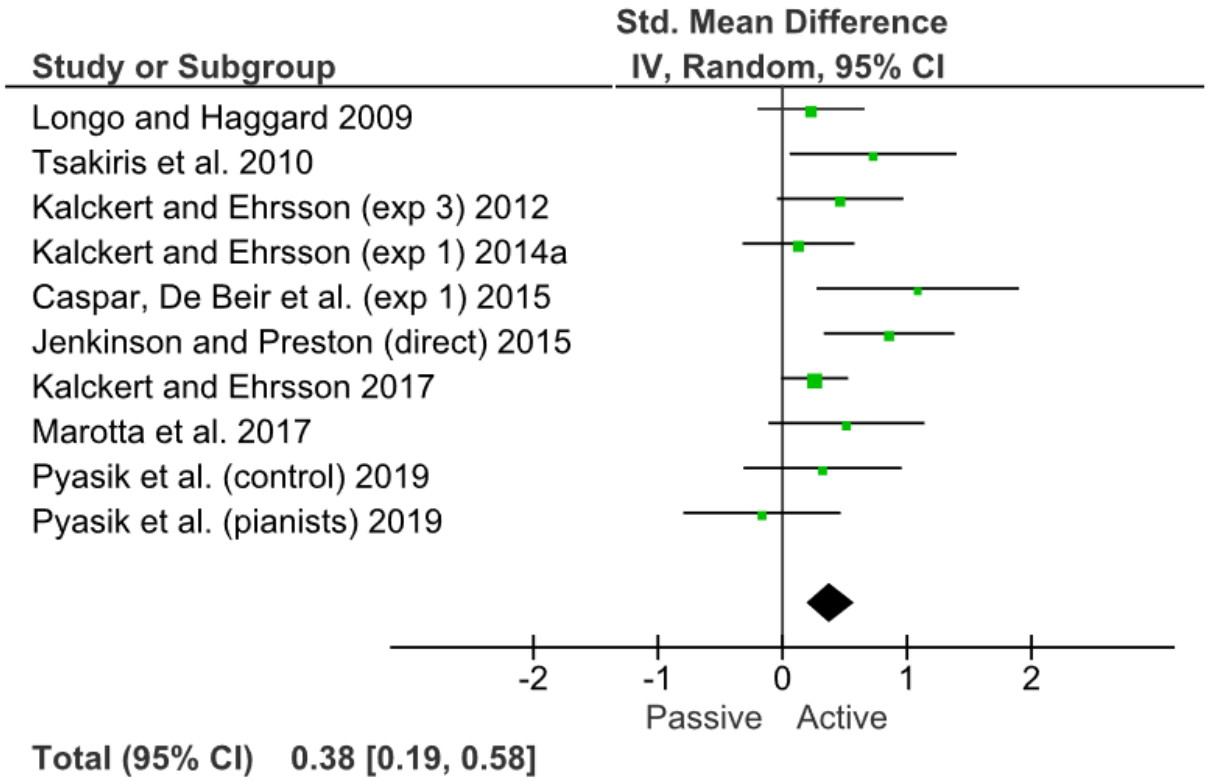
Study/Id	Passive	Active	Statements	Agency	Ownership	Induction	n	Hedge's g
1. Caspar, De Beir et al. (2015) exp 1	-0.03(1.32)	1.35(1.14)	8	4	4	Robotic	14	1.09
2. Jenkinson and Preston (2015) direct	0.14(1.61)	1.42(1.33)	8	2	2	Box	32	0.86
3. Kalckert and Ehrsson (2012) exp 3	1.57(1.30)	2.12(1.03)	16	4	4	Box	32	0.46
4. Kalckert and Ehrsson (2014a) exp 1	0.83(1.73)	1.06(1.81)	12	3	3	Box	40	0.13
5. Kalckert and Ehrsson (2017)	1.20(1.70)	1.63(1.61)	4	na	2	Box	117	0.26
6. Longo and Haggard (2009)	2.12(1.11)	2.36(0.96)	10	3	3	Video	44	0.23
7. Marotta et al. (2017) control	1.21(0.43)	1.40(0.28)	16	4	4	Box	21	0.51
8. Pyasik et al. (2019) control	0.18(1.98)	0.8(1.79)	6	na	3	Box	20	0.32
9. Pyasik et al. (2019) pianists	-1.00(1.56)	-1.28(1.77)	6	na	3	Box	20	-0.16
10. Tsakiris et al. (2010)	0.89(1.49)	1.98(1.44)	10	3	3	Video	19	0.73

