Acta Psychologica 179 (2017) 68–77

Contents lists available at ScienceDirect

Acta Psychologica

journal homepage: www.elsevier.com/locate/actpsy

No consistent cooling of the real hand in the rubber hand illusion

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ARTICLE INFO

Keywords:
Rubber hand illusion
Hand temperature drop
Skin temperature
Cooling
Body ownership
RHI

ABSTRACT

In the rubber hand illusion (RHI), participants view a rubber hand that is stroked synchronously with their real, hidden hand. This procedure results in experiencing an increased sense of ownership over the rubber hand and demonstrates how multisensory information (vision, touch) can influence the sense of body ownership. However, it has also been suggested that a (lack of) sense of ownership over an own body part may in turn influence bodily processes. This suggestion has previously been supported by the observation that a decrease in skin temperature in the real hand correlated with ownership over the rubber hand. However, this finding has not been consistently replicated. Our lab has conducted several studies in which we recorded temperature of the hands during the RHI using various measures and in different circumstances, including continuous temperature measurements in a temperature-controlled room. An overall analysis of our results, covering five attempts to replicate the traditional RHI experiment and totalling 167 participants, does not show a reliable cooling of the real hand during the RHI. We discuss this failure to replicate and consider several possible explanations for inconsistencies between reports of hand temperature during the RHI.

1. Introduction

Consider a simple task such as walking towards another person – say, this huge big shot you noticed at a conference – and shaking hands. Your brain is charged with the challenging mission of walking, while making an appropriate arm movement, without knocking other things over, shaking the wrong hand, colliding forcefully with the target hand, or crushing it if you managed to reach it without accidents. Also, among this sea of moving limbs you will need to keep track of which ones are yours, so you can walk away again without making a complete fool out of yourself. To do so, your brain needs to know which parts of the world are "you" and which parts are not. To no surprise, the concept of body ownership, or recognition that your body indeed is your own, has received ample attention (De Vignemont, 2011; Ehrsson, Spence, & Passingham, 2004; Kilteni, Maselli, Kording, & Slater, 2015; Serino et al., 2013; Tsakiris, 2010, 2016; Tsakiris, Hesse, Boy, Haggard, & Fink, 2007).

While body ownership is considered a basic part of the sense of the self (Blanke, 2012; Gallagher, 2000; Serino et al., 2013), various illusions have shown that body ownership is surprisingly malleable (Alimardani, Nishio, & Ishiguro, 2016; Botvinick & Cohen, 1998; Ehrsson, 2007; Newport, Pearce, & Preston, 2010; Petkova & Ehrsson, 2008; Slater, Spanlang, Sanchez-Vives, & Blanke, 2010; van der Hoort, Guterstam, & Ehrsson, 2011). In these illusions, healthy participants are made to feel that an artificial object (Botvinick & Cohen, 1998; Ma & Hommel, 2015; Pasqualotto & Proulx, 2015) (or even artificial body such as a complete mannequin) (Maselli & Slater, 2013; Petkova & Ehrsson, 2008; Petkova, Khoshnevis, & Ehrsson, 2011; Salomon, Lim, Pfeiffer, Gassert, & Blanke, 2013; Slater et al., 2010) is part of their body by providing "false" multisensory information. In the most widely used version, the rubber hand illusion (RHI), a rubber hand is being stroked synchronously with one's own unseen hand. This causes integration of the visual and tactile input about the stroking which is felt on the rubber hand. This leads to the experience that the rubber hand feels like the own real hand (Botvinick & Cohen, 1998). Apart from the subjective changes assessed with questionnaires, the estimated position of the real hand is drifted towards the rubber hand (proprioceptive drift).

This illusion reveals that the brain's ability to integrate bottom-up multisensory input (vision, touch) heavily influences the sense of body ownership. Interestingly, gaining ownership of a foreign hand has consequences for the perception of the own "replaced" hand. Indeed, it has been suggested that the hand for which the illusion is evoked is somewhat disowned (Lane, Yeh, Tseng, & Chang, 2017; Lewis & Lloyd, 2010; Longo, Schüür, Kammers, Tsakiris, & Haggard, 2008; Preston, 2013; Valenzuela Moguillansky, O'Regan, & Petitmengin, 2013)

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http://dx.doi.org/10.1016/j.actpsy.2017.07.003
Received 3 January 2017; Received in revised form 21 June 2017; Accepted 7 July 2017
Available online 20 July 2017
0001-6918/

(However see De Vignemont, 2011; Folegatti, de Vignemont, Pavani, Rossetti, & Farné, 2009; Schütz-Bosbach, Tausche, & Weiss, 2009). This may in turn influence various physiological processes. For example, Barnsley et al. (2011) showed that histamine reactivity was increased after conducting the RHI, an effect that was only present for the stimulated, "replaced" arm. Hegedüs et al. (2014) reported higher pain thresholds of the real hand after RHI induction (although it should be noted that Mohan et al. (2012) did not find any influence on pain ratings of noxious heat stimuli). Moreover, it has been suggested that the RHI leads to slower processing of tactile stimuli on the "replaced" arm (Moseley et al., 2008).

One influential and widely cited effect of the RHI is a drop in skin temperature for the replaced own hand (Moseley et al., 2008). Moseley et al. (2008) observed that many pathological conditions (e.g. anorexia nervosa, complex regional pain, stroke) are characterised by both body ownership problems and a disturbed thermoregulation. They hypothesised that these symptoms are related, which could explain why disruption of temperature regulation can be restricted to a specific limb. This would imply that body ownership is not only a cognitive phenomenon that arises from having to control a body and bodily processes, but may in turn influence physiological processing in the body. Using the traditional RHI, Moseley et al. (2008) showed a relative decrease in skin temperature in the real "replaced" hand of about 0.2 °C–0.8 °C that correlated with ownership over the rubber hand. Most importantly, in their Experiment 3 they compared synchronous with asynchronous stroking and showed that the hand temperature after a 7–8 min stroking period was lower with synchronous than with asynchronous stroking on the test hand, whereas no difference was found on the non-stimulated hand. This suggests that the cooling is related to the illusionary disowning of the real hand in favour of the rubber substitute.

