

# Staying in touch with our bodies: Stronger sense of ownership during self-compared to other touch despite temporal mismatches

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## ABSTRACT

Self-touch is considered important for bodily self-consciousness and self-other distinction and has been reported to improve clinical symptoms of disembodiment. To investigate the link between self-touch and disembodiment in healthy participants, we studied the effect of self-touch versus touch produced by another person (other-touch) on experimentally induced disembodiment. In a mixed reality paradigm, across two experiments, participants could see their own body and surroundings with a controllable visual delay and either stroked their own hand with a paintbrush or were stroked with it by the experimenter. Experiment 1 first assessed the sensitivity to temporal multimodal mismatches and delay-induced changes in the sense of body ownership in three conditions, namely self-touch, other-touch and hidden-self-touch (visually occluding the touching hand). In a second block, we compared phenomenological and physiological (threat response) measures of disembodiment between the self-touch and other-touch conditions. Experiment 2 roughly replicated the first block of Experiment 1 but included a condition in which participants performed the self-touch gesture without touching their hand. Such experiment attempted to control for the potential role of efferent signals. Our results show that increasing visual delay generally enhances the feeling of disembodiment, yet the decrease of body ownership is less pronounced during self-touch. For sensitivity to delay between conditions, however, diverging findings are discussed. This study provides evidence for the importance of self-touch in sustaining a healthy sense of body in the context of disembodiment.

## 1. Introduction

Self-touch is considered important for the development (Rochat & Hespos, 1997) and maintenance of bodily self-consciousness and self-other distinction (Boehme, Hauser, Gerling, Heilig, & Olausson, 2019; Hara et al., 2015; Husserl, 1952; Slatman, 2009). During self-touch, the body itself becomes simultaneously the perceiver and the object of perception, providing a unique situation of rich intermodal redundancies and temporospatial contingencies to integrate, finetune and update the sense of body (Schütz-Bosbach, Musil, & Haggard, 2009). Neural network and robotic models involving simulations of motor, proprioceptive, and tactile signals have confirmed self-touch as an efficient way to form a body scheme in three-dimensional space (Roncone, Hoffmann, Pattacini, & Metta, 2014; Roschin, Frolov, Burnod, & Maier, 2011). Self-touch-specific neurons have been found in somatosensory areas of rhesus monkeys (Sakata, Takaoka, Kawarasaki, & Shibutani, 1973), pointing at the neural distinction in the processing of self-

generated tactile signals, a distinction that may explain selective maintenance of self-touch sensitivity in hemianesthesia after brain damage (e.g. Weiskrantz & Zhang, 1987). During self-touch the corresponding tactile perception is attenuated in both the intensity of the sensation (Bays, Flanagan, & Wolpert, 2006; Blakemore, Frith, & Wolpert, 1999) and the related brain activation (Blakemore, Wolpert, & Frith, 1998; Boehme et al., 2019; Kilteni & Ehrsson, 2020). To account for this, a ‘forward model’ has been proposed, suggesting that the attenuation of tactile signals results from predicting the consequences of self-generated movement (Bays et al., 2006; Blakemore et al., 1999; Kilteni, Engeler, & Ehrsson, 2020), potentially also explaining the incapacity to tickle ourselves (Blakemore, Wolpert, & Frith, 2000; Weiskrantz, Elliott, & Darlington, 1971). Furthermore, a reduced neural activation during self- compared to other-produced touch has been found in neural regions involved in early somatosensory processing (such as the thalamus but even at the cervical spinal level) and those involved in social cognition and self-other distinction (Boehme et al.,

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2019). In line with this, patients with disturbances of self-consciousness such as in schizophrenia, showed altered self-monitoring mechanisms (Blakemore, Smith, Steel, Johnstone, & Frith, 2000; Frith, 1987; Synofzik, Thier, Leube, Schlotterbeck, & Lindner, 2010; Voss et al., 2010), and in patients with hallucinations reduced sensory attenuation as response to self-touch has been reported (Blakemore, Wolpert, & Frith, 2000).

Self-other distinction is intrinsically linked to the sense of body ownership, which is thought to be built upon a constant integration of multisensory and motor contingencies (Blanke, Slater, & Serino, 2015; Tsakiris, 2017), as demonstrated in body illusion paradigms (Azañón et al., 2016; Ehrsson, 2012). In an adapted version of the rubber hand illusion (Botvinick & Cohen, 1998), the manipulation of somatosensory cues in a passive self-touch setting has successfully induced illusory body ownership of a fake limb (Ehrsson, Holmes, & Passingham, 2005). Importantly, active self-touch has shown to have a stronger contribution for illusory ownership compared to both passive self- and externally induced touch (Hara et al., 2015), suggesting that the additional efferent information during self-touch introduces further predictive signals that, when matched with the tactile sensations, strengthens self-attribution of the fake hand. This enhancing of self-attribution is further corroborated by clinical observations suggesting that self-touch might beneficially influence patients with neurological disorders of body ownership, by decreasing symptoms of disembodiment (van Stralen, van Zandvoort, & Dijkerman, 2011). Patients with schizophrenia have been argued to be more susceptible to distortions in self-other distinction and experiences related to disembodiment (Klaver & Dijkerman, 2016; Thakkar, Nichols, McIntosh, & Park, 2011). Together with alterations in self-monitoring (Blakemore, Wolpert, & Frith, 2000; Frith, 1987; Synofzik et al., 2010; Voss et al., 2010), this might point at a link between distorted predictions and alterations in bodily self-consciousness.

To further investigate the role of self-touch in (dis)embodiment, we here studied in healthy participants how self- versus externally induced (*other-*) touch differentially modulate body ownership, delay perception and the phenomenology of disembodiment. This might inform on the potential link between distorted predictions and disembodiment in clinical populations, but also on the relevance of self-touch for maintaining a healthy sense of body. Previous literature showed that increasing the temporal mismatch of visuotactile and visuomotor signals induces a rising sense of disembodiment in healthy participants (Gentile, Guterstam, Brozzoli, & Ehrsson, 2013; Kannape, Smith, Moseley, Roy, & Lenggenhager, 2019; Roel Lesur, Weijs, Simon, Kannape, & Lenggenhager, 2020).

Here, participants saw their own real body from a first-person perspective on a head-mounted display with a controlled global (encompassing the whole visual field) visual delay. We performed two experiments. In Experiment 1, across two experimental blocks, we assessed the effect of visual delay on (dis)embodiment comparing self-versus other-induced touch. The first block consisted of multiple short trials with various visual delay steps for three conditions, namely self-touch, hidden self-touch, and other-touch. After each trial, a question on sensitivity to temporal multimodal mismatches and one on body ownership were presented. The second block consisted of a 90 s stimulation period comparing self- versus other-touch with either a synchronous or an asynchronous visual feed, followed by a skin conductance response (SCR) to threat as an implicit measure of body ownership (e.g. Gentile et al., 2013; Newport & Preston, 2010, 2011; but see Roel Lesur, Weijs, et al., 2020 for exceptions), and a detailed disembodiment questionnaire on phenomenological aspects (Roel Lesur, Weijs, et al., 2020). To control for the potential role of efferent signals, we performed Experiment 2, consisting of the same design as the first block of Experiment 1 but different conditions. This time the three conditions were self-touch, other-touch and a self-no-touch condition, in which participants performed the movement of the touching (right) hand without actually touching the left hand. Additionally, the movements of the touching hand were tracked throughout the stimulation procedure to

control for the stroking velocity between different delay steps.

