The supernumerary rubber hand illusion revisited: perceived duplication of limbs and visuotactile events

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Abstract

A controversial and unresolved issue in cognitive neuroscience is whether humans can experience supernumerary limbs as part of their own body. Some previous experiments have claimed that it is possible to elicit supernumerary hand illusions based on modified versions of the rubber hand illusion. However, other studies have provided conflicting results that suggest that only one rubber hand can be perceived as one's own. To address this issue, we developed a supernumerary hand illusion paradigm that allowed us to disambiguate ownership of individual rubber hands from simultaneous ownership of two fake hands. In our setup, the participant's real right hand was hidden under a platform, while two identical right rubber hands were placed in parallel on top of the platform in direct view of the participant. We applied synchronous strokes to both rubber hands and the real hand (SS), synchronous strokes to one rubber hand and the real hand and asynchronous strokes to the other model hand (AS and SA) or asynchronous strokes to both fake hands in relation to the real hand (AA). Our results demonstrate that a genuine illusion of owning two rubber hands can be elicited and that such a supernumerary hand illusion can be isolated from the sense of ownership of a single rubber hand both in terms of questionnaire ratings and threat-evoked skin conductance responses (SCRs). These findings advance our knowledge about the dynamic flexibility and fundamental constraints of body representation and emphasize the importance of correlated afferent signals for causal inference in body ownership.

Keywords: rubber hand illusion, multisensory integration, body ownership, limb perception

1 **Introduction**

2 Throughout evolution, the human body plan has remained constant. Human beings have two
3 arms, two legs, a torso and one head. This fixed body representation with four limbs has helped
4 us successfully interact with the external environment, perform complicated actions and
5 combine upright locomotion with dexterous manual tasks. Can we challenge this apparently
6 fixed body morphology? Could we have supernumerary limbs? Supernumerary limbs are
7 common in ancient mystical texts and comic books. Some Hindu gods (e.g., Brahma, Vishnu
8 & Shiva) have multiple limbs – sometimes even thousands of them – to demonstrate their
9 undefeatable power and unlimited strength. Even Doctor Octopus, the evil genius in Spider-
10 Man (Amazing Spider-Man #3 Vol. 1, Marvel Comics, 1963), demonstrates the utility of
11 supernumerary limbs to perform several evil tasks at the same time. More recently, there has
12 been a growing interest in the engineering community in designing supernumerary robotic
13 limbs to augment human physical capabilities in the workplace and rescue operations (Llorens-
14 Bonilla, Parietti, & Asada, 2012; Parietti & Asada, 2016; Sasaki, Saraiji, Fernando,
15 Minamizawa, & Inami, 2017). These engineering efforts have focused on the technical design
16 of such systems rather than on the fundamental question of to what extent such devices can be
17 incorporated into body representation (Makin, de Vignemont, & Faisal, 2017).

18
19 Previous studies on people with neurological disorders, including strokes, have demonstrated
20 the possibility of humans experiencing supernumerary phantom limbs. Hari et al. (Hari et al.,
21 1998) described a patient with frontal lobe lesions involving the pre-supplementary motor area
22 who perceived a duplicated “ghost arm” in the previous location of the real left arm. This

1 supernumerary phantom limb syndrome indicates the possible simultaneous perception of more
2 than two arms (Khateb et al., 2009). Additionally, Giummarra, Georgiou-Karistianis, Nicholls
3 & Bradshaw (Giummarra, Georgiou-Karistianis, Nicholls, & Bradshaw, 2011) reported that
4 some upper-limb amputees describe a rubber hand reflected in a mirror as a third, “phantom”
5 arm. Although the neural mechanism of supernumerary phantom limbs is unclear, clinical case
6 reports associate these unusual experiences with lesions in different cortical and subcortical
7 brain areas, including posterior parietal cortex (Vuilleumier, Reverdin, & Landis, 1997); frontal
8 association cortex, including non-primary motor areas (Hari et al., 1998; McGonigle et al.,
9 2002); basal ganglia (Halligan, Marshall, & Wade, 1993); and thalamus (Canavero, Bonicalzi,
10 Castellano, Perozzo, & Massa-Micon, 1999; Miyazawa, Hayashi, Komiya, & Akiyama, 2004).
11 Thus, structural disruption of the central pathways and regions involved in the sensorimotor
12 aspects of body representation can lead to supernumerary phantom limbs, but these reports do
13 not tell us whether healthy individuals can experience extra limbs.