However, replication of this effect has been inconsistent. To our knowledge, since the study by Moseley et al. (2008), eight studies have published results on hand temperature measurements during the traditional RHI in healthy participants (David, Fiori, & Aglioti, 2014; Grynberg & Pollatos, 2015; Kammers, Rose, & Haggard, 2011; Paton, Hohwy, & Enticott, 2012; Rohde, Wold, Karnath, & Ernst, 2013; Thakkar, Nichols, McIntosh, & Park, 2011; Tsakiris, Tajadura-Jiménez, & Costantini, 2011; Van Stralen et al., 2014). Only three of them could replicate the RHI related temperature drop. Kammers et al. (2011) showed a relative cooling of the hand in synchronous compared to asynchronous conditions in the RHI. They provide additional evidence for the link between the RHI and local temperature changes, as artificially lowering the hand temperature increased proprioceptive drift in the RHI, while increasing the hand temperature decreases proprioceptive drift. Hand temperature manipulation did not influence subjective ratings of body ownership, but it has been shown before that proprioceptive drift and body ownership questionnaires measure different aspects of the RHI (Abdulkarim & Ehrsson, 2016; Blanke, 2012; Fiorio et al., 2011; Rohde, Luca, & Ernst, 2011). Tsakiris et al. (2011) also found a lower hand temperature in synchronous compared to asynchronous stroking in the RHI, however only in participants with relatively low interoceptive sensitivity, and it appeared to be more related to the proprioceptive drift outcomes than the subjective ratings of the RHI. Also, hand temperature change only showed a very small correlation with the level of interoceptive sensitivity, so it seems not entirely clear what was causing most of the temperature change in this experiment. Finally, a study from our lab (Van Stralen et al., 2014) reported a RHI-related hand temperature drop with slower stroking velocities in the RHI, which elicit an affective touch sensation and increases the effect of the RHI. However, a second experiment in the same study and using the same methods, did not replicate the temperature change (while it did replicate the increase in proprioceptive drift with slower stroking). This therefore might suggest that affective, pleasant stoking may be linked to temperature changes of the hand. Indeed, literature on affective touch shows that stroking with a velocity around 3 cm/s activated C-tactile fibres that project to the posterior insula and is associated with a pleasant feeling. Interestingly, the posterior insula has also been linked to interoception, for instance of body temperature (Craig, 2002).

In studies using variations on the RHI or related bodily illusions, skin temperature drop has also occasionally been replicated. Hohwy and Paton (2010) showed a hand temperature change related to the synchrony of stroking using some variants of the (in this case virtual) rubber hand illusion, but did not find any temperature changes in other variations on the RHI (although these variations did elicit the changes in sense of ownership). Salomon et al. (2013) found a very small temperature decrease of on average around 0.010–0.015 °C after about half a minute of stroking (see their Supplementary Fig. S1) on the leg and back in congruent conditions of a full body illusion, in which illusionary ownership over a complete fake body was generated by the use of a virtual reality setup. Macauda et al. (2015) used visual and vestibular input to create a full body illusion and also reported a small but significant drop in hand and neck temperature in the congruent full body illusion condition.

However, many other studies report a failure of replication of the temperature drop in the RHI either finding no temperature changes, or temperature changes that are independent of stroking synchrony, so unrelated to the illusion of body ownership. Paton et al. (2012) found no cooling of the test hand in the RHI using sensitive temperature measurements (0.01 °C accuracy, 2 Hz sampling over 15 s) in either participants with autism spectrum disorder or healthy controls. Grynberg and Pollatos (2015) also found no relative cooling of the hand in the RHI in a study investigating possible links between RHI susceptibility and lower awareness of emotional and non-emotional internal bodily signals. Other studies did find a drop in hand temperature, but independent of the synchrony of stroking (David et al., 2014; Thakkar et al., 2011). A case study in our lab in a patient with problems in ownership of her left arm showed a temperature drop in the left arm as a result of the RHI procedure but not in the right arm, but this was again independent of stroking synchrony (van Stralen, van Zandvoort, Kappelle, & Dijkerman, 2013). One study specifically set out to investigate the relative cooling of the test hand in the RHI. Rohde et al. (2013) used a robot arm to apply the stroking and did not find any temperature changes over the course of a 3.3 min stroking period, nor after 5–7 min of continuous stroking, while subjective ratings of the illusion and proprioceptive drift were in the range generally reported in RHI literature. When reverting to manual stroking and mimicking the procedure of Moseley et al. (Moseley et al., 2008) as closely as possible, Rohde et al. (2013) found a significant drop in hand temperature of the stimulated hand, but this drop was independent of synchrony of stroking (although there was a trend) and did not correlate with vividness of the illusion. Also, subjective ratings of the illusion and proprioceptive drift did not differ between the automatically applied and manually applied conditions. Therefore, the authors suggested that uncontrolled low level properties of the stimuli applied in the traditional RHI rather than subjectively felt ownership may cause temperature changes in some studies but not others.

Overall, these studies raise the question whether hand temperature really is a reliable objective measure of hand disownership during the RHI, especially given the known publication bias for positive findings (Franco, Malhotra, & Simonovits, 2014). Unfortunately, the literature that reports hand temperature in the rubber hand illusion in healthy participants is limited and quite diverse in their analyses and coverage, making a meta-analysis problematic. Over the years, several studies in our lab have included hand temperature as a dependent variable in their design. As mentioned above, we did find an effect of the RHI on hand temperature in one experiment (Van Stralen et al., 2014). Other studies in our lab have recorded temperature of the hands during the RHI with various measures and in different circumstances, but on a single study level did not find any illusion-related changes in hand temperature. This made us question the reliability of hand temperature

Table 1
Overview of the experiments analysed in the current study.

Experiment (dataset)	Participants	Test and control location	Temperature measurements	Stroking speed	Trials per condition
1	• 30 participants • All female • Mean age 21.8 ± 2.4 years	• Test hand: left • Control: cheek	• Laser thermometer • Once before, once after stroking	• ± 15–30 cm/s	2
2	• 63 participants • 39 female • Mean age 23.9 ± 4.4 years	• Test hand: both (counterbalanced order, data for both hands collapsed in the current analysis) • Control: other hand	• Laser thermometer • 5 × before, 5 × after stroking	• ± 15–30 cm/s	2
3	• 21 participants • 10 female • Mean age 23.9 ± 4.4 years	• Test hand: right • Control: left hand	• Laser thermometer • Once after stroking	• 3 cm/s • 30 cm/s	2
4	• 28 participants • 14 female • Mean age 32.0 ± 12.2 years	• Test hand: right • Control: left hand	• Laser thermometer • Once after stroking	• 0.3 cm/s • 3 cm/s • 30 cm/s	2
5	• 25 participants • 13 female • Mean age 22.4 ± 2.0 years	• Test hand: right • Control: left hand	• Button thermometer • Continuously during experiment, every second, resolution 0.0625 Co. • In a temperature-controlled room	• ± 15–30 cm/s	1

as a measure of body disownership in the RHI and we therefore performed a RHI study in a temperature-controlled room, using more sensitive temperature measuring equipment. In this manuscript we will analyse all experiments from our lab performed in the last five years covering hand temperature measurements during RHI induction together, including this last study in a temperature-controlled room, to investigate whether we can replicate the hand temperature drop shown by Moseley et al. (2008).