Based on the aforementioned findings suggesting a reduction of disembodiment symptoms after self-touch (van Stralen et al., 2011), and the general role of self-touch signals in maintaining and updating the sense of a bodily self (Hara et al., 2015), we expected that self- as opposed to other-induced signals maintain one's own sense of embodiment despite temporal mismatches. We thus hypothesized, for Experiment 1, a slower decline of agreement with the ownership rating with increasing delay in both self-touch conditions as compared to the other-touch condition in the first block. Moreover, sensitivity to temporal multimodal mismatches was expected to reduce during self- compared to other-touch given that a) it has been argued that with the presence of strong bodily cues and multimodal contingencies during illusory body ownership, sensitivity to temporal asynchronies is loosened (Maselli, Kiltner, López-Moliner, & Slater, 2016; Roel Lesur, Gaebler, Bertrand, & Lenggenhager, 2018) and b) preliminary exploration of phenomenological reports during self- versus other-touch in a similar disembodiment paradigm (Roel Lesur, Weijs, et al., 2020) has suggested a striking difference in phenomenal delay perception during asynchronous self-versus other-stroking. For the second block of Experiment 1, a similar pattern was expected, where disembodiment measured by both a questionnaire and a lower SCR in response to threat would be greater during other- as compared to self-induced stroking. For Experiment 2, we expected a reduced sense of body ownership for the other- compared to the self-touch condition, and generally less modulation of body ownership ratings in the self-no-touch condition, due to the lack of visuotactile temporal mismatches on the left hand.

## 2. Materials and methods

### 2.1. Participants

Twenty-nine volunteers (21 females; mean age 23.2 years,  $SD = 4.2$ ) participated in Experiment 1, and twenty-four volunteers (18 females; mean age 25.4 years,  $SD = 4.8$ ) participated in Experiment 2. One participant in Experiment 2 reported a lack of understanding of the tasks. Data of this participant were excluded from statistical analyses. These sample sizes were defined based on previous studies using a similar paradigm (Gentile et al., 2013; Kannape et al., 2019; Roel Lesur, Weijs, et al., 2020). All participants reported normal or corrected to normal vision and no history of psychiatric disorders and were recruited at the University of Zurich. They received course credit or a financial compensation for their participation. All participants gave their written consent prior to the start of the study. For Experiment 2, participants additionally performed a COVID-19 symptom check prior to the confirmation of the experimental session and upon arrival to the laboratory.

The study protocol was approved by the Ethics Committee of the Faculty of Arts and Social Sciences at the University of Zurich (Approval Number 17.12.15). The study was performed in accordance with the ethical standards of the Declaration of Helsinki.

### 2.2. Apparatus for stimulation

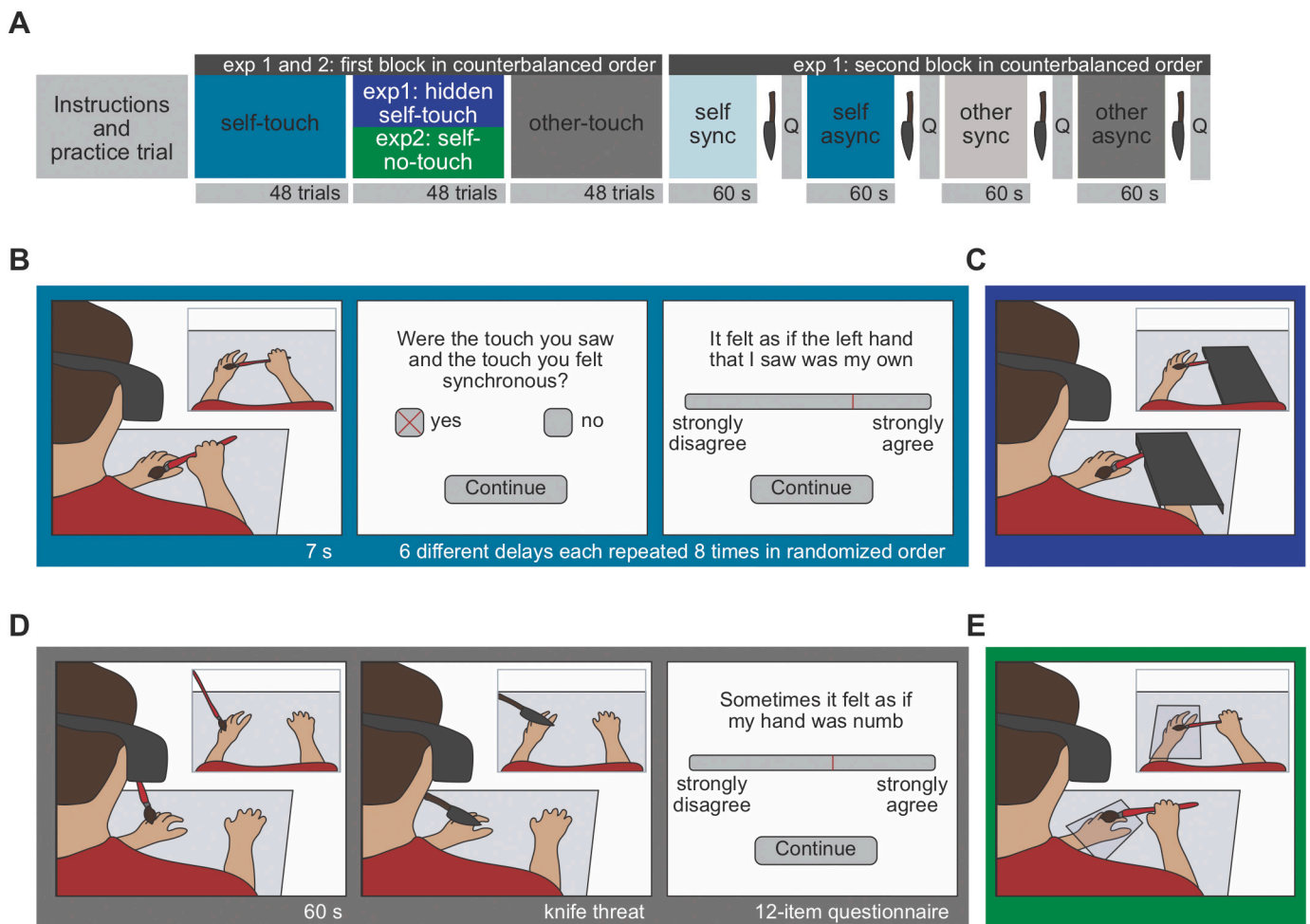
Visual stimulation was presented on an Oculus CV1 head-mounted display (HMD; Oculus VR, Irvine, CA, USA). An ELP 180° webcam (Ailipu Technology Co., Ltd., Guangdong, China) set to 30 frames per second and resolution of  $1024 \times 768$  pixels was positioned on the front of the HMD. The stimulation consisted of a video feed (i.e., not a computer-generated image) with a controllable delay. For depicting the full body, the camera was rotated so that the wide side of view (1024 pixels) was on the vertical axis. The software was designed using Unity 2018.2.8 and the camera feed was delayed using a buffer where the frames were dynamically stored and retrieved. The video feed was then rotated to match the perspective of the participants and mapped to a 3D mesh that approximately matched the distortion of the camera's lens.

This was then projected onto the HMD. The questionnaires, randomization and triggers for the physiological recordings were integrated in this software. The same settings from Roel Lesur, Weijs, et al. (2020) were used to approximately match the visual field of view in the HMD to that without the HMD as well as to the seen and felt (proprioceptive) position of the participants' body. The system ran on an Alienware 15 R3 computer (Nvidia Geforce GTX 1080 8GB; 16GB RAM; Intel Core i7; Windows 10), which added a mean intrinsic delay of 139.1 ms ( $SD = 18.3$  ms) to the camera feed. The same setup was used for responding to the questions and tasks. This feature is enabled by the built-in head-tracking system of the HMD, which allowed participants to select their responses by facing towards the corresponding position on the HMD and fixating on it for a period of 1 s. For Experiment 2 an Oculus Touch (Oculus VR, Irvine, CA, USA) controller with six degrees of freedom was used to track the hand movements within an updated version of the Unity-based software.

