

**THE RUBBER HAND ILLUSION
EFFECTIVENESS ON BODY OWNERSHIP
INDUCED BY SELF-PRODUCED MOVEMENTS:
A Meta-Analysis**

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Abstract

Body ownership can be studied via the rubber hand illusion (RHI), in which an artificial limb can be perceived as belonging to oneself. In the so-called moving RHI paradigm, both body ownership and *sense of agency*, induced by self-produced movements, can be investigated. The key question of this approach is whether movements generated by oneself increase the illusion of body ownership. Thus far, the results from moving RHI studies are inconsistent. This has led to uncertainty regarding the influences of the motor control mechanism on body ownership. Therefore, this study will present the first meta-analysis on moving RHI to estimate the illusory effectiveness induced by self-produced movements. A total of 23 experimental comparisons with 821 subjects were included in the meta-analysis. The results showed that the overall illusory effect induced by self-produced movements was superior to its control (e.g., asynchronous active movements) (Hedge's $g = 1.38$, $p < 0.001$). However, due to dissimilarity in results between the studies, the sample size in the meta-analysis may not represent the general population. The subgroup analysis showed that studies using physical hands, such as wooden hands, yielded the largest effect compared to studies using a virtual projected hand or a video recorded image of the participant's own hands. It can be speculated whether a three-dimensional hand with "realness" has an illusory advantage compared to hands presented in virtual or video image settings. Future studies need to apply a unified framework, particularly in experimental setups and measurements. This would obtain consistent results of the strength of the illusion within the moving RHI paradigm.

Keywords: rubber hand illusion; body ownership; sense of agency; motor control mechanisms; meta-analysis

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Introduction

In cognitive neuroscience terms, *body ownership* refers to the experience of that one's body belongs to oneself. If we voluntarily move a body part, such as our hand, then we experience body ownership for that hand. We also experience *a sense of agency* (i.e., the feeling of controlling one's own actions) for the generated hand movement. Body ownership and agency are two separate cognitive processes contributing to the conscious experience of oneself (Gallagher, 2000). Recent research has tried to understand the cognitive and neural mechanisms underlying these fundamental aspects of oneself (e.g., Kalckert & Ehrsson, 2012; Tsakiris, Longo, & Haggard, 2010). A working hypothesis suggests that movements produced by oneself could strengthen one's bodily boundaries in the external world and induce a more vivid and authentic feeling of body ownership (Gallagher, 2012).

Body ownership and a sense of agency have been studied via the moving rubber hand illusion (RHI). However, moving RHI studies differ in results, which is likely based on differences in experimental designs. This study aims to determine the moving RHI effectiveness on body ownership induced by self-produced movements, as well as identify and discuss the inconsistencies in the thus far published results.

Body ownership induced by tactile stimulation

Though ownership and agency coincide and are indistinguishable in self-produced movements, research has mostly studied them separately. The sense of agency has often been studied with intentional binding paradigms (see Moore & Obhi, 2012, for a review). However, our understanding of body ownership largely relies on the RHI (Botvinick & Cohen, 1998). In the classical RHI, participants are presented with an artificial hand, while their real hand is hidden from view. The experimenter strokes both hands at the same place at the same pace. Within less than a minute and often as fast as within 10 seconds (Ehrsson, Spence, & Passingham, 2004; Lloyd, 2007), most participants feel that the artificial hand is a part of their own body. The illusion is a result of the integration of visual and somatosensory input. Initially, when the experimenter strokes both hands, the felt touches from the real hand, the seen touches on the artificial hand, and the felt muscle sense (i.e., proprioception) cause a sensory conflict. However, the brain continuously strives to maintain a consistent internal body representation (Ehrsson, 2020). Therefore, the brain tries to resolve this conflict by re-evaluating the available sensory information. This leads to mistakenly perceiving the artificial

hand as one's own (Botvinick & Cohen, 1998; Ehrsson et al., 2004; Tsakiris & Haggard, 2005).

In order to induce the illusion, certain perceptual rules must be fulfilled. These perceptual rules are temporal and spatial congruency, as well as an anatomically plausible position of the artificial hand. This means that asynchronous touches abolish or reduce the illusion (the more delay, the more reduction) (Botvinick & Cohen, 1998; Slater, Perez-Marcos, Ehrsson, & Sanchez-Vives, 2009; Tsakiris & Haggard, 2005). A significant reduction of the illusion also occurs when the artificial hand is placed more than 30 cm from the real hand (Kalckert & Ehrsson, 2014b; Kalckert, Perera, Ganesan, & Tan, 2019; Lloyd, 2007; Preston, 2013). Rotating the artificial hand in an incongruent position, such as 180°, also reduces the illusion (Ehrsson et al., 2004; Ide, 2013; Tsakiris & Haggard, 2005). Together, these perceptual rules are in accordance with bottom-up accounts, such as the Bayesian perceptual learning theory (Armel & Ramachandran, 2003). Bottom-up accounts assume that perceived body ownership results from multisensory matching of the seen object and the felt touch.

However, a number of studies have shown that the illusion also depends on internal conceptions of how a human hand should look like. For instance, Kalckert, Bico and Fong (2019) found that participants reported significantly less body ownership when a balloon was used as the artificial object (but see Armel & Ramachandran, 2003, who observed that participants could perceive ownership over a table). In contrast, the illusion is still intact when both hands differ in skin structure (Haans, Ijsselstein, & de Kort, 2008) or skin color (Lira et al., 2017). Ijsselstein, de Kort and Haans (2006) demonstrated that the hand's volume seems to matter. The authors compared two-dimensional (2D) hands on screens with a three-dimensional (3D) standard prosthetic hand. Participants reported a more substantial illusionary effect when they watched the latter hand. These results suggest that body ownership is also modulated by top-down influences based on visual, proprioceptive, and functional representations of the own body (Tsakiris, 2010). Top-down accounts, such as the neurocognitive model of sense of ownership (Tsakiris, 2010), postulate a much stronger involvement of preexisting references to one's own body compared to bottom-up accounts. Tsakiris (2010) have argued that body ownership is evoked by the interaction between present multisensory information and preexisting models of the body.

Currently, there is strong agreement in the research field that top-down processes, to some degree, are structuring the somatosensory information. However, how strongly these processes modulate body ownership is unclear (Braun et al., 2018).

In order to quantify the strength of the ownership illusion, subjective and objective measurements are used. In the subjective measures, the participants report their perspective and experience of the illusion. This occurs typically via questionnaires including statements which capture the subjective experience, for instance, “I felt as if the artificial hand was my own hand” (Botvinick & Cohen, 1998). In contrast, objective measures quantify the illusion by measuring an expressed observable behavior. The most commonly used objective measure is the proprioceptive drift. In this behavioral task, the participants close their eyes and indicate the location of the real hand. Usually, this task reveals a localization bias of the real hand towards the artificial hand (Botvinick & Cohen, 1998; Kalckert & Ehrsson, 2014b). Another objective procedure involves threatening the artificial hand, e.g., hitting the artificial hand with a hammer (Armell & Ramachandran, 2003). The threat leads to a physical stress response, captured via skin conductive response (SCR) or galvanic skin response (GSR).

However, within the RHI paradigm, there are inconsistencies between studies regarding these measurements. Some studies have used both subjective and objective measures (e.g., Tsakiris & Haggard, 2005). Other studies have applied either subjective (e.g., Kalckert & Ehrsson, 2017) or objective measures (e.g., Tsakiris, Prabhu, & Haggard, 2006). Several studies have demonstrated that proprioceptive drift alone is not a reliable single measure of the illusion (Romano, Caffa, Hernandez-Arieta, Brugger, & Maravita, 2015; Rohde et al., 2011; Wen et al., 2016). Therefore, most researchers in the field have argued that both subjective and objective measures should be performed to provide multiple lines of evidence. The importance of complementary measures has been highlighted recently (e.g., Rohde, Di Luca, & Ernst, 2011).

Comparative control conditions are used to investigate whether participants experience the ownership illusion. These control conditions do not evoke an illusory experience of ownership as these conditions do not follow the perceptual rules outlined above. The most common control condition is asynchronous stimulation of the participant’s own hand and the artificial hand. This means that the stroking does not temporally coincide. A delay of approximately 500 ms is often added (Botvinick & Cohen, 1998; Tsakiris & Haggard, 2005). Another control condition is to place the artificial hand in an anatomically implausible position, such as 180° (Ehrsson et al., 2004; Kalckert & Ehrsson, 2012). Some studies have also controlled the illusion by using objects that are not human-like, such as a piece of wood (Tsakiris & Haggard, 2005).

Body ownership and agency induced by self-produced movements

Although the classical RHI has helped us understand how to induce a sense of ownership based on visuotactile stimulation, the experiment does not seem to reflect reality (Tsakiris, Schütz-Bosbach, & Gallagher, 2007). In most everyday life situations, we do not experience our bodies in a static position as in the classical RHI, but in constant motion. In movements (both self-produced and passive), more sensory channels are available to the process underlying the experience of body ownership. For instance, sensory input from muscle spindle, muscle tension, and joint receptors are activated. This, in turn, provides us with proprioceptive information about where our bodies are located in space and bodily postures (Butler, Héroux, & Gandevia, 2017; Kalckert, 2018). None of these are engaged in the classical RHI.