14
15 Over the last decade, several experimental studies on healthy participants have been carried out
16 to investigate whether it is possible to elicit supernumerary limb sensation (or “third arm
17 illusion”) (H. H. Ehrsson, 2009; Folegatti, Farne, Salemme, & de Vignemont, 2012; Giummarra
18 et al., 2011; Guterstam, Petkova, & Ehrsson, 2011; Newport, Pearce, & Preston, 2010) based
19 on modified versions of the classical rubber hand illusion (RHI) (Botvinick & Cohen, 1998).
20 The rubber hand illusion is a well-established model system used to investigate the
21 neurocognitive basis of limb ownership in healthy participants (H.H. Ehrsson, 2012, 2020). In
22 the classical rubber hand illusion, participants observe synchronous strokes applied to a rubber

hand, in view, and their real hand, which is hidden from view behind a screen. A period of repeated stroking elicits the illusion that the rubber hand senses the touches that one sees (“referral of touch”) and that the model hand is one’s own hand (“sense of body ownership”)(Blanke, Slater, & Serino, 2015; H.H. Ehrsson, 2012, 2020; Kilteni, Maselli, Kording, & Slater, 2015; Makin, Holmes, & Ehrsson, 2008). Asynchronous strokes applied to the rubber hand and the real hand eliminate the illusion and serve as a well-matched control condition. In the first supernumerary limb illusion study, Ehrsson (H. H. Ehrsson, 2009) placed two right rubber hands next to one another in parallel on the table in view while keeping the participant’s real right hand hidden under the table. When synchronous brushing was applied to both rubber hands and the real right hand, skin conductance responses (SCRs) to physical threat applied to either rubber hand, an often-used objective measure of body ownership (Armel & Ramachandran, 2003; Gentile, Guterstam, Brozzoli, & Ehrsson, 2013; Guterstam, Gentile, & Ehrsson, 2013; Petkova & Ehrsson, 2009), were significantly greater than when such threats were applied in a control condition with asynchronous stroking of the hands. Guterstam, Petkova and Ehrsson (Guterstam et al., 2011) took a different approach and demonstrated that even when the real right hand is fully visible and placed next to a right rubber hand, illusory ownership of the rubber hands can still be elicited while ownership of the real hand is maintained, thus eliciting an illusion of owning one extra right (rubber) hand. Collectively, the results presented in Ehrsson (2009) and Guterstam, Petkova and Ehrsson (Guterstam et al., 2011) suggest that when the brain is presented with two right hands, both receiving congruent multisensory stimulation, both limbs are incorporated into body representation and consciously experienced as one’s own.

1
2 However, the existence of a supernumerary hand illusion has been questioned (Folegatti et al.,
3 2012). By using a setup based on augmented reality, Newport, Pearce & Preston (Newport et
4 al., 2010) presented two digital images of left hands at equal distances from the real left hand
5 position. They found that only the fake hand on the right, i.e., closest to the body midline, could
6 be controlled and hence incorporated into the body representation for action (body schema).
7 Folegatti, Farne, Salemme & de Vignemont (Folegatti et al., 2012), placed two rubber hands to
8 the left of and adjacent to the participant's real hand and found that only the rubber hand closest
9 to the participant's real hand was fully embodied. Moreover, the relatively modest sample sizes
10 in Ehrsson (H. H. Ehrsson, 2009) ($N = 20$), Newport, Pearce & Preston (Newport et al., 2010)
11 ($N = 12$), and Folegatti, Farne, Salemme & de Vignemont (Folegatti et al., 2012)(Max $N = 12$
12 in each group) made the subjective and objective measures of ownership in the supernumerary
13 limbs illusion prone to both type I and type II errors. In addition to these concerns, the paradigm
14 by Guterstam, Petkova & Ehrsson (Guterstam et al., 2011) could be seen as a special case of
15 the classical rubber hand illusion, in which only one rubber hand is presented and default
16 ownership of the real hand maintained. Moreover, in the study by Ehrsson (H. H. Ehrsson,
17 2009), no questionnaire data were collected, so what the participants subjectively perceived
18 during the experiments is unclear. As pointed out by Folegatti, Farne, Salemme & de Vignemont
19 (Folegatti et al., 2012), it the possibility that the threat-evoked SCRs observed in Ehrsson (H.
20 H. Ehrsson, 2009) could be explained by the participants owning only one of the two rubber
21 hands at any one time cannot be fully excluded because it is unclear whether this physiological
22 measure has sufficient spatial resolution to differentiate between threats applied to two model

1 hands placed in close proximity. In sum, the results from previous studies on ownership of
2 supernumerary rubber hands are mixed and inconclusive. Given the above concerns, a study
3 revisiting supernumerary limb illusion is much needed.