2.3. Procedure

2.3.1. Experiment 1

2.3.1.1. General procedure and preparation. For Experiment 1, participants were informed about the tasks and had the opportunity to practice the different conditions while sitting with their left hand lying on a table: the self-touch condition in which they stroked their left hand with a paintbrush held in the right hand; the hidden self-touch condition in which a box occluded their right hand but not the paintbrush; and the other-touch condition in which the experimenter stroked the participants' left hand with the paintbrush (see Fig. 1 for an overview of the experimental design and setup). These tasks were practiced with a metronome (set at 1 Hz) to get acquainted with the timing at which the stroking should be performed. In all conditions the stroking occurred upwards on the back of the hand from the tip of the index finger to the base of the wrist at a rate of 0.5 Hz. The first click of the metronome signified a stroke upwards and subsequent release, and the second click the going back without touching for starting the next stroke. Participants were informed that a threat in terms of a realistically looking plastic knife would be presented at some point during the experiment. They



**Fig. 1.** (A) Experimental design and procedure for both Experiment 1 (both blocks) and 2 (for the single block, in the image referred to as the first block). The overall procedure lasted about 60 min in both experiments and concluded with a short debriefing. The knife illustrated in the second block indicates a single threat presented for each condition at second 60 after starting the stimulation and the Q the disembodiment questionnaire. (B) Experimental setup and tasks for the first block of Experiment 1 depicting the self-touch condition, where the image on the left shows a participant wearing an HMD in which the participant's first-person perspective is portrayed. The next image to the right shows the multimodal mismatch sensitivity task, followed by the question of body ownership. (C) Depiction of the hidden self-touch condition in Experiment 1 including the perspective seen by the participant. (D) Experimental setup for the second block. The leftmost image shows the other-touch condition, followed by a threat, both depicting the corresponding perspective of the participant. On the right panel, one item of the questionnaire is illustrated. (E) Depiction of the self-no-touch condition in Experiment 2, where an acrylic glass was placed above the participant's left hand.

were then helped to put on the HMD. The experiment consisted of two different blocks. The first block included the three aforementioned conditions, each consisting of multiple trials of short stimulation with different visual delays (tactile cues always preceded visual ones), followed by a second block with four conditions of longer stimulation corresponding to self or other, both either synchronous or delayed (no self-hidden condition was included in the second block). After reading the instructions on the HMD, they had to confirm that they understood the instructions and knew how to select the corresponding position on a visual analogue scale (VAS) with their head movements. Afterwards they were required to look at another button for 1 s to confirm. A few seconds of exposure to a synchronous video feed of their own body and hands on the table followed to familiarize participants with the stimulus presentation. Participants were instructed to not move their left hand and keep their head in a fixed position during stimulation.

**2.3.1.2. First block.** In this block, each trial lasted 7 s, after which a single forced-choice item was included to assess sensitivity to multimodal temporal mismatches followed by a single question on body ownership to be answered on a VAS. The question on delay sensitivity asked whether the touch they felt and saw were synchronous. They were instructed to answer in regard to the touch on the left hand. Each condition consisted of 48 trials with eight repetitions of six possible delay steps of 150 ms each, namely 139, 289, 439, 589, 739 and 889 ms (including the intrinsic delay). The various delay steps were presented in a pseudorandom order and the sequence of the conditions was counterbalanced across participants.

**2.3.1.3. Second block.** Upon finalizing the first block, the electrodes for the SCR measurements were put on. A second block of 90 s stimulation periods with four counterbalanced conditions followed (either self or other and either synchronous or delayed; the self-hidden condition was not included in this block). In both asynchronous conditions, a visual delay of 1000 ms (plus the intrinsic 139.1 ms system delay) was added. The stroking continued for a period of 90 s. At second 60 for each condition a single threat was presented by sliding a realistically looking plastic knife above the participants' hand (a noticeable visual cue for the experimenter appeared as a message on the screen to onset the threat). After each condition, they were asked to answer a disembodiment questionnaire adapted from Roel Lesur, Weijts, et al. (2020).

### 2.3.2. Experiment 2

For Experiment 2, roughly the same procedure as for the first block of Experiment 1 was followed, with the same delay steps and repetitions. However, participants additionally wore a face mask for protective reasons, and instead of directly holding a paintbrush, both participants and the experimenter held an Oculus Touch controller to which a paintbrush was attached. Participants were instructed to perform the same movements of the paintbrush as described above for the self- and the other-touch conditions, while holding the controller. An additional self-no-touch condition was included in this experiment. For the self-no-touch condition a transparent acrylic glass was positioned above the participants' left hand, and they were instructed to stroke on the acrylic glass as if they were actually stroking their own hand (see Fig. 1E) while holding the controller. For the question on multimodal delay sensitivity, they were told that exclusively for the self-no-touch condition they should answer considering the touch that they felt on the touching hand in response to the pressure of the paintbrush on the acrylic glass.

## 2.4. Measures

### 2.4.1. Multimodal mismatch sensitivity

A single forced-choice question "Were the touch you saw and the touch you felt synchronous?" was presented after each trial of the first block, which could be answered by selecting *yes* or *no* on the HMD. This

measure was taken for the first block of Experiment 1 and for Experiment 2. The results of this task were used to calculate the point of subjective equality (PSE); however, this measure assumes a balanced task in which the experiment conveys equal chances of any modality preceding the other. Here, due to the incapacity to delay tactile signals but instead only using visual delay our task was not balanced and thus our PSE measure is different from its common use (e.g., Costantini et al., 2016). Instead, it reflects the point where participants were equally likely to respond that the visual stimulus was or was not delayed.

### 2.4.2. Body ownership

One item "It felt as if the left hand that I saw was my own" that could be answered on a VAS ranging from *strongly disagree* to *strongly agree* (mapped to values ranging from 0 to 1) followed the multimodal mismatch sensitivity item after each trial of the first block. This was assessed for both the first block of Experiment 1 and for Experiment 2.

### 2.4.3. Hand tracking

For Experiment 2, the movement of the controller held in the stroking hand was measured at an average rate of 78.1 Hz. The tracking and data logging were performed within the same stimulation software.

### 2.4.4. Disembodiment questionnaire

A 12-item questionnaire (see Table S1) was applied for phenomenal assessment after the stimulation for each condition of the second block of Experiment 1. The questionnaire is adapted from a previous disembodiment study (Roel Lesur, Weijts, et al., 2020) and includes 9 items related to different aspects of disembodiment, an item related to the perceived causal link between tactile and visual signals (q11), a control question regarding the perceived shape of the hand (q3) and an item to assess agency over the stroking hand. Participants indicated on a VAS ranging from *strongly disagree* to *strongly agree* (corresponding to 0 and 1, respectively) how much they agreed with each statement.

### 2.4.5. Skin conductance response

Threat-evoked SCRs were recorded with a Biopac MP150 system and EDA100C amplifier (Goleta, USA) at a 250 Hz sampling rate for the second block of Experiment 1. Two electrodes with electrode paste were placed on the palmar tips of the participant's index and middle finger of the left hand. A salient visual cue on the computer screen was presented for the experimenter to perform the action after 60 s of stimulation. The cue was synchronized with a trigger sent to the Biopac system to later assess the response. Upon seeing the cue, the experimenter threatened the participant's left hand by making a sliding motion with the plastic knife on top of the hand without touching it.

## 2.5. Data processing and statistics

### 2.5.1. Data analysis

Statistical analysis for both experiments was performed with R (R Core Team, 2018) version 3.6.1. The alpha level was set at 0.05, or 95% confidence intervals excluding 0. *P*-values were corrected for multiple comparisons using false discovery rate (FDR) corrections (Benjamini & Hochberg, 1995). Data were visually inspected for normality using Q-Q plots and histograms, and the corresponding tests were chosen based on the data distribution as reported separately below for each measure. Linear mixed models were used to analyze the VAS responses. These were fitted with the lme4 (Bates, Mächler, Bolker, & Walker, 2015), and lmerTest packages in R (Kuznetsova, Brockhoff, & Christensen, 2017).