Based on the notion that movements would have a facilitatory effect on body ownership, moving RHI paradigms have induced the illusion by using visuomotor stimulation. Within the moving RHI paradigm, different experimental setups have been used to induce body ownership. Most studies use a simple finger or hand movement without a specific goal to induce the illusion. For instance, Kalckert and Ehrsson (2014a) used a wooden hand where one finger was connected with wooden rods to the participant's finger. Experiments have also used virtual reality (VR) techniques to induce the illusion. In these experimental setups, the participants' movements were captured through, e.g., infrared cameras, and then animated virtually (e.g., Yuan & Steed, 2010). This allows to animate a wider range of movements; for example, in the Ismail and Shimada (2016) study, participants controlled the movements by closing and opening their whole hand. Other experimental setups have used cameras to record the participant's moving hand and then projected it on a screen (e.g., Longo & Haggard, 2009). See Appendix A for an additional description of the different experimental setups.

The experience of ownership induced by movements is thought to rely on the same perceptual rules as the classical version. As mentioned earlier, the classical version depends on the integration of vision, touch, and proprioception. However, in the moving RHI paradigm, body ownership relies on the integration of vision, motor cues, and proprioception. This means that the ownership illusion is evoked when the participants move their hand either voluntarily (i.e., self-produced movements) or passively (i.e., the experimenter moves the hand). Even if the experimenter moves the participant's hand, he or she still experiences ownership over the hand (Kalckert & Ehrsson, 2012). Nevertheless, this means that the

illusion is not induced when there is a delay between the movements of the artificial hand and the participant's hand (Ismail & Shimada, 2016; Riemer, Kleinböhl, Hölzl, & Trojan, 2013). Ownership is also abolished when the artificial hand is placed in front of the participants in an anatomically implausible position (Kalckert & Ehrsson, 2012; Salomon et al., 2016), or detached from the body (Brugada-Ramentol et al., 2019). Further, the illusion is reduced when the hands are placed too far from each other (Kalckert and Ehrsson, 2014b). These findings speak for that the moving RHI seems to be based on the same multisensory mechanisms as involved in the classical version (Armell & Ramachandran, 2003; Botvinick & Cohen, 1998).

Classical RHI studies have demonstrated that the illusion is not induced when using non-human objects (Kalckert et al., 2019; Tsakiris & Haggard, 2005). Following these findings, Yuan and Steed (2010) have shown that participants did not report body ownership for a virtual moving arrow. Together these results are in accordance with top-down accounts, arguing that body parts are incorporated only if they are reminiscent permanent internal body representations (Tsakiris, 2010). However, Ma and Hommel (2015a) have found a weak but intact ownership illusion for a virtual moving balloon. The authors have argued that temporal and spatial congruency seem to be enough to induce the illusion. This observation provides support for bottom-up accounts (e.g., Armell & Ramachandran, 2003).

Passive movements and visuotactile stimulation are initiated by external factors, such as the experimenter. Self-produced movements, however, do not include such external interferences. Instead, the self-produced movements are initiated and controlled by oneself. Therefore, the moving RHI paradigm can be used to study the sense of agency (Gallagher, 2000). When the participants move their index finger, they not only experience ownership for that finger but also a sense of agency for the finger movement. Agency is considered to be a complementary source of body ownership. When acting upon the world, one's bodily boundaries are thought to be strengthened. Consequently, this will entail a more vivid and authentic feeling of body ownership (Gallagher, 2012).

In one of the first moving RHI studies, Tsakiris et al. (2006) investigated the role of agency for body ownership. The experimental setup consisted of a recorded video projected image of the participant's own hand. Participants watched the finger of the hand on the video image being synchronously touched or moved actively or passively while their real hand received the corresponding stimulation. The participants reported that the proprioceptive drift was equally strong regardless of the condition. In passive movements and tactile stimulation, the proprioceptive drift was located to the specific stimulated finger. However, in self-

produced movements, the proprioceptive drift was spread to the entire hand. This suggests that self-produced movements, compared to passive sensory stimulation, may integrate body-parts into a coherent body representation, leading to a more unified awareness of the body (Tsakiris et al., 2006).

Strong evidence for that ownership and sense of agency complement each other has been shown in a systematic investigation by Kalckert and Ehrsson (2012). In this experiment, a wooden hand was moved synchronously with the participant's real hand movements via a rod tied between the index finger of both hands. The researchers manipulated several factors known to influence the experience of ownership and agency. They manipulated the movement mode (active versus passive), the timing of the finger movements (synchronous versus asynchronous), and the placement of the artificial hand (anatomically plausible versus anatomically implausible). The authors found that synchronous passive movements abolished a sense of agency but not ownership, asynchronous movements reduced both ownership and a sense of agency, and an implausible anatomical position reduced ownership but not a sense of agency. The latter finding can be explained in the same terms as the experience of agency related to "tool-use." This means that top-down processes influenced the agency ratings. The hand was perceived more as a useful tool than a human hand (Kalckert & Ehrsson, 2012). For instance, a professional tennis player may sense agency over his tennis racket without necessarily perceiving it as belonging to his body. In this way, the tennis racket (or other tools) can alter one's body representation and change the spatial relationship between the body and the external object (D'Angelo, di Pellegrino, Seriani, Gallina, & Frassinetti, 2018; Kalckert & Ehrsson, 2012).

How is the sense of agency produced? The sense of agency is considered to be a complex phenomenon (Haggard, 2017). Different models try to explain how we get the experience of agency. Each model points out different aspects of the movement. The most accepted theory of a sense of agency has been the comparator model (Frith, Blakemore, & Wolpert, 2000). This model is based on the motor control system, suggesting that internal forward models use efferent information derived from motor commands to predict the sensory consequences of the movement. If the efferent information and the sensory feedback match, the movement is considered to be executed as planned. Consequently, a sense of agency emerges. Conversely, a mismatch between movements and their sensory consequences results in a reduced sense of agency (Frith et al., 2000). Several studies support the notion that a sense of agency is closely related to sensorimotor processes. For instance, Ismail and Shimada (2016) demonstrated that movement delays reduced the sense of agency. The more delay

between the movements, the greater reduction of the agency. However, other studies have suggested that the sense of agency could be temporally plastic. For instance, repeatedly experiencing a sensory outcome (e.g., a tone) that follows an action (e.g., a keypress) can cause a learned feeling that keypress produces the tone. In this way, a sense of agency can be experienced over the tone (Sato & Yasuda, 2005). Such findings may imply that agency is not only dependent on the match between the predicted and the sensory feedback of the movement. It could also mean that the agency depends on other factors, such as motor intention and motor outcome (Kalckert, 2018). Because of such diversity, recent accounts have argued that the comparator model is not a satisfactory model to explain the agentic experience (Christensen & Grünbaum, 2018). This has led to new models trying to explain the variety of observations in agency studies (e.g., David, Newen, & Vogeley, 2008; Moore & Fletcher, 2012; Synofzik, Vosgerau, & Newen, 2008; Wegner, 2003).

According to the theory of apparent mental causation (Wegner, 2003), a sense of agency can be retrospectively inferred from outcomes rather than being directly perceived. In contrast to the comparator model, Wegner (2003) rejects such a strong involvement of the motor system in the sense of agency. Instead, the theory holds that a sense of agency is based on cues external to motor control mechanisms. For instance, the “I spy” experiment by Wegner and Wheatley (1999) had shown that when there was a match between participant’s thoughts and the watched action, they experienced agency over movements that were not generated by themselves.

Synofzik et al. (2008) have developed a model trying to compromise the comparator model and the view of mental causation. This model consists of two levels: the feeling of agency and the judgement of agency. The first level is explained in terms of comparator mechanisms. In contrast, the following level reflects a higher-order process that refers to one’s interpretation of being the agent of an action. The integration of different cues, such as information about the environment, background beliefs, and sensory information, gives rise to the agency experience (Synofzik et al., 2008).

Nevertheless, whereas mental causation (Wegner, 2003) and Synofzik et al.’s (2008) judgment of agency are related to the general experience of agency, the moving RHI is more concerned over sensorimotor processes (i.e., direct bodily agency). In this way, the experienced agency within the moving RHI paradigm is best explained by the comparator model.

Inconsistent results in the moving rubber hand illusion

Sensory information derived from the movement itself and the advantage of motor control mechanisms are factors considered to enhance the experience of body ownership. Does the moving RHI paradigm lead to a stronger illusory effect because it provides more sensory information than the classical version? Moreover, do efferent signals from motor commands have a facilitatory effect on body ownership during self-produced movements? These questions remain unclear. The reason for the uncertainty is that moving RHI studies have reported contradictory results. For instance, several studies have found that subjective ratings are equal regardless of whether the induction consists of self-produced movements, passive movements, or tactile stimulation (e.g., Kalckert & Ehrsson, 2014a). However, Kokkinara and Slater (2014) observed an increase of ownership over a virtual leg in self-produced movements compared to visuotactile stimulation. Others have found that subjective ratings were similar, but the proprioceptive drift was larger for self-produced movements (Riemer et al., 2013). Moreover, Walsh, Moseley, Taylor, and Gandevia (2011) found that ownership ratings for passive movements were higher than for self-produced movements, suggesting that voluntary movements are not crucial for inducing body ownership. In contrast, other studies have observed the opposite: self-produced movements increased the feeling of body ownership (Dummer, Picot-Annand, Neal, & Moore, 2009; Kalckert & Ehrsson, 2017).