Meta-analysis

The random-effects meta-analysis showed a small effect for active movements and ownership compared to passive movements (Hedge's g=0.38, 95% CI [0.19, 0.58], p=0.0001) (see Figure 2). The results of the Chi² test showed no significant heterogeneity between the studies (p=0.16). The results of the I² test showed low heterogeneity with 31%.

Figure 2.

Forest plot and total effect size. The forest plot shows the standard mean difference for each study and the total standard mean difference. The column to the left of the figure lists the included study by year of publication. The green squares in the graph show the effect size for each study (Hedge's g), and the horizontal bars going through them show the 95% confidence interval. The size of the green squares indicates the weight of each included study. The black diamond shows the total meta-analyses effect size with a 95% confidence interval (the width of the diamond). The numbers following the row labelled total is the total standard mean difference of the meta-analyses.

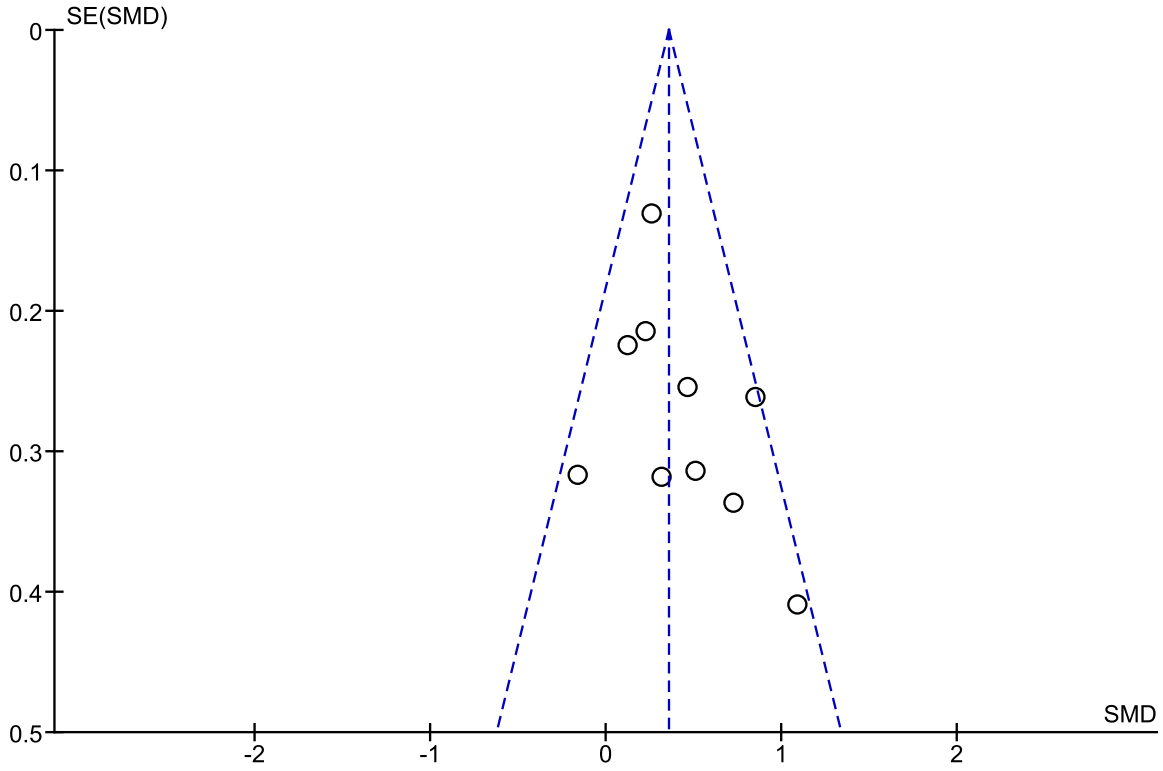


Publication Bias

A funnel plot was produced to evaluate the publication bias. From visual inspection, the funnel plot is symmetrical (see Figure 3). There is a symmetrical scatter with five studies on each side of the standard mean difference. The results indicate that there is no significant bias. Egger's regression was used to test for significant bias and no significant bias was found (Egger's test=0.08, 95% (-1.26 – 1.43), p=0.89).

Figure 3.

Funnel plot. A funnel plot of the included studies of the meta-analysis. The y-axis shows the standard errors, and the x-axis shows the standard mean difference. Each circle in the figure illustrates an experiment from the included studies. The dotted lines show the 95% confidence interval.



Discussion

This thesis aimed to investigate if agency affects the sense of bodily ownership. This question was examined by quantifying the results of studies that have used passive and active movements in the RHI. The comparison between active and passive movements in the RHI was chosen as a majority of studies examining this show that active movements induce a sense of agency, and passive movements do not, yet both induce a sense of ownership (e.g., Dummer et al., 2009; Kalckert & Ehrsson, 2012, 2014a). The literature search of this thesis resulted in nine studies with 10 experiments and a total of 359 participants. The meta-analysis found that there was a small but significant effect on ownership by active movements compared to passive movements (Hedge's g=0.38, 95% CI [0.19, 0.58], p=<0.0001). The symmetry of the funnel plot of the studies and the Egger's regression shows that there was no significant bias. The results showed that there was a low heterogeneity between the studies (I^2=31%). These results show that agency has a small effect on the sense of body ownership.