### 2.5.2. Multimodal mismatch sensitivity

For each participant and each condition, the PSE was calculated by fitting a logistic psychometric function to the forced-choice synchrony judgements. We used a binomial Generalized Linear Model (glm) with delay as a predictor. The estimated coefficients of the glm were used to calculate the PSE:  $-\beta_0 / \beta_1$ , where  $\beta_0$  corresponds to the intercept and

$\beta$ 1 to the slope. Goodness of fit was assessed with the Hosmer-Lemeshow test, which showed that in Experiment 1, seven participants had to be excluded due to bad fit of the individual logistic regression in one of the conditions. In Experiment 2, three participants had to be excluded due to bad fit of one or more of the psychometric curves, and one because of an extreme PSE value ( $> 889$  ms, the maximum delay used in the study).

### 2.5.3. Body ownership ratings

For Experiment 1, a linear mixed model was fitted to the VAS ownership ratings in the first block, across different delays, which ensured adequate power while considering the repeated measures within individuals. The intraclass correlation demonstrated that observations within individuals were non-independent ( $ICC(1) = 0.22$ ,  $F(28, 4149) = 40.8$ ,  $p < .001$ ). Visual inspection of diagnostic plots of the residuals showed that these were normally distributed. The model that included both a random intercept and slope for individuals, where VAS ratings were explained as a function of delay, fitted the data better than the model that included only the random intercept and no random slope ( $BIC_{randomintercept} = -2020.7$  vs.  $BIC_{randominterceptandslope} = -2653.4$ ,  $X^2(2) = 649$ ,  $p < .001$ ). Therefore, we used the random intercept and slope model for further hypothesis testing. To determine the fixed effect structure, the interaction of condition with delay, and the second and third polynomial of delay were added in a stepwise manner (see Table S2). The third polynomial of delay showed the best fit, and this model was thus used for hypothesis testing.

For Experiment 2 the same procedure was followed. The intraclass correlation demonstrated that observations within individuals were non-independent ( $ICC(1) = 0.32$ ,  $F(22, 3278) = 68.2$ ,  $p < .001$ ). Visual inspection of diagnostic plots of the residuals showed that these were normally distributed. The model that included both a random intercept and slope for individuals, where VAS ratings were explained as a function of delay, fitted the data better than the model that included only the random intercept and no random slope ( $BIC_{randomintercept} = -1006.5$  vs.  $BIC_{randominterceptandslope} = -1657.8$ ,  $X^2(2) = 667.3$ ,  $p < .001$ ). Therefore, we used the random intercept and slope model for further hypothesis testing. To determine the fixed effect structure, the interaction of condition with delay was added to the model. We assessed the presence of any linear or cubic effects of delay on body ownership ratings by adding the second and third polynomial of delay to the model in a stepwise manner (see Table S2). The third polynomial of delay showed the best fit, and this model was thus used for hypothesis testing.

### 2.5.4. Hand movement

For Experiment 2, the instantaneous velocity of the hand was calculated as the difference between two subsequent sampled positions, divided by the time between the two measures. Values above 1 m per sample and equal to 0 m were discarded due to implausibility of such fast movements or no movements at all, which were indicative of tracking errors. The mean percentage of removed samples from the total number of measurements across participants was 0.36%. Values were normalized after removing the errors. An average velocity was then calculated for each trial. Data from one participant was lost due to a corruption on the hand tracking log file.

Linear mixed models were fitted to the velocity measures. The intraclass correlation demonstrated that observations within individuals were non-independent ( $ICC(1) = 0.12$ ,  $F(21, 3136) = 20.36$ ,  $p < .001$ ). Visual inspection of diagnostic plots of the residuals showed that these were normally distributed. When fitting velocity values as a function of delay, no improvement in fit was found when including both the intercept and slope for individuals ( $BIC_{randomintercept} = 12,470$  vs.  $BIC_{randominterceptandslope} = 12,484$ ,  $X^2(2) = 1.28$ ,  $p = .53$ ). Therefore, we used the model with random intercept only for further hypothesis testing.

### 2.5.5. Disembodiment questionnaire

Based on a previous study using a principal component analysis (Roel

Lesur, Weijs, et al., 2020), the subscales of disownership, deafference, and embodiment were calculated as the mean of responses to each statement within the subscale. Due to non-normality of the questionnaire data, aligned rank transformed repeated-measure ANOVAs (Kay & Wobbrock, 2020; Wobbrock, Findlater, Gergle, & Higgins, 2011) were used to assess effects of synchrony and condition for the individual statements and the subscales. Three participants were excluded from these analyses, as they all had missing data in one condition due to technical errors.

### 2.5.6. Skin conductance response

The data was processed using the Ledalab version 3.4.9 ([www.ledalab.de](http://www.ledalab.de)) toolbox in MATLAB. Data of seven participants were excluded due to missing triggers. A 1 Hz lowpass filter was applied to the raw data, which was also manually cleaned from electrical artifacts. A through-to-peak analysis was performed to extract the amplitudes in the time window from 2 s to 7 s after the trigger. This is the time it took for the experimenter to apply the knife threat after a visual cue appeared on the screen for the experimenter to begin the threat, and thus the trigger was sent. Only amplitudes over 0.01  $\mu$ S were considered, and absent responses were registered as 0. Individual Z-scores were calculated. Due to non-normality of the data, Aligned Rank Transform (ART) ANOVAs were used to test differences between conditions and to determine the effects of synchrony and condition.

## 3. Results

### 3.1. Results Experiment 1

#### 3.1.1. Forced-choice delay perception

Comparison of the average PSEs between conditions did not show any significant differences between the three conditions (one-way repeated measures ANOVA,  $n = 20$ ,  $F(2, 38) = 1.40$ ,  $p = .26$ ,  $\eta^2 = 0.02$ ; self:  $M = 371$  ms,  $SD = 132$  ms; self-hidden:  $M = 376$  ms,  $SD = 110$  ms; other:  $M = 343$  ms,  $SD = 92$  ms, see Fig. 2A).

#### 3.1.2. Body ownership ratings

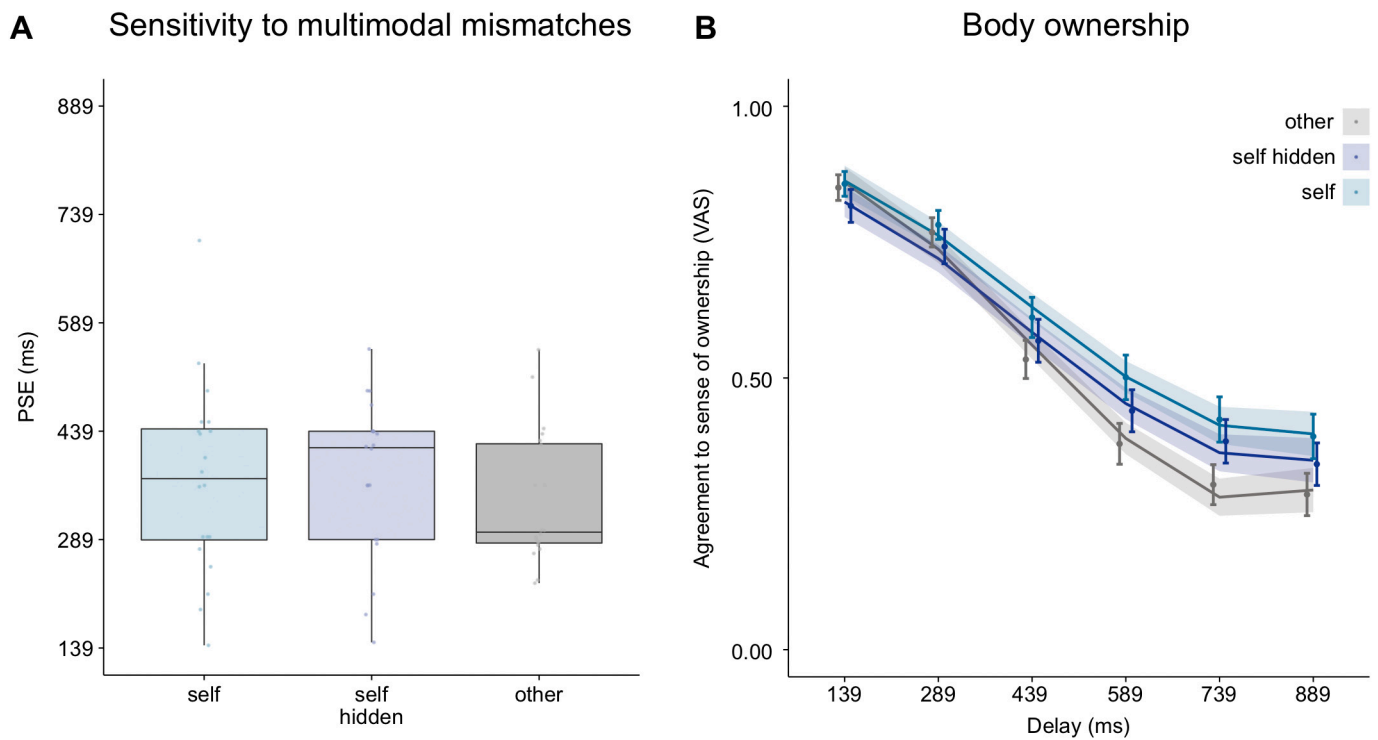
The model showed a significant main effect for condition ( $F(2, 4110) = 75.8$ ,  $p < .001$ ) for the cubic term of delay ( $F(3, 79) = 141.1$ ,  $p < .001$ ), and a significant condition\*delay<sup>3</sup> interaction ( $F(6, 4110) = 12.1$ ,  $p < .001$ , see Fig. 2B, and Table S3 for model coefficients). Post-hoc Tukey tests revealed significant differences in ownership ratings between self-touch and other-touch from 439 ms onwards and between hidden self-touch and other-touch from 589 ms onwards (see Table 1).