2. Methods

2.1. Experiments

Out of all experiments in our lab in the last five years, five recent experiments have been included in this study based on 3 criteria: 1) the traditional RHI was conducted (synchronous and asynchronous stroking), 2) in healthy participants, and 3) temperature was measured before and after stroking on both the test hand and a control location. The included experiments and specifics are presented in Table 1. All participants were naive to the purpose of the various experiments and written informed consent was obtained from all individual participants prior to the experiments. These experiments were conducted in accordance with the standards of the local ethical committee and the declaration of Helsinki.

Experiment 3 included conditions in which stroking was performed with a plastic mesh instead of the generally used soft brush, but these conditions were not included in this analysis. Experiment 4 included condition on the ventral side of the hand (palm of the hand) but these were not included for analysis. Experiment 5 included conditions in which the RHI was performed inside a MIRAGE setup (Newport et al., 2010; Newport, Preston, Pearce, & Holton, 2009), but these conditions were also not included in this study. The data on proprioceptive drift and questionnaire responses (but not temperature data) from Experiment 1 was previously published in Keizer, Smeets, Postma, van Elburg, & Dijkerman (2014) as a control group. The data on proprioceptive drift and questionnaire responses (but not temperature data) from Experiment 2 was published in Smit, Kooistra, van der Ham, & Dijkerman (2017). The data from Experiments 3 and 4 was previously published in Van Stralen et al. (2014).

2.2. Setup

Participants were seated with their forearms resting palms down on a table, within a wooden framework (75 × 50 × 25 cm). A rubber hand (including forearm) was placed in front of the participant, 17.5 (Experiments 1 & 2), 14 (Experiments 3 & 4) or 20 (Experiment 5) cm more to the body midline than the real hand it substituted (see Fig. 1). A screen could be placed either vertically, occluding the real test hand from view during stroking but not the other hand or the rubber hand, or horizontally, occluding all three hands during proprioceptive drift recordings. The arms were covered from view by the wooden framework.

2.3. Tactile stimulation

Tactile stimulation (stroking) was delivered using a soft brush, to the dorsal side of the test hand and the rubber hand during 90 s. Stroking was always from knuckle to fingertip, and the stimulation of

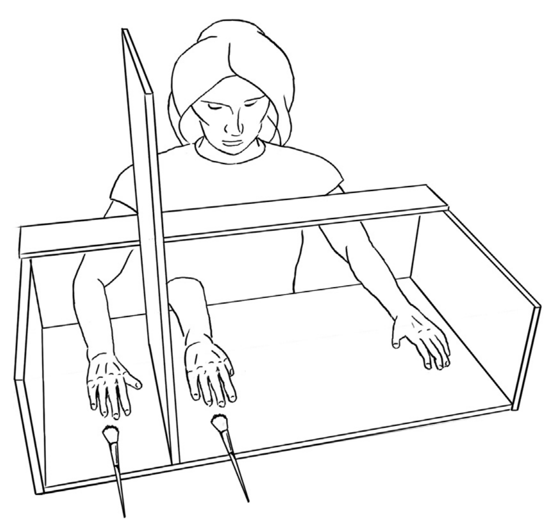

Fig. 1. Overview of the experimental setup. In Experiments 3, 4 and 5 and half of the trials in Experiment 2, the right hand was the test hand, as depicted here. In Experiment 1, as well as in half of the trials in Experiment 2, the left hand was the test hand. The large vertical screen is depicted hiding the test hand from view. It could also be placed horizontally on top of the setup, to hide all three hands from view.

the real and the rubber hand was either synchronous (both spatially and temporally aligned) or asynchronous (difference between stroking on the real and on the rubber hand was unpredictable) (trials in counter-balanced order in all experiments). Stroking speed was unpredictable in Experiments 1, 2 and 5 (around 20 cm/s), while in Experiments 3 and 4, it was controlled at respectively 3 cm/s and 30 cm/s (Experiment 3) or 0.3 cm/s, 3 cm/s and 30 cm/s (Experiment 4). Stroking speeds between 15 and 30 cm/s are quite frequently used in the literature, although the exact stroking speed is most often unknown as stroking frequency is reported instead (some recent examples: Dempsey-Jones & Kritikos, 2017; Grynberg & Pollatos, 2015; Lane, Yeh, Tseng, & Chang, 2017; Marotta et al., 2016; Suzuki, Garfinkel, Critchley, & Seth, 2013). Stroking speeds between 1 and 10 cm/s would specifically target C-tactile fibres, and are considered more pleasant than slower and faster stroking (Olausson et al., 2010; Morrison et al., 2010). Please see Van Stralen et al. (2014) for a discussion on how this affects the RHI experience. Within this manuscript, we will group stroking speeds above the optimal C-tactile fibre range under "normal".

2.4. Temperature recordings

In Experiments 1–4, temperature was recorded before and after stroking with a Raytek handheld Autopro (ST25) laser thermometer (resolution ± 0.2 °C) on the dorsal side of the test hand, as well as on a control location (cheek in Experiment 1, the non-stimulated hand in Experiments 2–5). In Experiment 5, the temperature of the test hand, non-stimulated hand and the rubber hand (environment) was measured continuously with a frequency of 1 Hz and a resolution of 0.0625 °C using iButton® temperature loggers (DS1922L) placed on the centre of the dorsal side of the hands. This experiment was conducted in a temperature-controlled room (19 °C).

2.5. Procedure

At the start of a trial, all three hands were occluded from view by the wooden screen (horizontally placed). In Experiments 1–4, skin temperature was measured at the dorsal side of the test hand and on the control location. In Experiment 5, the computer time at the start of stroking was logged as skin temperature was measured continuously during the whole experiment. Furthermore, in all experiments, the perceived location of the test hand and the non-stimulated hand was recorded. The experimenter moved her index finger along the back of the setup where a ruler was attached out of view from the participant. The direction was counterbalanced. Participants reported verbally when they thought the experimenter's finger mirrored the perceived location of their own index finger. This was performed for both hands. Next, participants closed their eyes, and the wooden screen was put up vertically to reveal the rubber hand and non-stimulated hand. Stroking was then applied (synchronous or asynchronous) after which participants were asked to close their eyes again so that all hands could be occluded from view. Skin temperature and perceived location of both hands were obtained again. Then, the participant was asked to fill out the 'rubber hand illusion questionnaire' (Botvinick & Cohen, 1998; Kammers, de Vignemont, Verhagen, & Dijkerman, 2009). At this time, they removed their hands from the setup.

The rubber hand illusion questionnaire consisted of ten statements (Kammers, de Vignemont, et al., 2009) (see Supplementary material); the first three statements are illusion-related and the remaining seven are control statements. For Experiment 5, an additional statement was added, which was not analysed in the current study (statement 11; 'It felt as if my real hand was at the location of the rubber hand'), as pilot testing showed some participants considered the original 3 illusion-related statements did not describe their experience in the MIRAGE setup sufficiently (not included in this analysis). Participants were asked to indicate how much they agreed with each statement on a 10-point Likert scale ranging from 1 "I strongly disagree" to 10 "I strongly agree". In the current study, the first three (illusion-related) statements were analysed: "1) It seemed as if I was feeling the touch at the location where I saw the rubber hand being touched", "2) It seemed as though the touch I felt had caused the stimulation on the rubber hand" and "3) I felt as if the rubber hand was my own hand".