What might be the reason for this inconsistency? Differences in experimental setups may cause these different results. For instance, some studies have induced the illusion via the video-recorded projection of the participant's own hand (e.g., Longo & Haggard, 2009; Tsakiris et al., 2006). Others have used physical model hands (e.g., Dummer et al., 2009; Kalckert & Ehrsson, 2012; Riemer et al., 2013; Walsh et al., 2011), or virtual reality technology (e.g., Ismail & Shimada, 2016; Kokkinara & Slater, 2014; Sanchez-Vives, Spanlang, Frisoli, Bergamasco, & Slater, 2010). The experience of the illusion seems to depend on the chosen induction method. Ijsselstein et al. (2006) observed that the illusion was strongest when they used a physical hand. Compared to the video image setup, there was also a stronger experience of ownership in the VR setup. According to the authors, top-down mechanisms specifying objects in order for RHI to be induced (i.e., a concrete 3D human-like hand) seem to be the reason for these differences (Ijsselstein, de Kort, & Haans, 2006).

Furthermore, studies differ in their choice of measurements. There is no consistency in which measures have been used. Some studies have used questionnaires together with objective measurements, such as proprioceptive drift (e.g., Riemer et al., 2013). Others have

used a questionnaire together with SCR (Kokkinara & Slater, 2014). Some studies have used only questionnaires (e.g., Kalckert & Ehrsson, 2017), whereas others have used proprioceptive drift only (e.g., Tsakiris et al., 2006). To further contribute to confusion, studies have used different questionnaires. Most studies have used the original statements based on Botvinick and Cohen (1998) (e.g., “I felt as if the artificial hand was my hand”). In contrast, others have used an extended ownership questionnaire (“It seemed as if I were sensing the movement of my finger in the location where the artificial finger moved”) (Kalckert & Ehrsson, 2012). Agreement to ownership statements is typically given on a Likert scale consisting of 7 levels (e.g., Salomon et al., 2016). However, Likert scales consisting of 10 levels (e.g., Kammers, de Vignemont, Verhagen, & Dijkerman, 2009), or visual analog scales (VAS) have also been used (e.g., Palmer, Paton, Kirkovski, Enticott, & Hohwy, 2015).

Finally, some researchers have argued that earlier settings using a video-image projection and movable physical hands lack ecological validity and should be replaced with virtual hand illusions (VHI) (Ma & Hommel, 2015a). The argument for this statement is that VR hand setups allow for a more convincing subjective experience than using a physical hand or a video projection. For instance, credible and engaging 3D virtual environments can facilitate sensorimotor stimulation. This would, in turn, lead to more natural movements and thereby to additional sensory input (Ma & Hommel, 2015b). Also, some researches hold that VR setups are more accurate because the advanced technology enables the participant’s real movement and the virtual movement to move in synchrony. The human factor is not involved as in the physical setups using, for instance, a wooden hand. Together these factors are believed to induce a stronger ownership illusion (Ma & Hommel, 2015b; Maselli & Slater, 2013).

Altogether, moving RHI studies differ in their experimental designs. Notably, there are dissimilarities in experimental setups and used measurements. Unsurprisingly, the results from moving RHI studies are inconsistent. There is no consensus regarding the strength of the illusion in terms of body ownership. Since studies have provided different results, there is still uncertainty whether movements induce a stronger ownership illusion than tactile stimulation. With this, there is still no consensus on what impact agency processes have on body ownership. These ambiguities entail that there is no clarity in how well body ownership can be induced by movements at all.

The present study

Although moving RHI studies have been conducted for almost 15 years, there is still no consensus on the effectiveness of the ownership illusion. Therefore, this study will be the first meta-analysis to evaluate quantitative data from available studies within the moving RHI paradigm. Thereby, I provide an estimation of the overall effect of interest. More precisely, the objective of this meta-analysis is to (1) investigate the summary effect size of self-produced movements on body ownership in the moving RHI, and (2) identify and discuss what factors may be the reason for the inconsistencies in the thus far published results.

Methods

Sample selection

The literature search was conducted following PRISMA guidelines and checklists for reporting systematic reviews and meta-analyses (Moher, Liberati, Tetzlaff, & Altman, 2009) and the Cochrane Handbook (Higgins et al., 2019). To ensure that as many relevant studies as possible were identified, as well as minimize selection bias, the electronic literature search was conducted on two databases: Scopus and Medline. The search included articles published between January 2006 (one of the first moving RHI studies) and December 2019. Search words used were: “rubber hand illusion” AND ownership AND agency AND movements.

Publications were selected based on titles and abstracts. Then, they were examined for chosen inclusion criteria (see Selection criteria). Reference lists of included studies, as well as reviews related to the topic, were controlled for further potential articles. The authors of the study were contacted if there were questions about the presented data (e.g., parameters needed for the meta-analysis, such as mean score and standard deviation). Only studies written in English were included in the meta-analysis. A central problem with meta-analysis is that only studies that have been published can be analyzed. Significant results often represent these studies, leading to the question: how many studies with non-significant results have not been published? Altogether, this so-called publication bias may disturb the balance of findings and favor positive results. In order to reduce the effects of publication bias, a manual search was conducted on Google and Google Scholar. Further, an expert in the field was asked to identify any studies that were missed out or to identify potential unpublished studies. The last step in the literature search process was to extract information from the included studies by creating a coding manual. Included items in the coding manual were publication year, the number of participants, objective measures, and used control conditions (see Appendix B).

Selection criteria

The following inclusion criteria were used to identify studies for quantitative analysis: (1) self-produced movements as an experimental condition; (2) valid and reliable subjective questionnaires to measure the illusory effect (e.g., Botnivick & Cohen, 1998; Kalckert & Ehrsson, 2012; Longo, Schüür, Kammers, Tsakiris, & Haggard, 2008); (3) control condition known for reducing the ownership illusion (e.g., asynchronous movements); and (4) effect sizes or statistics of key results (e.g., mean, standard deviation, *t*- or *z*- values), either presented as tables or figures or provided by the authors. Furthermore, only full-text peer-reviewed publications investigating healthy human adults were included. RHI studies examining animals, robots, children, and individuals with brain damage, or neurological or psychological diseases, were excluded. Studies which used other forms of induction methods, such as mixed induction protocols with movements and touch (e.g., Shibuya, Unenaka, Zama, Shimada, & Ohki, 2018a), self-touch (e.g., Kilteni & Ehrsson, 2017), and full-body illusions (e.g., Banakou & Slater, 2014) were not considered. Further, studies which manipulated the mechanisms involved in motor control, such as short-term limb immobilization (e.g., Burin et al., 2017), long-term motor practice (e.g., Pyasik, Salatino, & Pia, 2019), or brain-computer interface (BCI) (e.g., Bashford & Mehring, 2016) were excluded. Also, studies that interfered with brain activity by using methods such as transcranial magnetic stimulation (TMS) or transcranial direct current stimulation (TDCS) (e.g., Bassolino et al., 2018) were not included. All included studies were controlled for inclusion criteria by thesis supervisor A. K.

Statistical analysis

Computing effect sizes. Once the studies were identified and characteristics coded, the effect size from each study was computed. The selected studies reported different values (e.g., mean / standard deviation, or *z*-value / *t*-statistic). This meta-analysis used the effect measure Hedge's *g* (*g*) to explore the relationship between illusory body ownership and the outcome. Hedge's *g* is a common form of the standardized mean difference and is interpreted in a similar way as Cohen's *d*. That is, 0.2 is considered a small effect size, 0.5 represents a medium effect size, and 0.8 or more a large effect size. However, in contrast to Cohen's *d*, the *g* is weighted by the sample size of each group (or condition) and corrected for smaller sample sizes (Borenstein, Hedges, & Rothstein, 2007). The Comprehensive Meta-Analysis (CMA) Version 3.0 (Borenstein, Hedges, Higgins, & Rothstein, 2013) was used to compute the difference between the illusion and control condition.

Total effect sizes. After each study's effect size was estimated, the effect sizes were summed across studies. In order to estimate the total effect size, one must choose between two analyses: the fixed-effect analysis or the random-effects analysis. The choice depends on whether the sample size from all studies shares the same general effect size, and whether one wants to generalize the results beyond the included studies (Borenstein, Hedges, Higgins, & Rothstein, 2009). The assumption for the present meta-analysis was that the included studies had numerous differences. For instance, experimental design, number of participants, and effect sizes or statistics of key results were variations that were not due to chance. In this manner, the studies were in themselves not representative of the entire (i.e., general) population. Additionally, the results of the included studies might be generalized to future studies. Based on these assumptions, the random-effects analysis was chosen. By choosing this model, the effect size within and between studies is allowed to vary. On the one hand, this leads to more substantial standard errors between the studies. On the other hand, there is a more balanced weight difference between studies with larger and smaller sample sizes (contrary to the fixed-effect analysis) (Borenstein et al., 2009).

Subgroup analysis. In order to determine potential sources of variability among the study designs, a subgroup analysis among the different moving RHI paradigms (i.e., video hand, physical hand, and VR hand) was conducted. Since the variability across the subgroups was assumed to be rather low, a mixed model was used, in which the differences were assessed via the fixed-effect model. In contrast, the subtotal effects within subgroups were estimated using the random-effects model (Borenstein et al., 2009).

Meta-regression analyzes. A meta-regression analysis can be used to assess dissimilarity. This approach establishes whether there is a significant relationship between the independent variable and the dependent variable (i.e., the outcome of interest) (Borenstein et al., 2009). In the present meta-analysis, two independent variables were explored: sample size and publication year. The sample size aimed to explore whether the number of participants in the respective study influenced the outcome. Publication year was intended to investigate whether, for instance, newer studies yielded larger effect sizes. Regression models using the random-effects model were constructed. This model allows for both within and between study variation (Borenstein et al., 2009). A significance level of $p < 0.05$ was adopted for all tests.