#### 3.1.3. Disembodiment questionnaire

An ART ANOVA for non-parametric factorial analyses was computed for each of the questionnaire subscales as well as the separate questionnaire items (see Table S4 for descriptive statistics). The results (see Fig. 3) showed a main effect of synchrony for all the questionnaire subscales, namely disownership ( $F(1, 25) = 122.25$ ,  $p < .001$ ,  $\eta_p^2 = 0.83$ ), deafference ( $F(1, 25) = 35.09$ ,  $p < .001$ ,  $\eta_p^2 = 0.584$ ), and embodiment ( $F(1, 25) = 87.03$ ,  $p < .001$ ,  $\eta_p^2 = 0.777$ ). Additionally, there was a main effect of condition for disownership ( $F(1, 25) = 6.11$ ,  $p = .021$ ,  $\eta_p^2 = 0.197$ ) and embodiment ( $F(1, 25) = 6.28$ ,  $p = .019$ ,  $\eta_p^2 = 0.201$ ), but not for deafference ( $F(1, 25) = 1.94$ ,  $p = .176$ ,  $\eta_p^2 = 0.072$ ). No interaction effect was found for either disownership ( $F(1, 25) = 0.08$ ,  $p = .778$ ,  $\eta_p^2 = 0.003$ ), deafference ( $F(1, 25) = 0.02$ ,  $p = .887$ ,  $\eta_p^2 = 0.001$ ), nor embodiment ( $F(1, 25) = 2.98$ ,  $p = .097$ ,  $\eta_p^2 = 0.107$ ). See Table S5 for further results of the ART ANOVAs of each individual item and their corresponding subscale.

#### 3.1.4. Skin conductance response

An ART ANOVA showed that there were no significant effects of synchrony ( $F(1, 21) = 0.05$ ,  $p = .830$ ,  $\eta_p^2 = 0.002$ ), condition ( $F(1, 21) = 0.60$ ,  $p = .446$ ,  $\eta_p^2 = 0.028$ ), or the interaction ( $F(1, 21) = 0.01$ ,  $p = .916$ ,



**Fig. 2.** Results from Experiment 1. (A) Sensitivity to multimodal mismatches was assessed by calculating the PSE (ms). Boxplots show median PSE as a line. The box indicates the first to third quartile, and the whiskers show upper and lower extremes. Individual observations are overlaid. (B) Body ownership ratings on a VAS between 0 and 1, as predicted by delay and condition. Error bars show observed mean ratings and standard errors, whereas the line and shaded areas show predicted values with standard errors from the final mixed models included in the analyses.

**Table 1**  
Pairwise comparisons of body ownership ratings using Tukey contrasts with Bonferroni corrected p-values.

Delay	Condition	Estimate	SE	Z	<i>p</i> <sub>corrected</sub>
139 ms	Self - hidden	0.04	0.01	2.724	0.99
	Self - other	0.01	0.01	0.460	1
	Hidden - other	-0.03	0.01	-2.264	1
289 ms	Self - hidden	0.04	0.01	2.665	1
	Self - other	0.01	0.01	0.923	1
	Hidden - other	-0.03	0.01	-1.742	1
439 ms	Self - hidden	0.04	0.01	2.898	0.574
	Self - other	0.08	0.01	5.203	<0.001
	Hidden - other	0.03	0.01	2.302	1
589 ms	Self - hidden	0.06	0.01	4.127	0.006
	Self - other	0.12	0.01	8.199	<0.001
	Hidden - other	0.06	0.01	4.072	0.007
739 ms	Self - hidden	0.04	0.01	2.687	1
	Self - other	0.12	0.01	8.035	<0.001
	Hidden - other	0.08	0.01	5.348	<0.001
889 ms	Self - hidden	0.05	0.01	3.458	0.083
	Self - other	0.11	0.01	7.197	<0.001
	Hidden - other	0.06	0.01	3.735	0.029

$\eta_p^2 = 0.001$ ) on skin conductance responses (see Table S4 for descriptive statistics).

### 3.2. Results Experiment 2

#### 3.2.1. Multimodal mismatch sensitivity

The PSE differed significantly between the three conditions ( $F(2, 36) = 6.85, p = .003, \eta^2 = 0.07$ ; one-way repeated measures ANOVA,  $n = 19$ , see Fig. 4A). The PSE was higher in the other-touch condition ( $M = 443$  ms,  $SD = 107$  ms) than in both the self-touch ( $M = 388$  ms,  $SD = 134$  ms) and the self-no-touch condition ( $M = 373$  ms,  $SD = 107$  ms).

#### 3.2.2. Body ownership ratings

The model showed a significant main effect for condition ( $F(2, 3245) = 86.8, p < .001$ ) for the cubic term of delay ( $F(3, 61.2) = 60.0, p < .001$ ), and a significant condition\*delay<sup>3</sup> interaction ( $F(6, 3245.1) = 7.64, p < .001$ , see Fig. 4B and Table S6 for model coefficients). Planned contrasts for the three conditions at each level of delay revealed significant differences in ownership ratings between self-touch and other-touch from 739 ms onwards and between self- and self-no-touch from 139 ms onwards (see Table 2).

#### 3.2.3. Hand movement tracking

The model showed a significant main effect for condition ( $F(2, 3131) = 1011.2, p < .001$ ) for delay ( $F(1, 3131) = 14.71, p < .001$ ), and a significant condition\*delay interaction ( $F(2, 3131) = 7.41, p < .001$ , see Table S7 for model coefficients). Planned contrasts revealed no significant differences in velocity for neither other-touch nor self-touch between any of the delay steps. However, for the self-no-touch condition differences in velocity were found between the shortest delay (139 ms) and the three longest delays (namely 589, 739, and 889 ms; respectively  $p = .01, p < .001$ , and  $p < .001$ ) (see Table S8).