Additionally, three out of the five experiments tested how pleasant participants rated the stimuli. In Experiment 1, this was asked once, on a Likert scale of 1–10. In Experiments 3 and 4, pleasantness was rated after every trial, on a visual analogue scale that gave an output range between 1 and 5.

2.6. Data analysis

2.6.1. Outlier selection

Within each individual dataset (one from each experiment), outliers (> 3 sd from the mean) were excluded for each outcome measure as well as participants who failed to follow instructions (for instance moved their hands during proprioceptive drift measurements). In dataset 1, out of 30 participants, 1 was excluded for the analysis of hand temperature (> 3 sd from average), 0 for the questionnaire and 2 for proprioceptive drift (> 3 sd from average). In dataset 2, no participants were excluded for any of the analyses. In dataset 3, out of 21 participants, 1 was excluded for all analyses due to scores > 3 sd from average. In dataset 4, out of 28 participants, 0 were excluded for the analysis of hand temperature: 1 for the questionnaire (failed to follow instructions) and 4 for proprioceptive drift (moved their hands or indicated something other than the felt location of the real hand). In dataset 5, out of 25 participants, 1 was excluded for all analyses (kept moving the hands), 1 was excluded for the analysis of hand temperature (> 3 sd from average), 0 for the questionnaire and 1 for proprioceptive drift (moved the hands on several occasions before indicating the perceived location).

2.6.2. Subjective ratings and proprioceptive drift

To verify whether the rubber hand illusion was successfully induced in the included experiments, we analysed subjective strength of the illusion and proprioceptive drift separately in each dataset.

Results of the questionnaire responses in dataset 1 (Keizer et al., 2014), 2 (Smit et al., 2017), 3 and 4 (Van Stralen et al., 2014) were previously published and are discussed in depth in these papers. No participants were excluded that were not also excluded in the published papers. We performed Wilcoxon signed-rank tests per dataset per stroking speed to compare the average ratings on the test statements (1, 2 and 3) to a (usually deemed "neutral") score of 5. As the data did not resemble normal distributions, we performed non-parametric tests, similar to Keizer et al. (2014) and Smit et al. (2017). Bayesian equivalents of these non-parametric tests are not yet commonly available.

We calculated proprioceptive drift by taking the difference between the perceived and the real location of the hand after stroking (averaged in case of 2 trials/condition), with a positive difference reflecting a drift in the direction of the rubber hand. Proprioceptive drift of the test hand was compared between synchronous and asynchronous stroking conditions per dataset per stroking speed using a paired samples comparison in JASP (JASP Team, 2017; Morey & Rouder, 2015), which uses a Jeffrey's Bayesian *t*-test (Rouder et al., 2009). This procedure compares a model with an effect of Synchrony (with a Cauchy prior, scaled $r = 0.707$, on effect size, so $H+: \delta \neq 0$,) with the Null model ($H0$, $\delta = 0$) (default uninformative priors in JASP). 2 participants from Experiment 1 were excluded based on proprioceptive drift values > 3 sd from average, that were not excluded in Keizer et al. (2014) due to the nature of their non-parametric analysis and a slightly different calculation of proprioceptive drift.

2.6.3. Temperature analysis

For each participant in all experiments, we calculated the temperature difference at the test hand and the control location by subtracting the temperature after stroking from the temperature before stroking. If an experiment contained two trials per condition, these two temperature differences were averaged. Temperature differences were calculated for the test hand and on a control location in the synchronous and asynchronous condition. Only the temperature data from dataset 3 and 4 were previously published in Van Stralen et al. (2014). No participants were excluded that were not also excluded in Van Stralen et al. (2014).

First, to investigate the collective picture these studies give, we performed a conventional meta-analysis. For this, temperature differences in the four conditions (location (2) × synchrony (2)) were combined into one outcome measure: we controlled the difference in temperature change in the test hand and the control location in synchronous ("sync") condition for that in asynchronous ("async") condition. Thus, Tdc = (Tchange test hand sync − Tchange control location sync) − (Tchange test hand async − Tchange control location async) with Tchange = (temperature at end of stroking) − (temperature at start of stroking). A negative Tdc would imply a drop in temperature as a result of the RHI. For the meta-analysis we used a random effects model in OpenMetaAnalist. Within subject conditions in Experiments 3 and 4 (stroking speed) were entered as separate studies.

Next, we used the BEST package in R (Kruschke, 2013): to get a Bayesian posterior estimate for average hand temperature change in the test hand in RHI conditions minus control conditions. This package can handle informative priors. We investigated how much of the posterior distribution fell inside a region of practical equivalence (ROPE) (Kruschke, 2013). The model used was a t-distribution, with mean μ, standard deviation σ and degrees-of-freedom parameter df. For σ and df, we used broad priors as described by Kruschke (2013) (prior σ: gamma distribution with mode = sd(data) and sd = sd(data) ∗ 5, prior df: gamma distribution with mean = 30 and sd = 30). We used an informative prior for μ based on the results by Moseley et al. (2008) who reported an average temperature change difference in the test hand between RHI and control conditions of − 0.27 degrees (SEM = 0.11, n = 11). We used the Bayesian MCMC process (3 chains) with an adaptive phase of 100 iterations, 1000 iterations burn-in and 33,334 iterations sampling (default settings in the BEST package). Convergence was reached for all parameters (potential scale reduction factor was 1.00 for μ and σ, 1.01 for df).

Finally, we did a Bayesian correlation analysis in JASP (Jeffreys, 1961; Ly, Verhagen, & Wagenmakers, 2016; van Doorn, Ly, Marsman, & Wagenmakers, 2016) to see if temperature changes in the temperature change of the test hand (both in synchronous and asynchronous conditions) correlated with subjective strength of the illusion (average questionnaire ratings on questions 1, 2 and 3) or proprioceptive drift of the test hand. We included both Synchrony conditions as some individuals in RHI experiments report some embodiment even in asynchronous conditions. As questionnaire ratings were not following a normal distribution, and temperature changes appeared to be more heavily tailed than a normal distribution, a rank correlation was performed. We also performed a rank correlation to investigate a possible relationship between pleasantness ratings and test hand temperature change. For the latter analysis, the pleasantness ratings of synchronous stroking in Experiments 3 and 4 were averaged and resized to 1–10 with the calculation (10 − 1) ∗ (rating − 1) / (5 − 1) + 1). Additionally, we performed a Bayesian Pearson correlation (Ly, Marsman, & Wagenmakers, 2017) to find out if there was a correlation between hand temperature at the start of an experiment and test hand temperature change.