Agency's role in the sense of bodily ownership would also indicate that the efference copy has a role in ownership. The result of this meta-analysis then shows that the efference copy has an effect on the sense of bodily ownership and has a role in creating the bodily self because of its essential role in the sense of agency (David et al., 2008). However, the efference copy might not be the only component of agency that affects body ownership. According to Haggard (2017) the intention and planning of a movement is as important for agency as the congruency of predicted and actual sensory feedback. The sense of agency is not produced without all three of these components: the efference copy, the intention of a movement, and the planning of a movement. This would suggest that the intention and planning of movements also has a role in how the body is attributed to the self. If it is one of these components or a combination of them that gives rise to the effect agency has on body ownership is not investigated in this thesis and should be examined in future research. Nevertheless, the results show that the sense of agency as a whole has an effect on the sense of body ownership and confirms the prior assumption that active movements would induce a stronger illusion (e.g., Kalckert & Ehrsson, 2012). Motor control and the self-attribution of movements seem to have a role in how the body is attributed to the self. The PPC has been observed to have activation that correlates with the sense of ownership (Ehrsson et al., 2004). In addition, PCC has been suggested to be important for the sense of agency according to the comparator model (David et al., 2008). Both the sense of ownership and agency seem to recruit the PPC and, therefore, might be a region of interest for future research regarding the neural correlates of these senses.

The hypothesis of the thesis is built on the assumption that the comparator model is true. The conduction of the meta-analysis relies on the suggestion that active movements produce a sense of agency and that passive movements do not (David et al., 2008). The

comparator model is one of the most prominent theories of motor control and agency. However, other motor control and agency theories should be taken into consideration (Wolpert & Ghahramani, 2000).