### 4. Discussion

Our results showed that increasing temporal mismatches between visual and other signals related to self-touch increased feelings of disembodiment as has previously been shown for externally induced (other-) touch (e.g. Gentile et al., 2013; Kannape et al., 2019; Roel Lesur, Weijjs, et al., 2020). For Experiment 1, higher body ownership was reported for the self-touch condition, followed by the self-hidden, and finally the other-touch condition, this pattern was found from intermediate delays onwards (from 439 ms when the stroking hand was seen, and from 589 ms when it was hidden). Similarly, for Experiment 2 higher body ownership was found self- compared to other-touch (for longer delays, namely 739 ms onwards) with generally lower values for

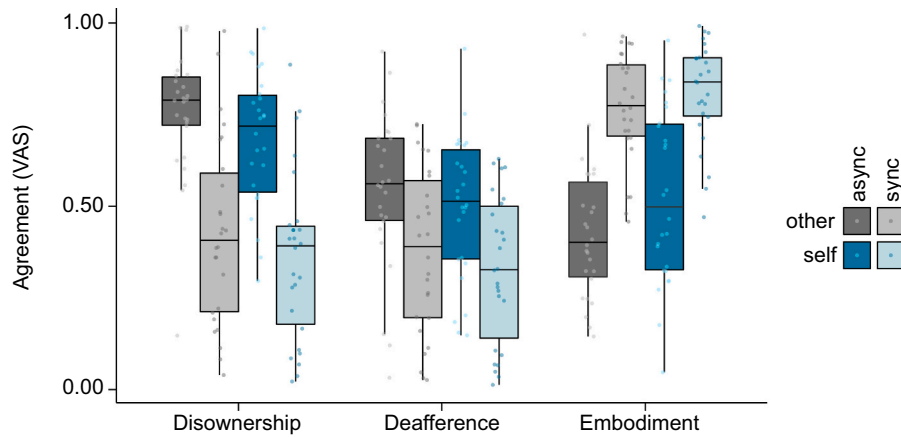


Fig. 3. Questionnaire responses for the second block of Experiment 1, averaged over the subscales of disownership, deafference and embodiment. There was a main effect of synchrony (sync, async) for each of the subscales, and no effect of condition (self-, other-touch) and the interaction of synchrony and condition.

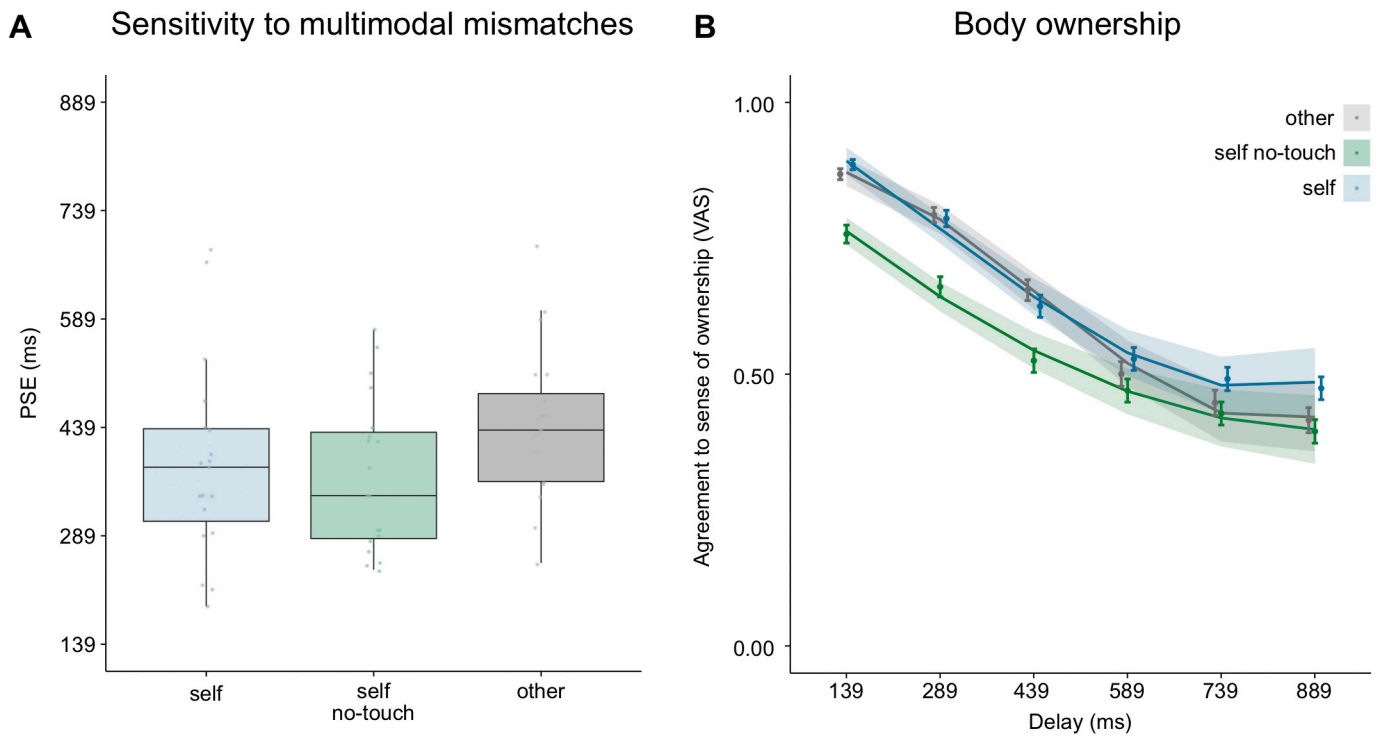


Fig. 4. Results from Experiment 2. (A) Sensitivity to multimodal mismatches was assessed by calculating the PSE. Boxes show median PSE (ms) as a line. The box indicates the first to third quantile, and the whiskers show upper and lower extremes. Individual observations are overlaid. (B) Body ownership ratings on a VAS between 0 and 1, as predicted by delay and condition. Error bars show observed mean ratings and standard errors, whereas the line and shaded areas show predicted values with standard errors from the final mixed models included in the analyses.

the self-no-touch condition, suggesting that the effect of self-touch is specific and not due to the role of efferent signals. Our findings overall point at the important contribution of self-touch for sustaining body ownership despite temporal mismatches.

4.1. Differential modulations of body ownership between conditions

4.1.1. Higher body ownership despite temporal mismatches during self- compared to other-touch

In line with our hypothesis, the first block of Experiment 1 and the data of the Experiment 2 showed that body ownership decreased faster with increasing visual delay for other- compared to self-touch. This suggests that body ownership is more strongly maintained despite

multimodal mismatches during self-touch. Such findings are compatible with clinical studies proposing that self-touch might be beneficial for patients with neurological disorders by decreasing symptoms of disembodiment (van Stralen et al., 2011). Similarly, studies in healthy participants have shown that for illusory ownership of a virtual limb, multimodal signals corresponding to self-touch resulted in a stronger illusion compared to both passive self- and externally induced touch (Hara et al., 2015). Importantly, we here studied how mismatching signals would affect the loss of (own) body ownership which is arguably more directly related to symptoms of disembodiment described in clinical conditions (e.g. Aglioti, Smania, Manfredi, & Berlucchi, 1996; Brugger & Lenggenhager, 2014; Löffler, Kleindienst, Cackowski, Schmidinger, & Bekrater-Bodmann, 2019; Otsuru et al., 2014; Vallar &

**Table 2**

Pairwise comparisons with Bonferroni corrected p-values for the ownership ratings of Experiment 2.

Delay	Condition	Estimate	SE	t-ratio	<i>P</i> <sub>corrected</sub>
139 ms	other - self-no-touch	0.110	0.018	6.156	<0.0001
	other - self	-0.018	0.018	-0.976	0.987
	self-no-touch - self	-0.128	0.018	-7.114	<0.0001
289 ms	other - self-no-touch	0.132	0.018	7.393	<0.0001
	other - self	0.006	0.018	0.324	1.000
	self-no-touch - self	-0.126	0.018	-7.048	<0.0001
439 ms	other - self-no-touch	0.130	0.018	7.250	<0.0001
	other - self	0.028	0.018	1.557	0.359
	self-no-touch - self	-0.102	0.018	-5.638	<0.0001
589 ms	other - self-no-touch	0.031	0.018	1.713	0.260
	other - self	-0.032	0.018	-1.761	0.235
	self-no-touch - self	-0.062	0.018	-3.469	0.002
739 ms	other - self-no-touch	0.020	0.018	1.102	0.812
	other - self	-0.048	0.018	-2.697	0.021
	self-no-touch - self	-0.068	0.018	-4.687	0.001
889 ms	other - self-no-touch	0.021	0.018	1.151	0.750
	other - self	-0.064	0.018	-3.539	0.001
	self-no-touch - self	-0.084	0.018	-4.687	<0.0001

Ronchi, 2009).