3. Results

First, it was made sure that all studies involved had successfully elicited the RHI. Results of the questionnaire responses and proprioceptive drift in datasets 1 (Keizer et al., 2014), 2 (Smit et al., 2017), 3 and 4 (Van Stralen et al., 2014) were previously published. Please see these papers for a more elaborate discussion of these results.

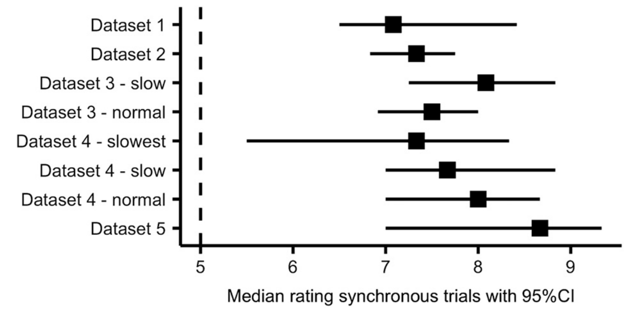

Fig. 2. Forest plot of group median questionnaire ratings on the test statements (rating of 1, 2 and 3 averaged) in synchronous conditions. Horizontal lines depict a (bootstrapped, 10,000 samples) 95% CI on the median. Note that all datasets show that ratings of the test statements were above a neutral score of 5.

3.1. Questionnaire ratings

Wilcoxon signed-rank tests showed that questionnaire ratings on the test statements in synchronous conditions were larger than a neutral score of 5 in each dataset (dataset 1: median 7.08, $p < 0.001$, $r = 0.51$; dataset 2: median 7.33, $p < 0.001$, $r = 0.76$; dataset 3,slow: median 8.08, $p < 0.001$, $r = 0.83$, normal: median 7.5, $p < 0.001$, $r = 0.83$; dataset 4, slowest: median 7.33, $p = 0.001$, $r = 0.60$, slow: median 7.67, $p = 0.001$, $r = 0.82$, normal: median 8.0, $p = 0.001$, $r = 0.76$).

The median ratings on the test statements (1,2 and 3 combined) after synchronous stroking is depicted in Fig. 2.

3.2. Proprioceptive drift

Average proprioceptive drift of the test hand was compared between synchronous and asynchronous conditions in each dataset. Bayes factors were in favour of the model that included an effect of Synchrony: i.e. proprioceptive drift was different in synchronous (sync) than in asynchronous (async) conditions, compared to a model without an effect of Synchrony. Estimated mean proprioceptive drift was larger with synchronous than with asynchronous stroking in all datasets. The estimated mean and standard deviation in cm, and BF are given in Fig. 3.

To summarise, the ratings of the test statements in the questionnaire and proprioceptive drift results suggest that all 5 studies successfully induced the rubber hand illusion.

3.3. Temperature: meta-analysis

The main goal of the current study was to see if we find evidence in favour of a hand temperature change related to the RHI. First, we performed a conventional meta-analysis of our five experiments. For this analysis, temperature differences in the four conditions (Location (2) × Synchrony (2)) were combined into one output measure (Tdc, see Methods section). This is the output measure used in Van Stralen et al. (2014), which covered datasets 3 and 4 and reported a RHI related temperature drop in the test hand. A negative Tdc would imply a drop in temperature as a result of the RHI. However, the meta-analysis showed no significant effect of RHI on hand temperature, the estimated Tdc was − 0.06 (95% CI − 0.17, 0.06, $p = 0.337$) (see Fig. 4).

The forest plot illustrates that the reported cooling of the hand in the RHI in Experiment 3 is rather eccentric (even compared to the original Moseley et al. (2008), who reported a Tdc of − 0.27) and it could not be replicated using the same methods (Experiment 4). Heterogeneity in the meta-analysis was significant with a I^2 of 77.6% ($tau^2 = 0.017$, $p < 0.001$), which indicates substantial heterogeneity, i.e. the studies are not all evaluating the same effect. This seems to be

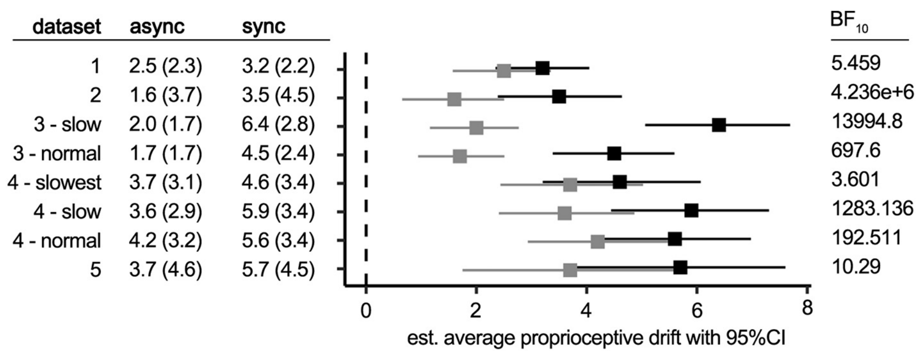

Fig. 3. Forest plot of estimated mean proprioceptive drift. Synchronous stroking is shown in black, asynchronous in gray. Horizontal lines depict a 95% CI on the mean. Note that all studies show proprioceptive drift of the test hand as a result of the RHI, although in the slowest stroking condition in dataset 4 this effect is less clear. In the table on the left, estimated mean and standard deviation per dataset is given, with on the right side of the graph the BF_{10}.

caused by the results from the slow stroking condition in Experiment 3 (3 cm/s), as I^2 drops to 20.1% ($tau^2 = 0.001$, $p = 0.276$) when excluding this data subset (but not that of the slow stroking condition in Experiment 4). A subgroup meta-analysis with stroking speed as the covariate (continuous random effects) shows a Tdc estimates of − 0.033 (95% CI − 0.080, 0.013) for normal stroking speeds, − 0.418 (95% CI − 1.281, 0.444) for slow stroking speed and 0.158 (95% CI 0.004, 0.304) for the slowest stroking speed. None of these subgroups show a significant RHI related hand temperature drop (normal: $p = 0.155$, slow: $p = 0.342$, slowest: NA as there is only one dataset with this stroking speed). When excluding the slow stroking condition in Experiment 3, the estimated Tdc was − 0.01 (95% CI − 0.06, 0.05; $p = 0.774$).

The slow stroking condition in Experiment 3 seems to have generated very different results from the identical experimental condition in Experiment 4. To test this, we ran an additional Bayesian unpaired comparison between the slow stroking condition in datasets 3 and 4 (see Gronau et al., 2017) using JASP. The Bayes factor of $BF_{10} = 217.8$ shows that the data were far more likely to have occurred under the alternative (dataset 3 ≠ dataset 4) than under the null hypothesis. Based on this finding and the heterogeneity analysis, we will report further analyses both including and excluding the data from the slow stroking condition in Experiment 3.