Interpreting the overall analysis. A forest plot was computed to provide an overview of the overall results. To explore whether effect sizes are consistent across the included studies, one should quantify the dissimilarity (i.e., heterogeneity). The Cochran Q -test was used to estimate the presence of heterogeneity. This test calculates the weighted sum of squares on a standardized scale reported with a p-value, where a low p-value is an indication of heterogeneity (Siddaway, Wood, & Hedges, 2019). However, the Q -test provides only a yes or no outcome for whether heterogeneity exists or not. Therefore, an I^2 test was applied to estimate the extent of the heterogeneity. According to the Cochrane Handbook (Higgins et al., 2019), an I^2 -value of zero means that all variability of study effect size estimates can be explained by sampling error within studies. Higher values over approximately 50% represent a moderate to substantial heterogeneity. High heterogeneity means that it may be misleading to assess overall value for the effectiveness of the interventions (Higgins et al., 2019). The sample size of the included studies may not represent the general population (Borenstein et al., 2011).

Publication bias. Publication bias refers to the assumption that studies with significant effects are more prone to be published compared to studies with no effects (Borenstein et al., 2009). This means that published research becomes skewed toward positive effects. Thereby, the meta-analysis will be biased. This bias can be prevented by identifying and including unpublished studies. Also, one can use different statistical techniques to discover publication bias. In the current study, a funnel plot was used to investigate the degree of publication bias. This plot represents the precision of the magnitude of the intervention effect. In the case of minor to no publication bias, the plots (i.e., the studies) are symmetrically distributed near the overall effect size. In contrast, in the case of potential publication bias, the plots are asymmetrically distributed. Consequently, an asymmetrical distribution may impact the validity of the overall conclusion (Borenstein et al., 2011; Siddaway et al., 2019). An Egger's regression test was used to determine if the asymmetry was statistically significant.

Questionnaire data

When comparing results from RHI studies, one must pay attention to what questionnaire statements have been used. Originally, Botvinick and Cohen (1998) introduced nine questionnaire statements using a 7-point Likert scale (with response options ranging from -3 to +3, in which -3 indicated "I totally disagree" and +3 "I totally agree"). All these statements assessed different phenomenological aspects of the RHI. However, only three of these

statements captured the predicted outcome: body ownership and referral of felt touch to the artificial hand. The other statements were control statements (i.e., “It seems as if I had more than one right hand”) (Kalckert & Ehrsson, 2014a), addressing, e.g., suggestibility effects.

Statements regarding the referral of felt touch to the artificial hand cannot be applied to the moving RHI. Therefore, the moving RHI paradigm can only measure the illusion using the statement, “I felt as if the artificial hand was my hand.” For this reason, studies investigating body ownership induced by movements have used different extended ownership questionnaires. For instance, Kalckert and Ehrsson (2012) developed a 16-statement questionnaire. In this questionnaire, four questions assess the experience of ownership (see Table 1), and four questions assess agency experience. The remaining statements refer to control statements.

Table 1

Example of used questionnaire statements for body ownership in the moving RHI (Kalckert & Ehrsson, 2012)

Body ownership	Q1	I felt as if I was looking at my own hand*
	Q2	I felt as if the artificial hand was part of my body
	Q3	It seemed as if I were sensing the movement of my finger in the location where the artificial finger moved
	Q4	I felt as if the artificial hand was my hand*

Note: In studies investigating the illusion using another external object than a hand, the word “hand” is exchanged to, e.g., arm or leg. *=statements which directly assess the ownership illusion.

However, the way moving RHI studies have grouped and analyzed the questionnaire statements is inconsistent. For instance, in the present meta-analysis, some included studies reported results based on two statements or more. In contrast, others reported results based on several statements, including self-location and corresponding control questions. Given these difficulties, results from statements that directly assess the ownership illusion (i.e., “I felt as if I was looking at my own hand” and “I felt as if the artificial hand was my hand”) have been the priority in the meta-analysis (see Table 1).

Results

Literature search

Database and reference searches identified 88 records for consideration after duplicates were removed. Additionally, eleven articles were found after a check of the reference lists of screened studies and reviews (Braun et al., 2018; Kilteni, Maselli, Kording, & Slater, 2015).

Titles and abstracts were examined to remove irrelevant records. In total, 77 records were excluded based on selection criteria. The additional search for potentially unpublished studies gave no hits. After assessing eligibility, 22 studies remained. One study included two suitable experiments (with different sample sizes); therefore, a total of 23 comparisons, which included 821 subjects, were synthesized in the meta-analysis (see Figure 1). Different moving RHI subgroups represented these studies. Two studies investigated the ownership illusion using a video-image projection of the participant's hands. Eleven studies used a physical artificial hand, and nine studies examined the VHI. For an overview of these articles, see Appendix B.

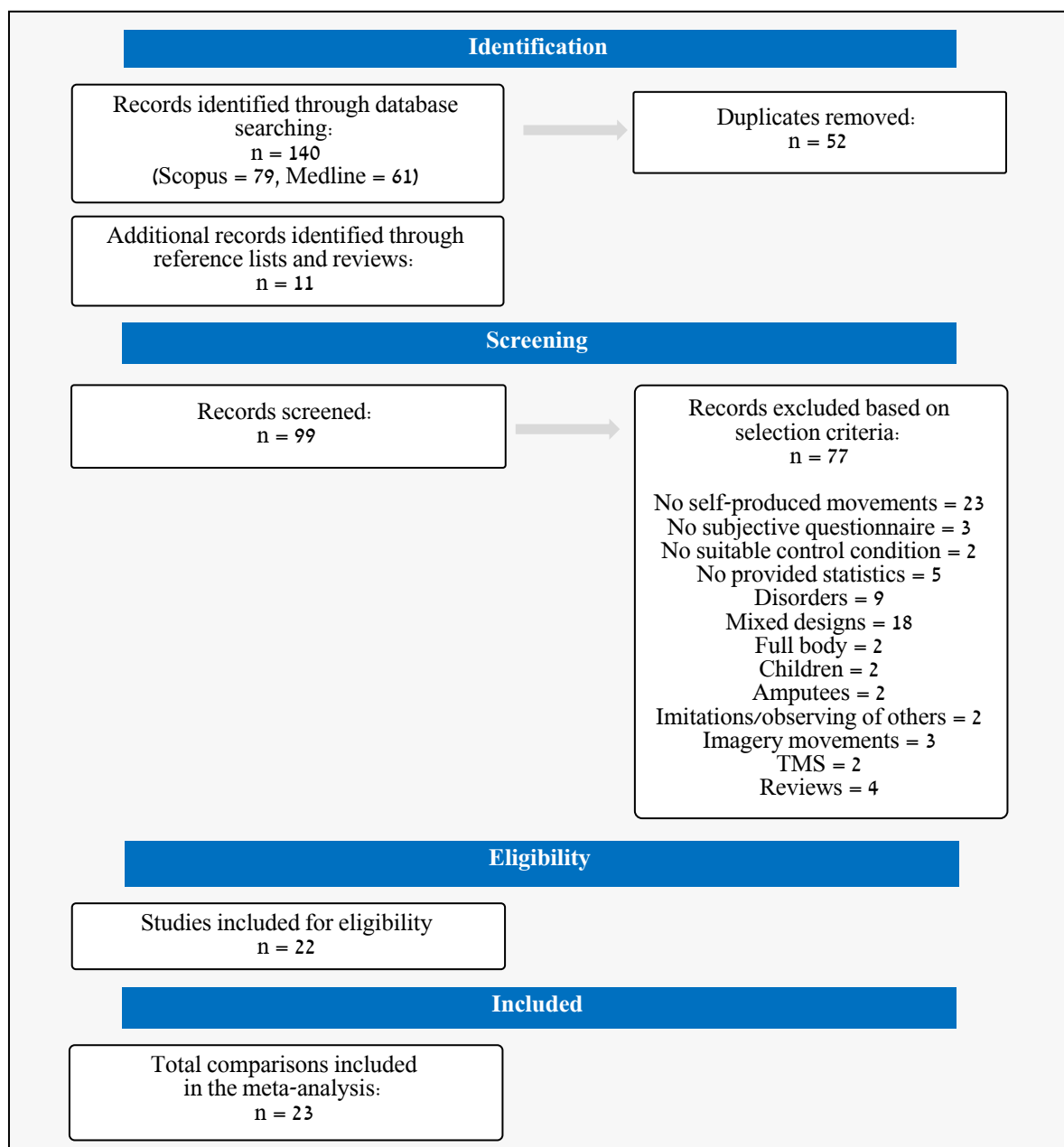


Figure 1. A flow-chart of the systematic literature search.

Statistical analysis

Total effect sizes. The random-effects analysis showed that the overall illusory effect was significant and superior to its control (Hedge's $g = 1.38$, 95% CI [0.87-1.57], $p < 0.001$) (see Figure 2). This indicates that the illusory intervention differed from the control condition by 1.38 standard deviations. However, the Cochran Q -test indicated significant heterogeneity between the studies ($Q = 61.8$, $p < 0.001$). A supplementary test showed moderate to substantial heterogeneity ($I^2 = 64.4\%$). See Table 2 for analyzed ownership statements and effect size calculations.

Table 2

Calculation of the random effects mean effect size (Hedge's g) for the illusory effectiveness on body ownership induced by self-produced movements versus control data.