The data from the more detailed phenomenal questionnaire of Experiment 1 suggest that the significant modulation of synchrony on the three main components (i.e. stronger body disownership, deaf-ference, and reduced embodiment during asynchronous stimulation; Roel Lesur, Weijjs, et al., 2020) was comparable during the self- and other-touch conditions. Yet, in line with the abovementioned findings of the first block, the body ownership question (q1) was differentially modulated, such that during self-touch ownership stayed higher despite the asynchronous condition than during other-touch. This suggests an effect on ownership but not on other subtleties of the disembodiment experience. The phenomenal complexity of disembodiment is just starting to be understood, yet, important differences between body ownership and disownership have been previously discussed (de Vignemont, 2011; Roel Lesur, Weijjs, et al., 2020). As suggested by our results, it could be that rather than self-touch more robustly preventing disembodiment in general, it particularly enhances own-body ownership.

#### 4.1.2. Visual input of the touching hand during self-touch

For the first block of Experiment 1, a significant difference of body ownership during self- compared to other-touch was found for delays of 439 ms onwards when the stroking hand was seen, and from 589 ms onwards when it was hidden. The latter condition was introduced to test whether the explicit visual cues that relate the source of the (touching) movement to the self during self-touch contribute to (dis)embodiment. In line with our expectations, the results suggest that the visual monitoring and recognition of the own hand mediate the binding of multimodal signals to the self. Along these lines, previous studies found that the perception of somatosensory signals in a self-touch paradigm was modulated by illusory embodiment of a supernumerary hand (Kilteni & Ehrsson, 2017; Pyasik et al., 2021), suggesting that somatosensory signals might be mediated by self-identification during self-touch. In our setup, we propose that the intrinsic self-identification with the (seen) own hand, by virtue of it visually being one's own, results in an enhanced self-binding mechanism for succeeding incoming signals. In other words, the visual recognition of the own hand might enhance self-identification, which follows vast evidence of visual dominance as an important aspect in manipulations of bodily self-consciousness (Botvinick & Cohen, 1998; Petkova, Zetterberg, & Ehrsson, 2012; Roel Lesur, Aicher, Delplanque, & Lenggenhager, 2020; Rohde, Luca, & Ernst, 2011). In contrast, when the stroking hand is visually occluded, the prior expectation of one's own hand being the source of the tactile signals is relatively reduced and thus the binding of mismatching signals might be

less relatable to the self already at shorter delays. Thus, explicit monitoring of self-related cues seems to be linked to body ownership during self-touch. This is important given that distorted self-monitoring has been suggested to underlie clinical conditions such as schizophrenia (Blakemore, Wolpert, & Frith, 2000; Frith, 1987; Synofzik et al., 2010; Voss et al., 2010), where both disembodiment sensations (e.g. Klaver & Dijkerman, 2016) and distorted somatosensory perception during self-touch (Blakemore, Wolpert, & Frith, 2000) have been reported. Our findings from the first block of Experiment 1 point at the link between the monitoring of self-generated signals and body ownership in healthy participants.

#### 4.1.3. The role of efferent signals in disembodiment

In Experiment 2, we included a self-no-touch condition to disentangle the role of efferent signals within our experimental context. The results show that body ownership is generally lower (compared to both self- and other-touch) when the touching hand moves in the same way as it would when touching the other hand, but without actually touching it, but instead touching a transparent surface. This might be due to the visual expectancy of touch being broken (the participants saw as if their hand was being touched, thus expecting the tactile sensations) despite the temporal mismatches. It has been previously demonstrated that the sole expectation of touch on a fake limb (a rubber hand) is enough to produce illusory ownership of such limb (Ferri, Chiarelli, Merla, Gallese, & Costantini, 2013). Thus, it is plausible that breaking that expectation is enough to reduce ownership of one's own limb. Furthermore, these findings are in line with a previous study suggesting that mismatching visuomotor signals contribute more strongly to disembodiment than visuotactile signals (Roel Lesur, Weijjs, et al., 2020). However, in our study, compared to the cited one, the ownership question was related to the static (left) hand. Still, it could be that the mismatching signals of the moving (right) hand might have had some impact on the ownership sensations of the static hand, which could further explain the reduction of ownership with increasing delay. Along these lines it has been suggested that experimentally-induced alterations of body part ownership in the context of bodily illusions might spread to the entire body (Petkova et al., 2011). Notably, during self-touch, despite these visuomotor mismatches, more agreement with the body ownership statement was found, suggesting that the relative enhancement of body ownership found in both studies is facilitated specifically by self-touch and not due to the involvement of motor signals.

A potential alternative explanation for these findings, however, might stem from a methodological detail. While participants were asked to focus on the left (touched) hand for the body ownership question across conditions, for the self-no-touch condition exclusively they were asked about the touch on the right (touching) hand for the question on sensitivity to multimodal mismatches. It could thus be argued that the different distribution of attentional resources might have contributed to the reduction of body ownership. However, it has been reported that while patients with feelings of disembodiment increase body ownership with attention (Fotopoulou et al., 2011; Jenkinson, Haggard, Ferreira, & Fotopoulou, 2013), that this is not affected in healthy controls (Jenkinson et al., 2013). Future studies could assess these questions for both hands to prevent this potential modulation.

#### 4.2. Sensitivity to multimodal mismatches

For the first block of Experiment 1, the results revealed no differences between conditions. However, for Experiment 2, contrary to our hypothesis based on preliminary observations, participants showed less sensitivity to delay for the other-touch compared to both the self-touch and self no-touch conditions. While these findings are conflicting, the divergence might be due to the relatively small power due to poor fit of the psychometric curves for several participants, mostly for Experiment 1. The results of Experiment 2, however, do not suggest any self-touch specific modulation, but rather that the presence of efferent signals

(present in both self-touch and self-no-touch conditions) might reduce sensitivity to multimodal mismatches. Previous research has suggested the opposite pattern, with more binding of diverging multisensory signals with the presence of self-generated signals (van Kemenade, Arian, Kircher, & Straube, 2016; Zierul, Tong, Bruns, & Röder, 2018), potentially due to the prediction of the self-generated consequences. In a more similar disembodiment paradigm, no difference in synchrony judgments between visuomotor and visuotactile mismatches was found (Roel Lesur, Weijs, et al., 2020), suggesting no modulation by efferent signals. Due to the conflicting findings, however, any potential explanation would be highly speculative. Such speculations should be systematically addressed in a larger sample and potentially use a staircase procedure for a more finetuned adaptation of the measure to the participants' individual sensitivity or a two-alternative-forced-choice task. As mentioned before, our task for assessing sensitivity to multimodal mismatches is not balanced given that tactile/motor cues always preceded vision but never the other way around. This asymmetry in our forced-choice task might have yielded a bias in the measurement that could be accounted for by providing equal chances for each modality to precede the other.

Quick recalibration of the temporal binding window after exposure to visuotactile delay has been reported (Lange, Kapala, Krause, Baumgarten, & Schnitzler, 2018), and self-touch-related sensory attenuation has been reported to be adaptive after exposure to delays (Kilteni, Houborg, & Ehrsson, 2019). It could be that different adaptation processes occur with the involvement of efferent signals compared to only visuotactile stimulation. However, to our knowledge, no study so far has compared these processes directly. In Experiment 2, we measured the velocity of the stroking hand to confirm that it was consistent throughout each condition despite the changes in delay, which could be linked to differences in sensitivity to the multimodal mismatches. Indeed, there were no differences between delays for neither the self-touch nor the other-touch condition.