3.4. Dissimilarity of dataset 3

We were interested to see what caused the dissimilar Tdc in dataset 3. It has been suggested that RHI is larger when your hands are colder (Kammers et al., 2011). Room temperature in Experiment 3 was slightly lower (on average 18.4 °C) than in Experiments 1 (20.3 °C), 4 (22.4 °C) and 5 (20.8 °C) (no data on room temperature in Experiment 2 is available). Therefore, we checked whether hand temperature at the start of a condition correlated with temperature change in that hand in that condition in all datasets (collapsed). There was moderate evidence against such correlations (test hand sync: Pearson's $r = 0.062$, $BF_{10} = 0.128$, async: $r = 0.165$, $BF_{10} = 1.809$; control sync: $r = 0.047$, $BF_{10} = 0.107$, async $r = -0.045$, $BF_{10} = 0.104$). Also, hand temperature at the start of trials was not lower in Experiment 3 than in the others (Bayesian independent samples *t*-test: sync trials: $BF_{10} = 0.188$, async: $BF_{10} = 0.194$).

Furthermore, based on the conclusions of Van Stralen et al. (2014), temperature differences in the hands may relate to affective experience rather than changes in embodiment. Three out of the five experiments tested how pleasant participants rated the stimuli. However, when excluding dataset 3, slow condition, there was moderate evidence against a correlation between pleasantness ratings and temperature change of the test hand (Kendall's tau = − 0.029, $BF_{10} = 0.138$). (When including dataset 3, slow condition, the Bayes factor is indecisive: Kendall's tau = − 0.156, $BF_{10} = 0.912$.)

We have found no direct explanation for the dissimilar results in Experiment 3 in our data. We will speculate on further possible differences between Experiments 3 and 4 that may have caused the temperature changes in Experiment 3 in the Discussion section.

3.5. Evidence for the null effect

The conventional meta-analysis did not find a significant RHI related temperature change. To investigate the strength of this null effect, we directly examined how much evidence we find that for the idea that the RHI results in a meaningful temperature drop in the test hand. Bayesian statistics offers the possibility to include previous beliefs. As Moseley et al. (2008) give mean and variance information on the temperature drop in the hands, we could include this as an informative prior. We investigated what percentage of the posterior distribution of temperature change in the test hand in synchronous minus asynchronous conditions, falls inside a region of practical equivalence (ROPE) to zero temperature change (Kruschke, 2013).

Fig. 5A illustrates how the credible t-distributions described our data (excluding slow condition in dataset 3), as well as the difference with the data from Moseley et al. (2008). As can be seen in Fig. 5B, the estimated mean RHI related temperature change in the test hand (μ in the model) was 0.00383 °C, and the 95% HDI is from − 0.0504 to 0.0579. Estimation for σ was 0.33521 (HDI 0.2717 to 0.3996) (which is similar to the standard deviation in the data from Moseley et al., $0.11 * \sqrt{11} = 0.3648287$) and df 3.95845 (HDI 1.9267 to 6.5541). Using a ROPE of [− 0.1: 0.1 °C], 100% of the posterior distribution fell within the ROPE, i.e. was equivalent to zero (see Fig. 5B). Given the resolution of the measuring equipment used in all but 1 of the studies

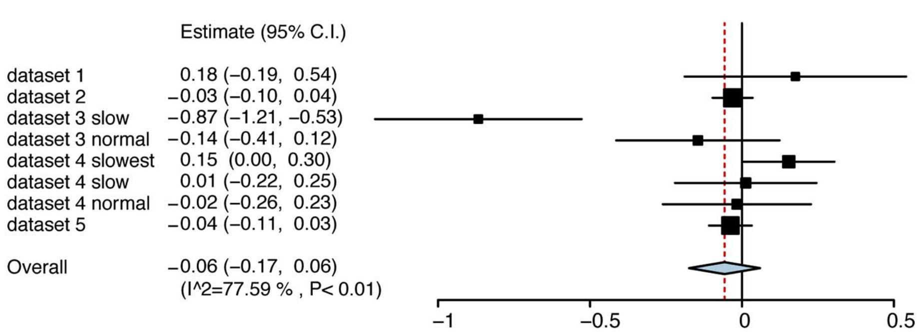

Fig. 4. Forest plot of average Tdc in the different Experiments and Stroking Speed conditions. The Tdc represents the change in temperature of the test hand in synchronous versus asynchronous conditions, relative to the same temperature change in the control location. A negative Tdc would imply a drop in temperature as a result of the RHI. The diamond shape depicts the weighted average (including dataset 3), which is not significantly different from zero.

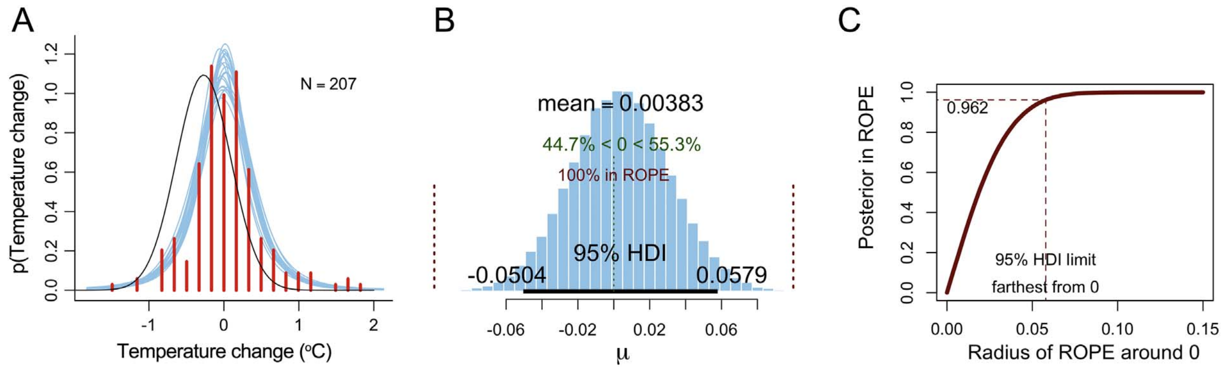

Fig. 5. Results from the ROPE procedure with an informative prior based on the data from Moseley et al. (2008). Panel A shows in red (medium gray when printing grayscale) a histogram of our data on the temperature change in the test hand in RHI trials minus control trials, with 20 credible t-distributions in blue (lightest gray). Superimposed in black is the prior distribution we used (normal distribution, mean = − 0.27, sd = 0.11 ∗ √11). Panel B shows the posterior probability distribution for μ in blue, with HDI credible interval in black, percentage of the distribution above and below zero in green and ROPE in red (dotted red lines represent the ROPE boundaries). Note that 100% of the posterior distribution fell within the ROPE, i.e. was equivalent to zero. Panel C shows the relation between the choice of ROPE radius and fraction of the posterior that falls within the ROPE. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

(± 0.2 °C) we consider this a reasonable ROPE, but we plotted dependence of how much of the posterior falls inside the ROPE as a function of the width of the ROPE in Fig. 5C so readers can consider their own thresholds. When including the slow condition in dataset 3, results are similar. Estimated μ: − 0.0348 °C, (HDI − 0.0914 to 0.0223), σ: 0.3560 (HDI 0.2941 to 0.4225) and df: 2.9598 (HDI 1.7640 to 4.3793), 99% within a − 0.1: 0.1 °C ROPE.