ID/Study	Questionnaire statements	Hedges's g	Standard error	Variance	p-value
1. Longo (2009)	Q1	1.47	0.47	0.22	0.002
2. Tsakiris (2010)	Q1	0.90	0.33	0.11	0.007
3. Dummer (2009)	Q4	1.89	0.24	0.06	<0.001
4. Kalckert (2012)	Q1-Q4	1.88	0.17	0.03	<0.001
5. Riemer (2013)	Q4	0.81	0.23	0.05	<0.001
6. Braun (2014)	Q1-Q4	1.77	0.33	0.11	<0.001
7. Kalckert (2014a)	Q1, Q2, Q4	1.21	0.25	0.06	<0.001
8. Kalckert (2014b)	Q1, Q2, Q4	1.39	0.26	0.07	<0.001
9. Louzolo (2015)	Q1, Q4	1.45	0.20	0.04	<0.001
10. Jenkinson (2015)	Q1-Q4	2.72	0.20	0.12	<0.001
11. Caspar (2015) 1	Q1-Q4	1.65	0.43	0.18	<0.001
12. Caspar (2015) 2	Q1-Q4	1.76	0.44	0.19	<0.001
13. Kalckert (2017)	Q1, Q4	1.44	0.16	0.03	<0.001
14. Aymerich-Franch (2018)	Q2, Q4	1.31	0.35	0.13	<0.001
15. Sanches-Vives (2010)	Q4	1.18	0.40	0.16	0.003
16. Yuan (2010)	Q4 ^a	0.99	0.33	0.11	0.003
17. Kokkinara (2014)	Q4	1.49	0.30	0.09	<0.001
18. Ma (2015b)	Q4	0.94	0.22	0.05	<0.001
19. Ismail (2016)	Q1-Q4	2.23	0.44	0.20	<0.001
20. Salomon (2016)	Q1-Q4	0.78	0.32	0.10	0.016
21. Shibuya (2018b)	Q3, Q4	1.07	0.32	0.10	<0.001
22. D'Angelo (2018)	Q4	0.95	0.30	0.09	0.002
23. Brugada-Ramentol (2019)	Q1-Q4	0.82	0.24	0.06	<0.001

Note: Questionnaire statements used in the meta-analysis to calculate each study's effect size of illusory body ownership. See Table 1 for more details of the ownership statements. ^a=two other statements, including control statements.

Subgroup analysis. The mixed-effect analysis of subgroups showed that physical hand setups yielded the highest illusory effect (Hedge's $g = 1.56$, 95% CI [1.42-1.69], $p < 0.001$) (see Figure 2). The VR hand and the video hand yielded effect sizes of ($g = 1.06$, 95% CI [0.87-1.26], $p < 0.001$) and ($g = 1.09$, 95% CI [0.86-1.27], $p < 0.001$), respectively. However, in contrast to VR hand and video hand settings, the heterogeneity across physical hand settings was significant ($p = 0.001$, $I^2 = 65.5\%$).

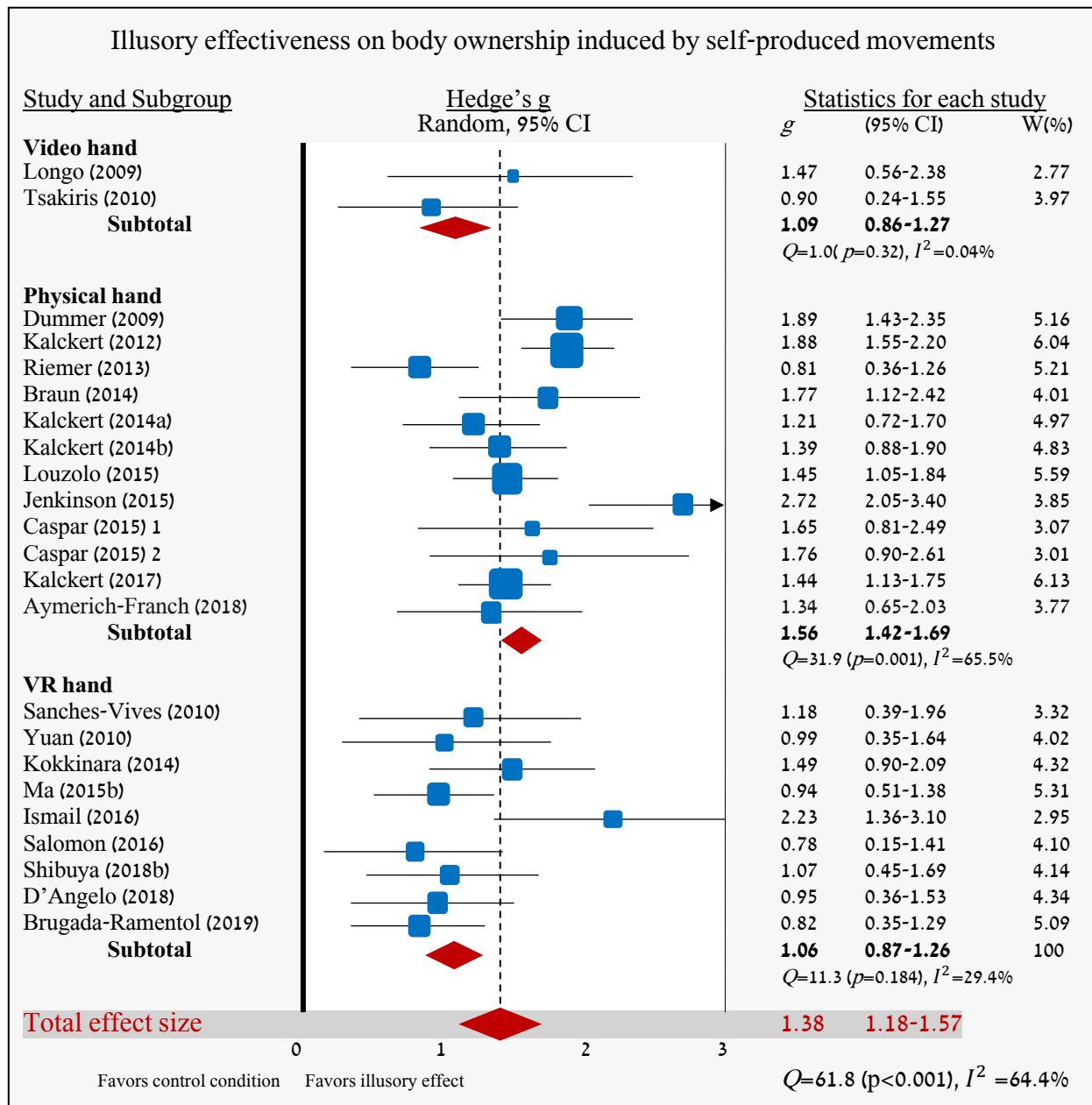


Figure 2. Forest plot showing illusory body ownership induced by self-produced movements.

An overview of all studies included in the meta-analysis. The blue squares indicate the effect size (g) of each study (i.e., the difference between illusory intervention and control condition). The bars indicate the 95% confidence interval (CI) of each study. The red diamond at the bottom of the figure indicates the meta-analytic effect size and its CI. The red diamonds in the middle indicate each subgroup effect size and its CI. *Abbreviations:* g =Hedge's g , W(%)=Percentage weight.

Meta-regression analyzes. Meta-regressions were used to examine the strength of the relationship between the independent variables sample size and publication year and the dependent variable effect sizes. The random-effects model meta-regression analysis indicated that the sample size was not related to effect size ($p = 0.379$) (see Figure 3). This suggests that the number of participants in a specific study did not influence the overall effect size in the meta-analysis. Consequently, the sample size is not a potential source of the dissimilarity between the studies.

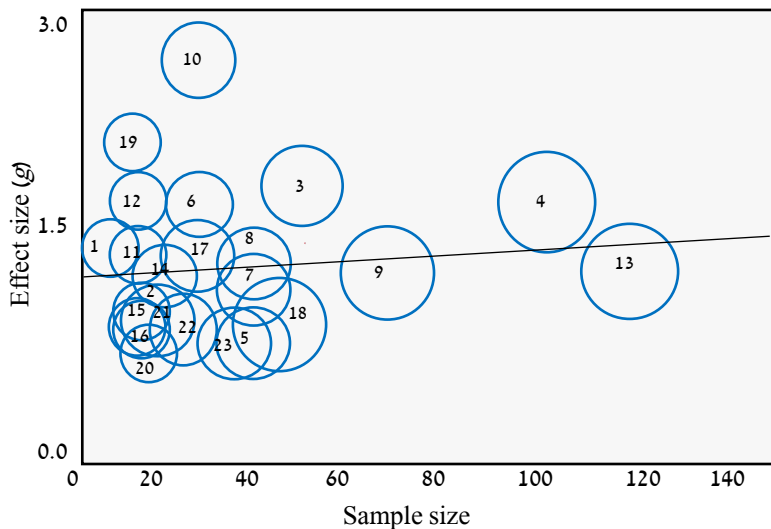


Figure 3. Regression of Hedge's g on Sample size. The numbers within circles indicate the study ID, see Table 2. The different sizes of the circles indicate the sample size of each study.

The random-effects meta-regression analysis of the publication year showed that the publication year was not related to effect size ($p = 0.331$) (see Figure 4). This result indicates that the publication year had no impact on the overall effect size in the meta-analysis, suggesting that publication year is not a potential source for the unexplained heterogeneity.