The comparator model's suggestion that active movement produces a sense of agency and that passive movements do not is mirrored in behavioural studies using RHI (e.g., Dummer et al., 2009; Kalckert & Ehrsson, 2012, 2014a). All of the studies included in this meta-analysis that examined both ownership and agency have found that agency is absent in passive movements and that active movements produce agency (e.g., Kalckert & Ehrsson, 2012, 2014a; Longo & Haggard, 2009). In addition, the subjective questionnaires showed a higher mean for the induced sense of ownership in the active movement condition in all the included studies, except for the pianist group from Pyasik et al. (2019) (see Table 1). Instead, the pianist group showed that no movement condition induced a sense of ownership and a lower ownership rating for active movements (see Figure 2). Pyasik et al. (2019) argue the reason for these results might be that the pianists have many years of motor practice and might depend more on kinesthesis and touch. Therefore, the visual input is not dominant, and the illusion is not induced.

About 30% of participants in RHI experiments do no experience the illusion of ownership. It has been suggested that these are participants with refined usage of their body, such as musicians or dancers (Ehrsson, 2012). Another suggestion is individual differences in dependency on exteroceptive or interoceptive input to create the bodily self (Tsakiris, 2017). In addition, the differences in dependency can explain why the illusion differ in strength for some participants. Individuals who depend more on interoceptive input are negatively correlated with classical RHI. This could indicate that musicians depend more on interoceptive input and proprioception. The manipulation of visuotactile input in classical RHI and manipulating visual and afferent signals in moving RHI might not overwrite these individuals' proprioception, and because of this the illusion is not induced. If this is the case, it could be why neither of the movement conditions induced the illusion in the pianist group from Pyasik et al. (2019). It might also have affected the control group, as all participants in this group were non-musicians. The study by Pyasik et al. (2019) did not examine the sense of agency, so it is unknown if passive or active movements induced a sense of agency over the fake hand for both the control and pianist group. The relationship between individuals with refined usage of their body and the dependency on interoceptive input should be investigated in the future to determine if this affects the induced sense of ownership and agency in RHI experiments and the creation of the bodily self.

Refined body usage has not necessarily affected the other studies. The remaining included studies all used a random selection of healthy participants, and within-subject comparisons of the movement conditions were used. Any participants that might have had

refined usage of their body would be in both groups, and any effects this would have on the groups would have so on both groups.

Limitation

The studies showed low heterogeneity (I^2=31%) of the results. The studies were, however, conducted in many different ways. The studies induced the illusion using different methods (e.g., video-projection image and robotic hand), all of the studies used more conditions than passive and active movements (e.g., incongruent movements, asynchronous movement, and visuotactile), and some studies only examined the comparison as a sub-analysis (e.g., Kalckert & Ehrsson, 2017). The induction methods may differ in the strength of the induced illusion, and the experiments with more conditions may have been affected by participant fatigue.

The thesis has only examined the results of subjective questionnaires and has disregarded proprioceptive drift. Half of the included experiments measured proprioceptive drift (Caspar, De Beir et al., 2015; Jenkinson & Preston, 2015; Kalckert & Ehrsson, 2012; Pyasik et al., 2019) and half did not (Kalckert & Ehrsson, 2014a, 2017; Longo & Haggard, 2009; Marotta et al., 2017; Tsakiris et al., 2010). It has been suggested in RHI literature that subjective questionnaires and proprioceptive drift should be used in combination to determine the induced sense of ownership (Kalckert & Ehrsson, 2014a). The questionnaires of the studies included used a variety of statements to examine the induced sense of ownership, and one study did not use control statements regarding ownership (Caspar, De Beir et al., 2015). Moreover, two studies with a total of three of the experiments used in the meta-analysis did not measure agency (Kalckert & Ehrsson, 2017; Pyasik et al., 2019). As they did not measure agency, it is unknown if these two studies induced a sense of agency in the active movement condition or if the sense of agency was absent in the passive movement condition. However, the studies by Kalckert and Ehrsson (2017) and Pyasik et al. (2019) used identical setup and procedure as Kalckert and Ehrsson (2012, 2014a), which did produce agency, based on this, it could be assumed that these experiments induced a sense of agency. The remaining seven studies examined agency using a similar questionnaire as for the sense of ownership, and all found that only active movements induced a sense of agency. Yet, it is unknown if the sense of agency was generated in three out of 10 experiments of this meta-analysis. This makes it problematic to make clear inferences about the effect agency has on the sense of ownership.