3.6. Correlation analyses

Finally, we checked whether over all conditions, temperature change of the test hand (both in synchronous and asynchronous conditions) correlated with subjective strength of the illusion (average questionnaire ratings on questions 1, 2 and 3), including both synchronous and asynchronous stroking. The BF_{10} that quantifies evidence in favour of a two-sided alternative hypothesis that the population correlation does not equal 0, was 0.207 (Kendall's tau = − 0.051), which suggests moderate evidence in favour of the Null model (similar when including dataset 3-slow: Kendall's tau = − 0.048, BF_{10} = 0.197). Similarly, there was moderate evidence against a correlation between proprioceptive drift of the test hand and temperature change of the test hand (Kendall's tau = − 0.033, BF_{10} = 0.107, similar when including dataset 3-slow: Kendall's tau = − 0.050, BF_{10} = 0.207) (see Fig. 6).

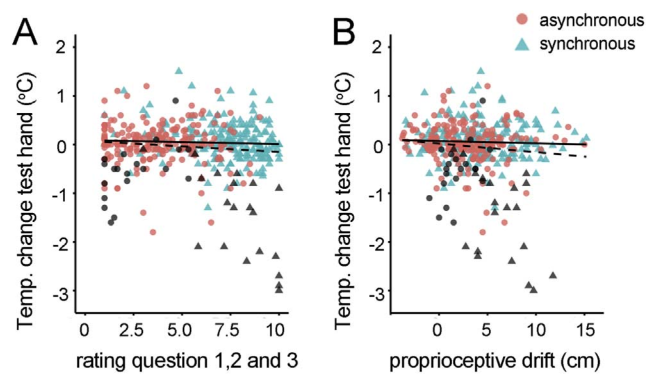

Fig. 6. Scatterplots of the correlation analyses. A: subjective strength of the RHI (average ratings on questionnaire items 1, 2 and 3) vs temperature change during stroking in the test hand (no correlation, BF_{10} = 0.207). B: proprioceptive drift of the test hand vs temperature change during stroking in the test hand (no correlation, BF_{10} = 0.107). Solid regression lines represent the model when excluding dataset 3 — slow condition, dotted lines when including it. For dataset 3, slow stroking, asynchronous stroking conditions are depicted by gray circles, synchronous stroking conditions by gray triangles (darkest gray when printing grayscale). For the other data points, asynchronous stroking conditions are depicted by red circles (lightest gray), synchronous stroking conditions by blue triangles (medium gray).

4. Discussion

The current study investigated whether temperature changes are a reliable measure of body (dis)ownership, as suggested in several studies (Hohwy & Paton, 2010; Kammers et al., 2011; Moseley et al., 2008; Tsakiris et al., 2011) but disputed in several others (David et al., 2014; Grynberg & Pollatos, 2015; Paton et al., 2012; Rohde et al., 2013; Thakkar et al., 2011). We conducted an analyses of data collected during five experiments from our lab (with a total of 167 participants) that used the rubber hand illusion (RHI) and measured hand temperature, to see whether we find evidence in favour of a hand temperature change as a result of the RHI. All experiments in the analysis replicated the subjective experience of body ownership over the fake hand, as well as proprioceptive drift of the test hand associated with the RHI. We found that a conventional (frequentist) meta-analysis of our results did not show a significant RHI related change in hand temperature. Moreover, Bayesian ROPE analysis showed that over all experiments, when correcting temperature change in the test hand with synchronous stroking for temperature change with asynchronous stroking, the estimated mean temperature change is equivalent to zero (100% within our defined ROPE), even though we included the results by Moseley et al. (2008) as an informative prior. Finally, a Bayesian correlation analysis showed that temperature differences did not correlate with subjective strength of the RHI or with proprioceptive drift. Concluding, based on our conducted experiments there is evidence against a RHI-dependent change in hand temperature. This suggests that a drop in temperature of the hand is not a reliable measure of hand (dis)ownership.

The current study therefore finds evidence that the temperature drop described in previous studies (e.g. Moseley et al., 2008) cannot be replicated. This is in line with other studies that show difficulty in replicating hand temperature change as an index of the RHI. Some studies showed an illusion-related hand temperature drop (Kammers et al., 2011; Moseley et al., 2008; Tsakiris et al., 2011) while others did not (David et al., 2014; Grynberg & Pollatos, 2015; Paton et al., 2012; Thakkar et al., 2011) or temperature change was present independent of stroking synchrony (Rohde et al., 2013). The inconsistency in replicating a temperature drop as a proxy of the RHI may suggest that other factors apart from the effect of the illusion influenced temperature of the skin. First, there is the hypothesis that stroking speed is an influential factor of temperature changes of the skin. This idea arises from literature on affective, pleasant touch. Pleasant touch is associated with the processing of signals from C-tactile fibres, situated in the hairy skin. C-tactile fibres have been shown to respond to stroking with a velocity between 1 and 10 cm/s and project to the posterior insula cortex (Olausson et al., 2010). Studies have shown that the processing of pleasant touch is tightly connected to the processing of bodily state such as temperature of the body (Rolls, 2010). For example, a skin-temperature of 32 °C results in the strongest feeling of pleasantness of stroking compared to lower or higher skin-temperatures (Ackerley et al., 2014). Therefore, the tight link between pleasantness and temperature might assume that temperature drop during the RHI may be more pronounced during slow stroking conditions. However, we do not find any evidence that slow stroking has a unique effect on temperature drop. First, the slow stroking conditions do not show a significantly higher temperature drop compared to higher stroking velocities. Although slow stroking in Experiment 3 resulted in a temperature drop (but not in Experiment 4), we showed that dataset 3 is deviant for reasons other than that of the effect of affective touch. Moreover, in the original experiment of Moseley et al. (2008), there was no specific stroking speed nor subjective ratings of pleasantness described. In the known replications of the RHI-related hand temperature drop, stroking speed was not particularly low (Kammers et al., 2011; Tsakiris et al., 2011; see also Rohde et al., 2013). Stroking frequencies of 1 Hz are reported, which would suggest stroking speeds between 15 and 30 cm/s. Replications with other bodily illusions and RHI variations use varying methods. Salomon et al. (2013) used a rather low stroking speed of 8 cm/s in the full body illusions, but Hohwy and Paton (2010) used tapping as tactile input instead of stroking and Macauda et al. (2015) used vestibular input instead of tactile. Overall, this suggests that stroking speed and pleasantness were unlikely to be responsible for the temperature drop. Second, we do not find a significant correlation between pleasantness of the stroking and temperature drop. That is, stroking that is regarded as more pleasant did not result in a stronger decrease of hand temperature. Therefore, these results suggest that the experience of pleasantness of stroking does not influence temperature of the hand during the RHI.