Beyond the findings from the short exposure to different delays, the second block of Experiment 1 included a question about the causal link between the seen and the felt touch (q2). The results suggest, in contrast to the sensitivity to mismatches measure, but in line with our initial hypothesis based on phenomenal descriptions, that participants perceived that the felt touch was caused by the seen action more in the asynchronous self-touch than the asynchronous other-touch condition. Important differences of the measure are clear, one being a single, explicit, questionnaire item on the causal link between touch and vision, and the other being a more fine grained measure of delay perception (Roel Lesur, Weijs, et al., 2020). While the questionnaire item potentially suggests stronger binding of multimodal signals despite the delay during self-touch, findings between the two measures are diverging.

Previous work on illusory body ownership has suggested that self-attribution might loosen the temporal judgment of body-related multimodal signals (Maselli et al., 2016; Roel Lesur et al., 2018). This is supported by evidence showing increased acuity of temporal judgment when touch was presented to a non-humanoid object compared to a humanoid body (both seen *as if* from a first person perspective on an HMD) and a correlation between participants' illusory body ownership ratings and their temporal binding window (Maselli et al., 2016). Further studies focusing on the link between self-attribution, disembodiment, and temporal sensitivity may be important for understanding principles of bodily self-plasticity which seems to be highly dependent on spatiotemporal correlations of different senses (Blanke, 2012; Costantini et al., 2016; Ehrsson, 2012). Disturbances such as schizophrenia have been linked to both alterations of embodiment (Klaver & Dijkerman, 2016; Thakkar et al., 2011) and multisensory temporal perception (Foucher, Lacambre, Pham, Giersch, & Elliott, 2007; Wallace & Stevenson, 2014), thus the scientific understanding of this condition may also benefit from more thorough research on this link.

#### 4.3. Physiological responses not in line with explicit reports

While several studies have found that electrodermal response to threat of an external limb is stronger when there is a subjective feeling of ownership of it (e.g. Armel & Ramachandran, 2003; Petkova & Ehrsson, 2008), and less strong when the own limb is disowned (e.g. Gentile et al., 2013; Newport & Preston, 2011), our results, unlike hypothesized, showed no evidence for a condition-specific modulation of the SCR despite the reported feeling of disembodiment after asynchronous signals. In consistency with several studies, our paradigm included a single threat per condition (Armel & Ramachandran, 2003; Petkova & Ehrsson, 2008; van der Hoort, Guterstam, & Ehrsson, 2011). Despite the divergent findings from similar literature studying disembodiment (e.g. Gentile et al., 2013; Newport & Preston, 2010, 2011), a previous study using a similar setup showed comparable results (Roel Lesur, Weijs, et al., 2020). In that work it was proposed that the highly ecological setup compared to others, by virtue of showing the participant's full body, perspective and surroundings, might elicit a fragile bodily illusion that may be lost as soon as attention is shifted away from the asynchronous stroking (e.g. towards the threat). However, at this stage such explanation is still speculative. Many studies have reported dissociated as well as contradicting findings between explicit and implicit measures of body ownership and disembodiment (e.g. see de Haan et al., 2017; Roel Lesur, Weijs, et al., 2020; Rohde et al., 2011; Rohde, Wold, Karnath, & Ernst, 2013). While a conciliatory model accounting for such results is still needed, reporting null results might help to contribute to such development.

#### 4.4. Outlook and limitations

Future studies addressing the link between self-touch and disembodiment in populations with clinical alterations of bodily self-consciousness would significantly increase our understanding of the phenomena. Alterations of self-other distinction (Asai, 2016; Jardri et al., 2011), peripersonal space (Ferri, Venskus, Fotia, Cooke, & Romei, 2018), and body ownership (Klaver & Dijkerman, 2016) have been linked to schizotypal traits. An impaired capacity to self-monitor has been argued to importantly underlie the condition (Blakemore, Smith, et al., 2000; Frith, 1987; Synofzik et al., 2010; Voss et al., 2010). In line with this, a brain imaging study proposed that alterations in self-touch somatosensory processing might be linked to distorted self-other distinction (Boehme et al., 2019) and somatosensory signals have shown to be altered in hallucinatory patients during self-touch (Blakemore, Smith, et al., 2000). It could be that a distorted bodily self-attribution and thus self-monitoring might underlie the distorted processing of somatosensory signals. Conforming to this link, our study showed that with the presence of self-related signals during self-touch, the sense of body is more robustly sustained despite incoming mismatching signals. The importance of self-monitoring is further evidenced by a smaller diminishment of ownership when the hand is shown during self-touch compared to when it is hidden. Moreover, psychiatric populations linked to bodily self-consciousness distortions have been reported to show altered temporal perception of multimodal signals (Foucher et al., 2007; Wallace & Stevenson, 2014). However, our results in this regard are inconclusive. Future studies could benefit from more robust psychophysical measures to assess the temporal binding window of multisensory integration of body related signals and how it relates to disembodiment. This could be assessed using two-alternative-forced-choice tasks where both modalities (vision and touch/movement) are equally likely to precede each other. However, providing tactile/motor and not only visual delay for a more balanced assessment is not an easy task. Robotic developments with precisely controlled timing could nevertheless offer potential solutions. Moreover, accounting for individual variability through adaptive measures would enhance the measuring resolution to more precise thresholds. Additionally, uni-sensory acuity, such as visual dominance has been argued to be related

to sensitivity to bodily illusions. Studying the link between general acuity of separate senses and susceptibility to disembodiment resulting from visual mismatches might further develop our understanding of the phenomenon. Lastly, assessing the sensation of both the touching and the touched hand might provide further evidence regarding the phenomenal quality of disembodiment and how it is differentially modulated by and for each hand.

#### 4.5. Conclusion

Overall, our results suggest that body ownership is more strongly sustained despite temporal mismatches during self- compared to other-touch and during motor activity without self-touch. This study extends existing knowledge on the role of self-touch in the sense of bodily self by showing that it does not only contribute to building up body ownership as in the case in supernumerary embodiment (Hara et al., 2015) but also to the maintenance of body ownership in the case of experimentally-induced disembodiment. This is important, given that disembodiment and the loss of body ownership, compared to embodiment of a supernumerary limb, are more commonly reported in clinical conditions (Aglioti et al., 1996; Brugger & Lenggenhager, 2014; Löffler et al., 2019; Vallar & Ronchi, 2009). More specifically, our results show that self-induced touch sustains the sense of body despite increasing body-related mismatching signals, which is further enhanced by the visual monitoring of the own touching hand. Importantly, the data show that this effect is specific to self-touch and not due to the involvement of efferent signals. In regard to the sensitivity to multimodal mismatches, despite the importance of studying this in the context of disembodiment, our results are inconclusive. The application of more finetuned measures using a similar setting is encouraged for future studies, though the compatibility of temporal judgment measures with the simultaneous assessment of (dis)embodiment should be considered. In accordance with the literature on healthy participants (Hara et al., 2015; Kilteni & Ehrsson, 2017; Schütz-Bosbach et al., 2009) our evidence points at the importance of self-touch signals for sustaining a healthy sense of embodiment. Accordingly, clinical findings have suggested improvement of symptoms related to disembodiment after self-touch (van Stralen et al., 2011) and improved sensitivity to self- versus other-touch in cases of hemianesthesia (Valentini, Kischka, & Halligan, 2008; Weiskrantz & Zhang, 1987).

The processes underlying the peculiarities of self-touch in somatosensation and self-attribution are not fully understood. Signal redundancy of the touching and the touched body part (Schütz-Bosbach et al., 2009), specific brain networks (Sakata et al., 1973), strong efferent predictive signals (Blakemore et al., 1999; Blakemore, Smith, et al., 2000; Kilteni et al., 2019), and the early development of both somatosensation and self-touch (Rochat & Hespos, 1997) are intertwined to form a highly specific condition. While important redundancies are manifested in other multimodal interactions such as when speaking or seeing the active motion of the body, the general importance of the near sense of somatosensation and its social-affective components for developing bodily boundaries (Gallace & Spence, 2010; McGlone, Wessberg, & Olausson, 2014) provides an important case for the study of bodily self-consciousness. Our findings further the understanding of this phenomenon that is of relevance for both fundamental science and clinical developments.

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#### Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.cognition.2021.104769>.

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