A limited number of studies examined active and passive movements within the RHI experimental paradigm. The decision to exclude studies only using one of the movement conditions and studies not using within-subject comparisons may have affected the results as the included studies may be too limited. Studies that have only used active movements (e.g., Shibuya et al., 2018) and studies that did not use within-subject comparisons (e.g., Dummer

et al., 2009) have been identified and excluded. However, no studies only using passive movements have been identified, and a majority of studies comparing active and passive movements that were identified used within-subject comparisons.

The Boolean operators used in the literature search may have been too limited. The limited search might have caused some studies fitting the inclusion criterion to be unidentified. In addition, one study with two experiments fitting the inclusion criteria had to be excluded as the author was unable to acquire the data, which affects the results.

Future research

The thesis has several limitations that future research should address. Future research should exclude studies that do not measure agency and ensure that each study included has found that passive movements do not induce a sense of agency and that active movements do. A future meta-analysis could examine the effects of passive and active movements on agency in RHI studies to clarify that passive movements do not induce a sense of agency and can be used as a condition for the absence of agency.

Future meta-analyses should also include an objective measure of ownership such as proprioceptive drift combined with subjective questionnaires to see if these measures correlate.

How the exclusion of studies that did not use within-subject comparisons might have affected the results should be examined in the future. The inclusion of one-sided studies should also be made to see how this would affect the results. More studies on the difference in ownership ratings induced by passive and active movements in the RHI should be made with larger sample sizes to help further answer whether agency affects body ownership.

Research on how refined usage of the body affects the sense of ownership within the RHI should be made using, e.g., different groups of musicians, dancers, or athletes. Refined body usage might be another factor that affects the sense of ownership. It might do so regardless of the effect's agency has on the sense of ownership and might be using different mechanisms (e.g., interoceptive input) to do so. Defining the role of refined body usage in the sense of body ownership would have similar implications as for defining the role of agency described below.

Societal and ethical aspects of enquiry

Ethical committees or review boards approved all included studies. The results of this study show that agency has a small effect on the sense of ownership. These findings carry importance for fields interested in how the bodily-self is created, e.g., prosthetic research, virtual reality research, and consciousness research.

That agency affects ownership is an important finding for developing more satisfactory and functional prosthetics and developing more immersive virtual reality. How

the bodily-self is created, and the mechanisms of the process is important for self-awareness and consciousness research.

The furthered understanding of how the bodily-self is created and what gives rise to the sense of bodily ownership is relevant to more fields than those regarding body ownership. It has been found in previous research that used body illusions with a different gender or race of the artificial body or hand that the illusion can affect stereotypes and subjective ratings of masculinity/femininity of the participants (e.g., Banakou et al., 2019; Tacikowski et al., 2020; Tsakiris, 2017). These findings have implications for research that focuses on the sense of ownership and research that focuses on aspects on higher cognitive levels and social questions, e.g., ingroup biases and identity.

Conclusion

The results of the meta-analysis show that agency has a small effect on body ownership. According to the comparator model, these results show that motor control is involved in the creation of the bodily self. The selection of studies in this thesis is problematic and bring about several limitations that should be addressed in future research to further clarify how large of a role agency has in attribution the body to the self. However, these findings show that agency creates a stronger sense of ownership over the body, and this is of interest for many fields regarding body ownership and might be interesting for fields regarding higher cognitive levels.