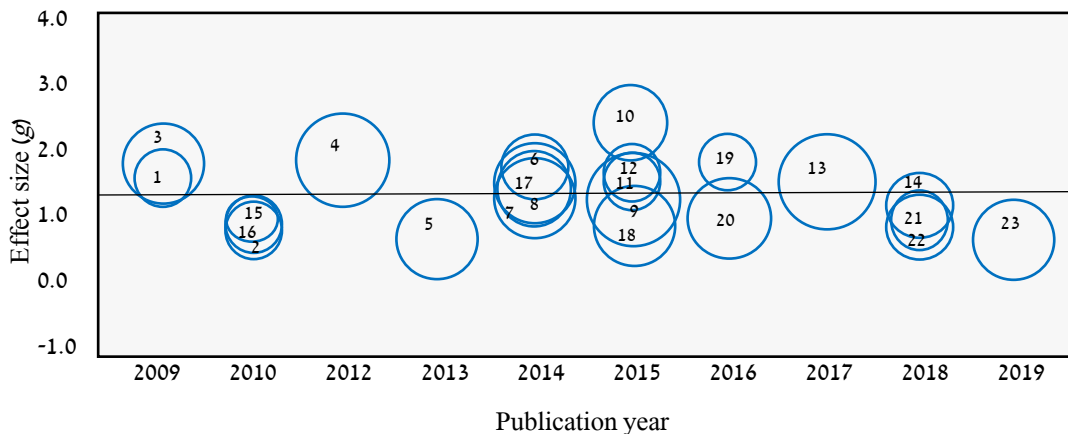


Figure 4. Regression of Hedge's g on Publication year. The numbers within circles indicate the study ID, see Table 2. The different sizes of the circles indicate the sample size of each study.

Publication bias. In order to evaluate the potential influence of publication bias, a funnel plot was generated. The funnel plot was asymmetrically distributed, which may indicate potential publication bias. Egger's regression test was used to determine whether there was a significant bias or not. The test demonstrated that no significant bias is likely to exist (Egger's test = -0.08, 95% [-2.57-2.40], $p = 0.945$) (see Figure 5).

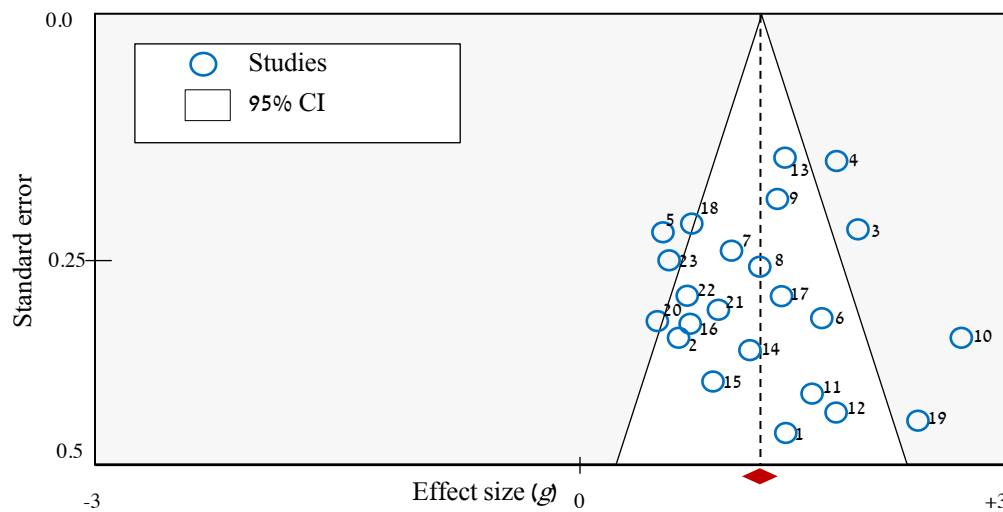


Figure 5. Funnel plot of standard error by Hedge's g . The dotted line and the diamond at the bottom represent the total effect size. The straight lines forming the inverted funnel refers to 95% confidence limits (CI). Each dot represents a single study. The numbers by the circles indicate the study ID, see Table 2.

Discussion

This study was the first meta-analysis to evaluate quantitative data from available studies within the moving RHI paradigm. Specifically, this meta-analysis aimed to investigate the effectiveness of body ownership induced by self-produced movements. The goal was also to identify and discuss what factors may explain the known inconsistency of results in the paradigm. The results showed that the total effect size of illusory body ownership was large and significant. In other words, the induction of the ownership illusion by self-produced movements was superior to the control conditions.

The dissimilarity across the studies was high. This indicates that the original studies did not represent the general population. Therefore, it can be misleading to determine the effectiveness of the intervention. Subgroups analysis showed that those studies using a physical hand produced a stronger effect. However, the dissimilarity among those studies was high. Accordingly, the present findings should not be taken to provide more definitive conclusions. Thereby, I can only speculate where the inconsistencies originate from.

Inconsistency between subgroups

The subgroup analysis results showed that studies using physical hands as an induction method had the largest effect size. Studies using VR hands produced a more robust effect size compared to studies using video projected images. These observations are in line with the results of Ijsselstein et al. (2006). They induced the illusion using visuotactile stimulation under three conditions similar to the subgroups in the current meta-analysis study. The rationale behind the study was to examine what factors may contribute to the vividness of the RHI (Ijsselstein et al., 2006). The experimental conditions differed in the aspects of the artificial hand's volume. The artificial hand in the VR and video hand conditions resembled a human hand in color and texture but was watched as a 2D image. However, in the physical hand condition, the prosthetic hand had a standard 3D surface. The authors speculated whether cues from internal body representations would differ depending on perceived condition. As the authors expected (and in accordance with the current meta-analysis study), the subjective ratings showed that the physical hand condition yielded the highest illusionary effect. The second-highest ratings were found in the VR condition, followed by the video hand condition (Ijsselstein et al., 2006). According to the authors, this result can be answered in the context of cognitive top-down processes (Ijsselstein et al., 2006).

In order to integrate an external object to one's body image, the external object must fulfill requirements for plausibility and congruency. Several RHI studies have found that the illusion depends on preexisting body representations (e.g., Kalckert et al., 2019; Tsakiris & Haggard, 2005; Yuan & Steed, 2010). Consequently, these results are in line with top-down accounts, suggesting that the illusion mainly relies on cognitive top-down processes (Tsakiris, 2010). Following requirements for top-down processes, studies using recorded 2D images of projected moving hands have observed significantly weaker ratings of ownership than those studies using a 3D moving hand (Riemer, Trojan, Beauchamp, & Fuchs, 2019). A 2D video projected hand differs in hand volume compared to a 3D hand (Ijsselstein et al., 2006). Nevertheless, in contrast to a concrete 3D hand, a 2D video projected hand is missing depth cues. Individual sensory cues as shadows, size, and textures create generalized representations of the 3D surface geometry (Tsutsui, Taira, & Sakata, 2005). Together these clues of an object provide us with a more realistic 3D input than, for instance, a screen, which may aid the RHI. However, nowadays, VR setups are in 3D, too. Thus, in contrast to physical hand studies, VR setups may suffer from being *less* realistic due to fewer depth cues compared to a concrete 3D hand. The sensory integration of depth cues may imply that the 3Dness derived

from a physical hand is not only related to top-down processes, as suggested by Ijsselstein et al. (2006). Instead, the 3Dness may be a fundamental feature related to bottom-up processes driven by sensory stimulation. Such speculations would fit with bottom-up accounts, holding that body ownership is mainly the result of multisensory integration (Armel & Ramachandran, 2003; Botvinick & Cohen, 1998).

There are other speculations about why physical hand settings could induce a more compelling experience of body ownership than the other experimental setups. It is not unusual for participants to be more familiar with a physical hand, such as a wooden hand, compared with advanced technology. Consequently, the unfamiliarity towards advanced technology in VR and video hand setups might impact the participant's ability to relax and stay focused. Nevertheless, as mentioned, the use of VR has increased, and with this, its familiarity.

Usually, technological systems have a minor lag in image processing. For instance, Ismail and Shimada (2016) had an inherent delay of approximately 90 ms in the synchronous condition. A minor delay can generate a general discomfort similar to motion sickness symptoms (i.e., "cybersickness") in some participants (Ng, Chan, & Lau, 2020). Further, the problem with "cybersickness" was probably more pronounced in older studies when the technology was older and slower.

The minor delay could have an impact on the strength of the illusion. Even in the synchronous condition, the inherent delay causes minimal asynchronicity. Such a temporal mismatch can reduce both illusory body ownership and a sense of agency (Kalckert & Ehrsson, 2012). Following the comparator model (Frith et al., 2000), the minor delay is potentially high enough to reduce the sense of agency due to the mismatch between the predicted movement and the actual sensory feedback. However, a temporal delay of more than 190 ms (see Ismail & Shimada, 2016) between the hands could cause a small but adequate discrepancy between the intention to move the hand and the perceived movement of the VR hand. Further, a temporal delay could lead to dissimilarities between the consequences of the action and the outcome. In accordance with the theory of apparent mental causation (Wegner, 2003), such dissimilarities between external cues and the action can reduce ownership and agency perception.

Nevertheless, the moving RHI is actively formed by sensorimotor processes, which allow for continuous comparison between the expected and the actual sensory consequences of the actions. Therefore, the reduction of a sense of agency and body ownership caused by minor lags in image processing in VR setups is best explained by the comparator model.

Despite these methodological issues, researchers have argued for the use of VR in RHI experiments. Recently, researchers have suggested that VR settings allow for a relatively realistic induction of visuomotor stimulation (e.g., Ma & Hommel, 2015b). This eventually results in a more vivid and authentic body ownership illusion compared to studies using physical hands (e.g., Ma & Hommel, 2015b). Consequently, some researchers using VR hand settings have argued for the advantages of VR over physical hand settings. The argument persists that the physical hand setup with restricted movements (see Kalckert & Ehrsson, 2012) moves the real effector, the artificial hand, in a limited way (Ma & Hommel, 2015b). Based on these arguments, Ma and Hommel (2015b) argued that the physical hand setup is “a particularly conservative, ecologically invalid measure of the perception of ownership ” (p. 279). According to the authors, this may explain the inconsistent results of studies using physical hands (Ma & Hommel, 2015b).