Some other factors can be proposed. First, environmental temperature fluctuations may increase variation of body temperature during the experiment and thereby masking possible effects of the RHI. However, one of the experiments conducted in our lab (Experiment 5) was conducted in a temperature controlled room and still did not detect temperature changes of the hand as a result of the illusion, suggesting that environmental factors are not the primary cause of not detecting temperature drops. Additionally, if power problems were the reason that a RHI-related temperature drop in the hand is not consistently replicated, it would be expected that the current meta-analysis ($N = 167$) showed a significant RHI-related temperature drop, which it did not. Nevertheless, room temperature in our Experiment 3, which did show an effect of the RHI on hand temperature, was slightly lower than in the other experiments. This did not seem to moderate a RHI related hand temperature change by influencing the strength of the RHI through baseline hand temperature (see Kammers et al., 2011), as there was no correlation between hand temperature at the start of a trial and hand temperature change. Still, it may have caused direct changes in hand temperature change, for instance if participants moved less in certain conditions. Heat is an important by-product of muscle contraction. If participants are more inclined to keep their hands really still with synchronous stroking, for instance trying not to break this interesting illusion, their hands will get colder. This could cause a correlation between illusion strength and temperature changes in Experiment 3 and possibly in other studies in the literature. While these temperature drops will be related to experimental condition, they are not directly related to feelings of body (dis-)ownership. This temperature change due to lack of movement would be larger in a colder room because the temperature difference between the hand and the room would be larger and the hand would cool down quicker. Furthermore, experimenters may show a bias in how they decide which trials to exclude or how to approach a participant in different conditions. For instance, being unconsciously inclined to be stricter about a participant keeping their hands motionless during a trial when it is a synchronous stroking trial could result in a relative lower temperature post-stroking of the hands in the synchronous condition as moving the hands will increase the hand temperature.

Another possible influence could be the duration of stroking. Moseley et al. (2008) used a rather long stroking duration of 7–8 min, while we used 1.5 min. Visual inspection of their Fig. 1 indicates that the long stroking duration in Moseley et al. (2008) may have increased hand temperature changes as a result of the RHI procedure, as it shows that hand temperatures kept decreasing for a few minutes. However, subjective experience of the illusion preceded temperature changes. It has been reported that for most participants, illusionary ownership over a rubber hand close to the real hand starts within 5–15 s (Ehrsson et al., 2004; Lloyd, 2007). A stroking duration of 1–2 min is therefore quite commonly used in RHI experiments (for example Abdulkarim & Ehrsson, 2016; David et al., 2014; Hegedüs et al., 2014; Kammers, de Vignemont, et al., 2009; Kammers, Verhagen, et al., 2009; Kilteni, Normand, Sanchez-Vives, & Slater, 2012; Lloyd, 2007; Mohan et al., 2012; Preston, 2013; Rohde et al., 2011) and Rohde et al. (2013) did not replicate an illusion related drop in hand temperature using a 7 min stroking period. Moreover, studies that did replicate the drop in hand (or body) temperature did not use particularly long stroking durations (90 s. in Kammers et al., 2011; 120 s in Tsakiris et al., 2011). Therefore, together these studies indicate that the shorter duration of stroking in the current study is unlikely to be a cause for the lack of observed skin temperature changes.

A third factor that may influence temperature outcome are the characteristics of the experimenter. In one of our studies, two experiments were conducted in an identical set-up, apart from the person that conducted the experiment (Van Stralen et al., 2014). In the first experiment (here Experiment 3), a clear temperature drop was found whereas in the second experiment (Experiment 4), which was conducted by another experimenter, this was not replicated. While this could be a coincidence, the influence of the experimenter on the experience of touch has been investigated by studies on social touch. There is evidence that neural activation varies depending on what the source of tactile stimulation is (Gallace & Spence, 2010). In a study of Gazzola et al. (2012), heterosexual male participants were made to believe to be caressed by either a man or a woman, although the stroking was in fact always delivered by a female. The perceived sex of the experiment leader changed the affective valence of the touch, and even more, it changed activation within the primary somatosensory cortex. Another study investigated ingroup-outgroup differences in visual remapping of touch (VRT), an effect in which the observation of touch on another's body leads to greater sensitivity to tactile stimulation on one's own body. Results showed that detecting touch was most enhanced when viewing a touched face of a person that is regarded as a member of the same group compared to the observation of touch of an outgroup member (Serino, Giovagnoli, & Làdavas, 2009). These studies suggest that the impression of the person that applies tactile stimulation influences tactile processing. Although it might be suggested that an altered tactile processing leads to a different effect on the rubber hand illusion, studies on this topic are scarce. It has been reported that a higher degree of empathy (as a characteristic of the participant) increases the strength of the RHI (Asai, Mao, Sugimori, & Tanno, 2011). Rohde et al. (2013) examined whether manual stroking applied by an experiment leader affected the RHI compared to automated stroking by a device, without a person present in the experimental room. Results show no effect on vividness of the RHI between automated and manual stroking. Interestingly, as discussed in the introduction, a drop in temperature of the hand was only objectified in the manual stroking condition, and not with the automated stroking by a device. This temperature drop was independent of the synchrony of stroking or the subjective experience of the RHI, i.e. the temperature drop was present in the experimental as well as the control condition. The authors offer several potential factors that explain the results, including the difference in characteristics of the stroking (force, irregularity or predictability of tactile and visual input) and the characteristics of the experiment leader (unconscious bias in how they perform the stroking in synchronous and asynchronous condition, arousal differences). Our results seem to support their finding that it might matter who – or what – is applying the tactile input. This underscores the great complexity of social touch, in which the exact role of skin temperature remains unclear.

In all, although the presence of temperature changes of the hands in RHI experiments might be determined by various factors, an overall analysis of RHI experiments in our lab in the last 5 years, covering five replications of the traditional RHI experiment and totalling 167 participants, shows evidence against a reliable cooling related to the RHI. In line with Rohde et al. (2013), our analysis therefore suggests that hand temperature changes in the RHI are not causally related to changes in body ownership.

Acknowledgments

This study was supported by a Vici grant (453-10-003) from NWO (Netherlands Organization for Scientific Research) to HCD. We would like to thank Marlies de Bruijn for her help with data acquisition.

Appendix A. Supplementary data

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.actpsy.2017.07.003.

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