References

Banakou, D., Kishore, S., & Slater, M. (2019). Virtually being Einstein results in an improvement in cognitive task performance and a decrease in age bias. *Frontiers in Psychology, 9*, 917. https://doi.org/10.3389/fpsyg.2018.00917

Botvinick, B., & Cohen, C. (1998). Rubber hand 'feel' touch that eyes see. *Nature, 391*(6669), 756-756. https://doi.org/10.1038/35784

Brundin, M. (2020). *The rubber hand illusion effectiveness on body ownership induced by self-produced movements: A meta-analysis*. [Master's thesis, University of Skövde]. DiVA Skövde. https://his.diva-portal.org/smash/record.jsf?pid=diva2:1445768

Caspar, E. A., Cleeremans, A., & Haggard, P. (2015). The relationship between human agency and embodiment. *Consciousness and Cognition, 33*, 226-236. https://doi.org/10.1016/j.concog.2015.01.007

Caspar, E. A., De Beir, A., Magalhaes De Saldanha Da Gama, P. A., Yernaux, F., Cleeremans, A., & Vanderborght, B. (2015). New frontiers in the rubber hand experiment: When a robotic hand becomes one's own. *Behavior Research Methods, 47*(3), 744-755. https://doi.org/10.3758/s13428-014-0498-3

Cullen, E. K. (2004). Sensory signals during active versus passive movements. *Current Opinion in Neurobiology, 14*(6), 698-706. https://doi.org/10.1016/j.conb.2004.10.002

David, N., Newen, A., & Vogeley, K. (2008). The "sense of agency" and its underlying cognitive and neural mechanisms. *Consciousness and Cognition*, 17(2), 523-534. https://doi.org/10.1016/j.concog.2008.03.004

Dummer, T., Picot-Annand, A., Neal, T., & Moore, C. (2009). Movement and the rubber hand illusion. *Perception*, 38(2), 271-280. https://doi.org/10.1068/p5921

Ehrsson, H. H. (2012). The concept of body ownership and its relation to multisensory integration. In B. E. Stein (Ed.), *The New Handbook of Multisensory Processes* (pp. 775-792). MIT Press.

Ehrsson, H. H., Spence, C., & Passingham, R. E. (2004). That's my hand! Activity in premotor cortex reflects feeling of ownership of a limb. *Science, 305(5685)*, 875-877. https://doi.org/10.1126/science.1097011

Gazzaniga, M. S., Ivry, R. B., & Mangun, G. R. (2014). *Cognitive neuroscience: The biology of the mind* (4th ed). W. W. Norton & Company.

Haggard, P. (2017). Sense of agency in the human brain. *Nature Reviews Neuroscience, 18(4)*, 197-208. https://doi.org/10.1038/nrn.2017.14

Jenkins, I. H., Jahanshai, M., Jueptner, M., Passingham, R. E., & Brooks, D. J. (2000). Self-initiated versus externally triggered movements. II. The effect of movement

predictability on regional cerebral blood flow. *Brain, 123(6)*, 1216-1228. https://doi.org/10.1093/brain/123.6.1216

Jenkinson, P., & Preston, C. (2015). New reflections on agency and body ownership: The moving rubber hand illusion in the mirror. *Consciousness and Cognition, 33*, 432-442. https://doi.org/10.1016/j.concog.2015.02.020

Kalckert, A., & Ehrsson, H. H. (2012). Moving a rubber hand that feels like your own: A dissociation of ownership and agency. *Frontiers in Human Neuroscience,* 6, 1-14. https://doi.org/10.3389/fnhum.2012.00040

Kalckert, A., & Ehrsson, H. H. (2014a). The moving rubber hand illusion revisited: Comparing movements and visuotactile stimulation to induce illusory ownership. *Consciousness and Cognition, 26*(1), 117-132. https://doi.org/10.1016/j.concog.2014.02.003'

Kalckert, A., & Ehrsson, H. H. (2014b). The spatial distance rule in the moving and classical rubber hand illusions. *Consciousness and Cognition, 30*, 118-132. https://doi.org/10.1016/j.concog.2014.08.022

Kalckert, A., & Ehrsson, H. H. (2017). The onset time of the ownership sensation in the moving rubber hand illusion. *Frontiers in Psychology, 8*, 1-9. https://doi.org/10.3389/fpsyg.2017.00344