Researchers have argued that VR settings allow the participants to “act upon the world” (e.g., Kokkinara & Slater, 2014; Ma & Hommel, 2015a). The environment and the hands can be systematically manipulated. For instance, hands can vary in size, color, and shape (Hoyet, Argelaguet, Nicole, & Lécuyer, 2016; Ma & Hommel., 2015a; Yuan & Steed, 2010). Participants can more freely move their hands in synchrony with the VR hand. This would, in particular, benefit proprioception. The movement activates sensory channels such as muscle spindles and skin receptors, providing the participants with richer sensory input where the body is located in space (Butler et al., 2017). Thereby, additional sensory information is available to enhance the ownership experience (Kokkinara & Slater, 2014).

However, additional signals also imply that more sensory channels need to be evaluated for congruency. In accordance with the comparator model, which holds the importance of efferent signals and sensory feedback (Frith et al., 2000), one could speculate which conditions are most favorable for body ownership. Does the experience of ownership benefit from a great number of diverse information channels or fewer but more robust sensory signals? Nevertheless, this question is not just aimed at VR setups. It is also relevant in studies using physical and video-image hands. Inducing the illusion using the movements of one finger, several fingers, or the whole hand raise the same question. Would additional sensory cues provide stronger experience of body ownership, or would too many available cues lead to an attenuating of the illusion?

Inconsistency within subgroups

The subgroup analysis showed that there was inconsistency among those RHI studies using physical hands. Most studies reported high effectiveness compared to the control condition in physical hand settings. However, one study differed in the illusionary effect. The study by Riemer et al. (2013) had a remarkably lower illusionary strength compared to the other studies. The researchers used a wooden hand in a horizontal experimental setup. In contrast, all the other studies used wooden hands in vertical setups. In the horizontal setup, both hands are positioned beside each other. Accordingly, in the vertical setup, both hands are placed on top of each other. The way the hands are positioned seems to matter. This was confirmed by Bekrater-Bodmann, Foell, Diers, and Flor (2012). They induced the illusion using visuotactile stimulation. The vertical setup yielded higher ratings of illusionary ownership compared to a horizontal setup. Could this be a potential explanation for why physical hand settings yielded the largest effect sizes? Nine out of 12 studies used a vertical set up (see Appendix B). However, Dummer et al. (2009) and Aymerich-Franch et al. (2018) also used horizontal setups. Their effect sizes were as large as in studies using vertical setups. Classical RHI studies have observed that the perceptual integration of vision, touch, and proprioception may differ depending on the spatial position of the two hands (Kalckert, Perera, Ganesan, & Tan, 2019; van Beers, Wolpert, & Haggard, 2002). However, whether spatial arrangement also differs in the moving RHI paradigm is not yet clarified.

The study by Jenkinson and Preston (2015) had a remarkably larger illusionary strength than the others. They induced the illusion by requesting participants to watch the wooden hand for 30 s, followed by 60 s active movements. The other included studies typically induced the illusion with 90 s active movements. Kalckert and Ehrsson (2017) observed that most participants reported the sensation of ownership within 60 s. A more efficient induction period might have caused a larger ownership experience in the Jenkinson and Preston (2015) study. Further, during the visual capture, the artificial hand was watched not only by the participant but also by the experimenter. Perhaps this may have increased the participant's attention to the hand, leading to a higher illusionary rating.

The VR hand setup has the advantage of manipulating the experimental settings more than the other methods. For instance, Ismail and Shimada (2016) investigated the illusionary effect by manipulating the temporal delay in specific setups. However, it can be argued that this freedom and flexibility could, to some degree, lead to too much variety. Several VHI studies present new inventive experimental setups. For instance, some VR studies include

predictions of external sensory consequences, such as keypress (e.g., Shibuya et al., 2018a). The match between the intention to act and the perception of action goals is associated with general mechanisms supporting agency experience. In this way, setups using action goals are more related to the theory of apparent mental causation (Wegner, 2003) than the comparator model. This leads to the question of whether the agency of simple movements (such as moving one's index finger) and the agency causing changes in the sensory environment is derived from the same process. Because of the constant development of new VR paradigms, which may assess different agency processes, it is difficult to come to a final conclusion regarding the relationship between ownership and agency as any of the differences could be caused by the new technique. This is, for sure, a recurrent problem within all subgroups in the moving RHI.

Inconsistency in questionnaires

Studies within the moving RHI paradigm differ in their choice of subjective questionnaires. Most included studies in this meta-analysis have used the questionnaire from Kalckert and Ehrsson (2012). However, several studies have formulated their own statements based on the Kalckert and Ehrsson (2012) questionnaire. Usually, the participants are asked for the direct feeling of ownership (i.e., "I felt as if the artificial hand was my hand"). However, in some studies the participants were asked for: "*Overall*, I felt as if the artificial hand was my own hand" (e.g., Kokkinara & Slater, 2014). Other studies have used the phrase: "*Sometimes*, I felt as if the virtual balloon on the screen was my own hand or part of my body" (e.g., Ma & Hommel, 2015a). The latter statements are very different from the first one. If participants just for a second believe that the external object belongs to them, they would possibly respond positively to the latter formulations, even if the feeling of ownership would be fleeting. If participants also report low ownership ratings based on such statements, as in Ma and Hommel (2015a), one can argue about the credibility of the observed illusion.

A similar methodological inconstancy refers to the agency statements. Some statements refer to the direct feeling of agency, such as, "I felt as if I was causing the movement I saw" (e.g., Ismail & Shimada, 2016). However, some studies have used statements such as, "It seemed as if I could grab something with the artificial hand" (Riemer et al., 2014). Both these statements have their weaknesses. The first statement refers to an actual fact because the participants were, in fact, the ones causing the movement. The latter statement refers more to what one might be able to do with the artificial hand. The step from

feeling to being able to perform something with the artificial hand is enormous. With this, ratings could be lower for the latter statement compared to studies using statements assessing the direct feeling of agency. In fact, Riemer et al. (2014) and Salomon et al. (2016) have used statements identical or similar to the latter statement and observed lower agency ratings than, for instance, Ismail and Shimada (2016).

Moreover, these statements might measure different agency processes. While the first statement (“I felt as if I was causing the movement I saw”) refers to a direct bodily sensation of agency, the latter statement (“It seemed as if I could grab something with the artificial hand”) refers to inferences of the causes of the event rather than sensorimotor processes. The latter statement includes considerations, such as imagining the size or the shape of the grabbed object. In such a way, the latter agency statement is more a general indicator of the sense of agency. Thereby, the statement may go in line with Synofzik et al.’s (2008) higher-order level of agency, holding that agency cues are weighted based on their reliability and the specific context (Synofzik et al., 2008).

Most studies have used a 7-point Likert scale (ranging from -3 to +3, in which -3 has indicated “I totally disagree” and +3 “I totally agree,” and 0 “uncertainty”) (e.g., Kalckert & Ehrsson, 2012). Nevertheless, some studies have used a range covered only by positive numbers (e.g., 1 has indicated “totally disagree,” whereas 7 has indicated “totally agree”) (e.g., Kokkinara & Slater, 2014; Salomon et al., 2016). Different ranges of numbers may complicate the comparison between studies. Although the scales include the same labels (e.g., “totally disagree,” uncertainty,” and “totally agree”), they may not be interpreted similarly by the participants. A value of 0 on a -3 to + 3 scales may be interpreted as a neutral value, whereas a value of 4 on a 1-7 scale may be interpreted as indicating some degree of agreement.

Furthermore, there is no consistency in the way the data regarding the questionnaires is analyzed. In some studies, questionnaire ratings refer to an average of all ownership statements including separate control and target statements (e.g., Yuan & Steed, 2010). Other studies refer only to the particular statements capturing the direct experience of ownership (e.g., Kalckert & Ehrsson, 2017) (see Table 2). Together these differences regarding used and analyzed questionnaires and statements contribute to the inconsistency across the studies. A fundamental basis is to be aware of these methodological differences and understand what impact they have on the overall result.

Limitations

This meta-analysis has several limitations. First, there were limitations to the search strategy. A rather narrow search was conducted, with clear exclusion of studies that were not performed on healthy participants or included other forms of induction methods than self-produced movements, manipulations of motor mechanisms involved in motor control, as well as interferences with brain activity. Furthermore, several identified studies had mixed designs. These were, in some cases, hard to interpret and were thereby excluded. For instance, some studies induced the illusion using touch (e.g., Shibuya et al., 2018a) or passive movements (e.g., Holmes, Snijders, & Spence, 2006), followed by goal-oriented actions, such as keypress or reaching tasks.

Second, five studies were not included due to missing values. The inclusion of these studies might have had an impact on the overall results. In particular, it would have been interesting to include the Walsh et al. (2011) study. This study found the opposite pattern: in the presence of self-produced movements, the ownership illusion was less pronounced compared to passive movements. The study's result could have influenced the overall and the subgroup's effect size on body ownership in the meta-analysis. Walsh et al. (2011) induced the illusion using horizontal finger movements. In contrast, most other studies using physical hands have applied vertical finger movements (e.g., Jenkinson & Preston, 2015). In horizontal finger movements, the participant's finger is moving freely in space. However, in vertical finger movements, the participants more or less tap the finger on the table. In this way, vertical finger movements involve self-produced touch. One could debate whether additional sensory input from touch in vertical finger movements may have a facilitatory effect on both the sense of agency and body ownership.