Kammers, M., Longo, M., Tsakiris, M., Dijkerman, H., & Haggard, H. (2009). Specificity and coherence of body representations. *Perception, 38*(12), 18004-1820. https://doi.org/10.1068/p6389

Longo, M., & Haggard, H. (2009).Sense of agency primes manual motor responses. *Perception, 38*(1), 69-78. https://doi.org/10.1068/p6045

Marotta, A., Bombieri, F., Zampini, M., Schena, F., Dallocchio, C., Fiorio, M., & Tinazzi, M. (2017).The moving rubber hand illusion reveals that explicit sense of agency for tapping movements is preserved in functional movement disorders. *Frontiers in Human Neuroscience, 11*, 1-15. https://doi.org/10.3389/fnhum.2017.00291

McGrath, S., Zhao, X., & Steele, R. (2020). Estimating the sample mean and standard deviation from commonly reported quantiles in meta-analysis. *Statistical Methods in Medical Research, 29(9)*, 2520-2537. https://doi.org/10.1177/0962280219889080

Moher, D., Liberati, A., Tetzlaff, J., Altman, D. G., & The PRISMA Group. (2009). Preferred reporting items for systematic reviews and meta-analyses: The PRISMA statement. *PLoS Med 6*(7): e1000097. https://doi.org/10.1371/journal.pmed.1000097

Petkova, V. I., & Ehrsson, H. H. (2008). If I were you: Perceptual illusion of body swapping. *PLoS ONE, 3*(12), e3832. https://doi.org/10.1371/journal.pone.0003832

Pyasik, M., Salatino, A., & Pia, L. (2019). Do movements contribute to sense of body ownership? Rubber hand illusion in expert pianists. *Psychological Research, 83*(1), 185-195. https://doi.org/10.1007/s00426-018-1137-x

Shibuya, S., Unenaka, S., & Ohki, Y. (2017). Body ownership and agency: task-dependent effects of the virtual hand illusion on proprioceptive drift. *Experimental Brain Research*, 235(1), 121-134. https://doi.org/10.1007/s00221-016-4777-3

Shibuya, S., Unenaka, S., & Ohki, Y. (2018). The relationship between the virtual hand illusion and motor performance. *Frontiers in Psychology, 9*, 1-9. https://doi.org/10.3389/fpsyg.2018.02242

Siddaway, A., Wood, A., & Hedges, L. (2019). How to do a systematic review: A best practice guide for conduction and reporting narrative reviews, meta-analyses, and meta-syntheses. *Annual Review of Psychology, 70*, 747-770. https://doi.org/10.1146/annurev-psych-010418-102803

Stein, B., & Stanford, T. (2008). Multisensory integration: Current issues from the perspective of the single neuron. *Nature Reviews Neuroscience, 9(4)*, 255-266. https://doi.org/10.1038/nrn2331

Tacikowski, P., Fust, J., & Ehrsson, H. H. (2020). Fluidity of gender identity induced by illusory body-sex change. *Scientific Reports, 10*(1), 1-14. https://doi.org/10.1038/s41598-020-71467-z

Tsakiris, M. (2017). The multisensory basis of the self: From body to identity to others. Quarterly Journal of Experimental Psychology, 70(4), 597-609. https://doi.org/10.1080/17470218.2016.1181768

Tsakiris, M., Longo, M., & Haggard, P. (2010). Having a body versus moving your body: Neural signatures of agency and body-ownership. *Neuropsychologia, 48*(9), 2740-2749. https://doi.org/10.1016/j.neuropsychologia.2010.05.021

Tsakiris, M., Prabhu, G., & Haggard, P. (2006). Having a body versus moving your body: How agency structures body-ownership. *Consciousness and Cognition, 15(2)*, 423-432. https://doi.org/10.1016/j.concog.2005.09.004

Wolpert, D., & Ghahramani, Z. (2000). Computational principles of movement neuroscience. *Nature Neuroscience, 3*(11s), 1212-1217. https://doi.org/10.1038/81497