Future directions

Moving RHI studies have reported inconsistent results between the strength of the illusion induced by active and passive movements. Some studies have shown that the mode of the movement did not differ (e.g., Kalckert & Ehrsson, 2014a), other studies have observed a larger subjective illusion in active movements (e.g., Dummer et al., 2009), whereas Walsh et al. (2011) have found that the illusion was more pronounced in passive movements. These controversial results have led to uncertainty regarding the processes of sensorimotor influence on RHI. In order to obtain consistent results on the strength of the illusion, researchers using the moving RHI paradigm need to apply a unified framework. This is particularly important

regarding used measurements (especially subjective questionnaires and proprioceptive drift) and experimental setups. A unified constitutive framework will pave the way for future studies to establish the contribution of motor control mechanisms and agency in body ownership illusions.

A further meta-analysis is needed to establish whether ownership induced by movements (both active and passive) yields a more significant illusory effect than visuotactile stimulation. This evidence may provide us with an understanding of whether movements, both self-produced and passive, facilitate body ownership more than the classical RHI paradigm.

Furthermore, future moving RHI studies need to investigate the role of the position between the artificial hand and the participant's real hand. Inducing the illusion horizontally versus vertically allows us to see whether the moving RHI follows the same pattern as the classical version (Bekrater-Bodmann et al., 2012). Moreover, moving RHI studies may compare the illusory strength in lateral versus distal positions and vary distance. This may lead to further understanding of what differentiates the moving RHI paradigm from the classical version (Kalckert et al., 2019).

There are many variants to implement motor responses within the moving RHI. The constant development of new paradigms seems to serve different agency processes. As stated by Christensen and Grünbaum (2018), a major task for future studies investigating the sense of agency is to distinguish between a sense of agency associated with the sensorimotor process and a sense of agency associated with external events. This distinction could facilitate the final conclusion regarding the relationship between ownership and agency.

Conclusion

The meta-analysis results extend the literature regarding the moving RHI paradigm's effectiveness on body ownership induced by self-produced movements. The results showed large illusory strength for self-induced movements compared to control conditions, such as asynchronous movements and an incongruent position of the artificial hand. However, the heterogeneity across the studies was too high to yield a reliable estimate of the total effect size. Studies inducing the illusion using physical hands yielded the largest effect. It can be speculated whether a 3D hand with "realness" has an illusory advantage compared to VR and video image hands. In order to obtain consistent results within the moving RHI paradigm, a unified framework, particularly regarding experimental setups and measurements, is needed.

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Appendix A

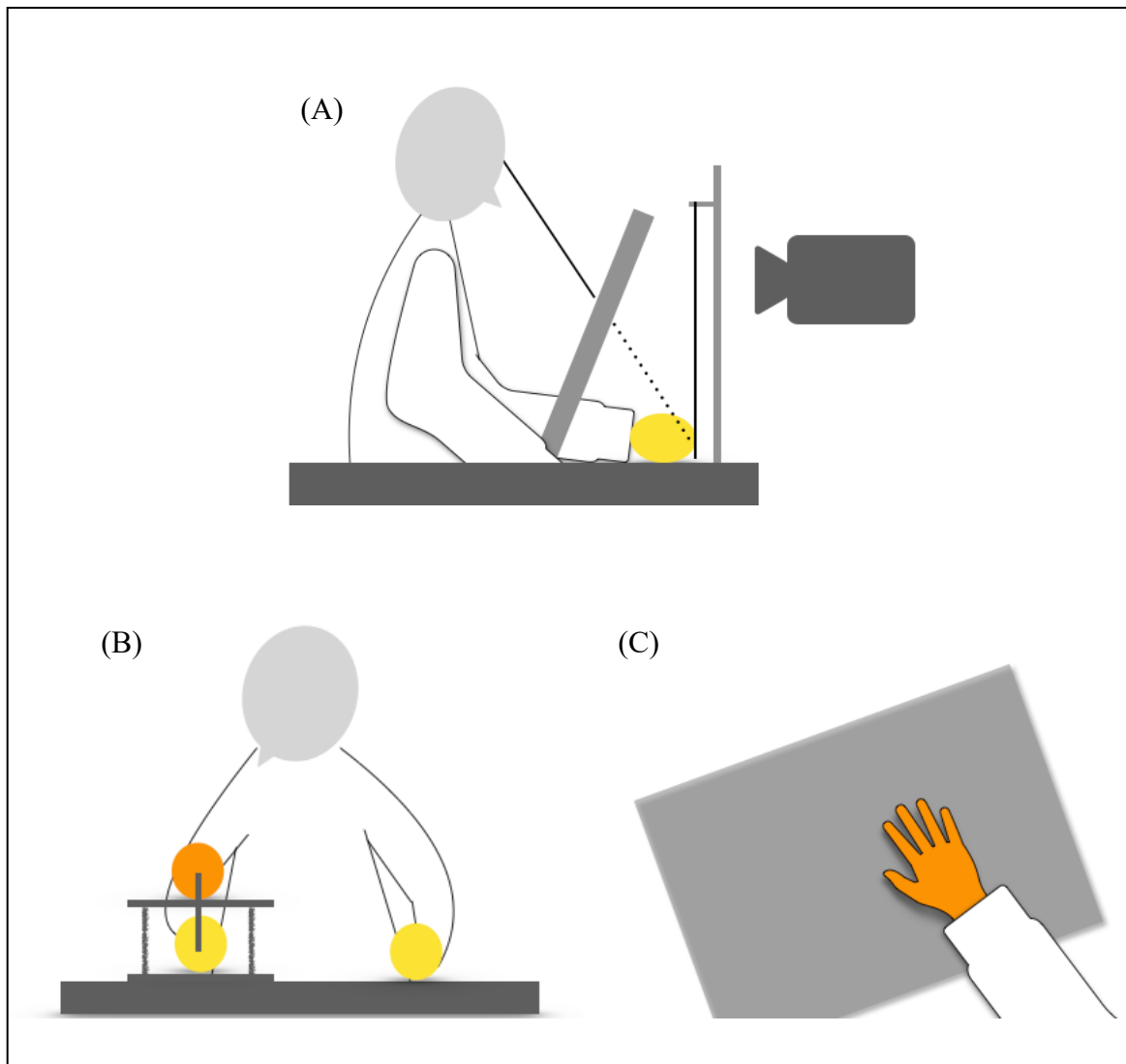


Figure 6. (A) Video hand: a video hand of the participant's real hand is displayed on the monitor either synchronously or asynchronously (e.g., Longo & Haggard, 2009). (B) Physical hand: in the vertical setup, the artificial hand is on top of a box, while the real hand is inside the box. The real and artificial index finger is connected via a mechanical device. When the participant moves his or her finger, the artificial finger moves as well. In passive conditions, the experimenter moves the mechanical device (e.g., Kalckert & Ehrsson, 2012). (C) VR hand: participants commonly wear a data glove and stereo glasses that translate the movements of the participant's real hand into the movements of the VR hand (either with a delay or not) (e.g., Sanches-Vives, 2010).

Appendix B

Table 3

Coded studies in the meta-analysis

ID	Study/Subgroup	Year	N	Setup	Objective measure	Control conditions
Video hand						
1	Longo	2009	11	Projection of the whole hand	-	Asynchronous
2	Tsakiris	2010	19	Projection of the whole hand	-	Asynchronous
Physical hand						
3	Dummer	2009	52	Prosthetic hand-whole; horizontal setup	-	Asynchronous
4	Kalckert	2012	104	Wooden hand-finger; vertical setup	Proprioceptive drift	Asynchronous + incongruent position
5	Riemer	2013	40	Wooden hand-finger; horizontal setup	Proprioceptive drift	Asynchronous
6	Braun	2014	25	Wooden hand-finger; vertical setup	Proprioceptive drift	Incongruent position
7	Kalckert (Exp.1)	2014a	40	Wooden hand-finger; vertical setup	Proprioceptive drift	Asynchronous
8	Kalckert (Exp.1)	2014b	40	Wooden hand-finger; vertical setup	Proprioceptive drift	Asynchronous
9	Louzolo	2015	71	Wooden hand-finger; vertical setup	-	Asynchronous
10	Jenkinson	2015	32	Wooden hand-finger; vertical setup	Proprioceptive drift	Asynchronous + incongruent position
11	Caspar (Exp. 2) 1	2015	14	Robotic hand-finger; vertical setup	Proprioceptive drift	Asynchronous
12	Caspar (Exp. 3) 2	2015	14	Robotic hand-diverse fingers; vertical setup	Proprioceptive drift	Incongruent condition
13	Kalckert	2017	117	Wooden hand-finger; vertical setup	-	Asynchronous
14	Aymerich-Franch (Exp. 2)	2018	19	Robotic hand-whole; horizontal setup	Proprioceptive drift	Asynchronous
VR hand						
15	Sanches-Vives	2010	14	VR arm	Proprioceptive drift	Asynchronous
16	Yuan	2010	20	VR hand; immersive VR	GSR	Non-human object
17	Kokkinara	2014	30	VR leg	SCR + breaks	Asynchronous

18	Ma	2015b	44	VR hand	Proprioceptive drift + SCR	Asynchronous + non-human object
19	Ismail	2016	16	VR robot hand	-	Asynchronous
20	Salomon (Exp. 2)	2016	20	VR hand and fingers	-	Incongruent position
21	D'Angelo (Exp.1)	2018	24	VR hand	-	Asynchronous
22	Shibuya	2018b	18	VR hand	-	Asynchronous
23	Brugada-Ramentol	2019	37	VR arm	-	Incongruent position

Abbreviations: SCR=skin conductive response, GSR=galvanic skin response.