4
5 To address all the above issues, we developed a modified version of the supernumerary rubber
6 hand illusion paradigm (H. H. Ehrsson, 2009). The rationale behind the paradigm was to
7 directly contrast ownership of two rubber hands (“dual-hand ownership”) with ownership of
8 individual hands in otherwise equivalent conditions. The participant’s real right hand was
9 hidden under a platform, while two identical right rubber hands were placed adjacent to one
10 another and above the hidden hand on the platform in full view. Note that in this setup both
11 rubber hands were placed at a distance from the real hand that is sufficiently short and within
12 “perihand space” to elicit a robust rubber hand illusion (Kalckert & Ehrsson, 2014b; Kalckert,
13 Perera, Ganesan, & Tan, 2019; Lloyd, 2007). The two rubber hands and the real hand were
14 stroked by three paintbrushes in the following four conditions: (1) both rubber hands
15 synchronously with the real hand (SS); (2) the left rubber hand synchronously and right rubber
16 hand asynchronously with the real hand (SA); (3) the left rubber hand asynchronously and the
17 right rubber hand synchronously with the real hand (AS); and (4) both rubber hands
18 asynchronously with the real hand (AA). This design allowed us to isolate the sensation of dual-
19 hand ownership (SS condition) from ownership of each rubber hand individually (AS and SA
20 conditions, with AA serving as a no-illusion control). In total, the study consists of five separate
21 experiments conducted with five different groups of healthy participants (n=216 in total). In the
22 first two experiments, we collected questionnaire ratings of various aspects of the subjective

1 illusion experience, and the latter three experiments registered threat-evoked SCR as indirect
2 objective physiological evidence of limb ownership. In the first experiment (Experiment 1), the
3 real hand was placed below the platform centered precisely between the two rubber hands, as
4 in Ehrsson (H. H. Ehrsson, 2009). However, we observed strong (clearly affirmative) ownership
5 ratings only for the rubber hand closest to the body midline (see Results). Therefore, in the
6 second experiment (Experiment 2), we shifted the position of the real hand slightly to the right
7 (lateral position) so that it was placed directly under the laterally placed rubber hand. We
8 reasoned that placing the real hand closer to the lateral rubber hand would promote the
9 supernumerary hand illusion by counteracting a general bias in ownership towards the medially
10 placed rubber hand that is closer to the body midline. In the SCR experiments (Experiments 3A,
11 B and C), we used a SCR procedure with a highly localized threat stimulus – a stick with a
12 needle at a precise location of a rubber finger – that allowed psychophysiological differentiation
13 of ownership of either one or two rubber hands. Collectively, our results provide conclusive
14 evidence for the existence of the supernumerary rubber hand illusion.

Methods

Participants

This study consisted of five separate behavioral experiments with 216 healthy participants in total (labelled Experiment 1, Experiment 2 and Experiments 3A-C). All participants were naïve to the purpose of our experiments. In Experiment 1, we tested 40 participants (20 females, age: 27.28 ± 4.27 yrs, mean $\pm$ *SD*); Experiment 2 also involved 40 participants (26 females, age: 27.92 ± 7.29 yrs, mean $\pm$ *SD*); Experiment 3A tested 45 participants (25 females, age: 28.73 ± 7.77 yrs, mean $\pm$ *SD*; 9 participants were excluded from the SCR data analysis as “nonresponders” owing to reasons and criteria described in the Procedures section below); Experiment 3B involved 41 participants (24 females, age: 28.83 ± 6.66 yrs, mean $\pm$ *SD*; 5 participants were excluded from the SCR data analysis); and Experiment 3C tested 50 participants (27 females, age: 29.3 ± 6.58 yrs, mean $\pm$ *SD*; 14 participants were excluded from the data analysis). The sample size was based on previous experiments on the rubber hand illusion (Kalckert & Ehrsson, 2014a). For the SCR experiments data was collected until we had reached the pre-determined target of 36 “responders”; a number that was chosen because it is the number closest to 40 that allows for perfect matching of the order of the conditions across participants (see below). All participants had normal or corrected-to-normal vision and gave informed consent. This study was approved by the Regional Ethical Review Board of Stockholm (now renamed the Swedish Ethical Review Authority).

Experimental setup

All experiments took place in a soundproof behavioral testing room (40-dB noise reduction). The participants were seated comfortably in front of a table and placed their right hand, palm down, on the lower level of a tilted two-level platform. On the upper level of the platform, 12.5 cm above their real hand, two identical cosmetic male prosthetic hands (“rubber hands”) (Natural Definition Glove, Color Y02, Fillauer LLC, Chattanooga, USA) filled with gypsum were placed in parallel, palm down, at a distance of 11 cm between the two rubber index fingers (Figure 1A). The platform was tilted approximately 30° vertically to allow for a good view of both model hands. A piece of black cloth blocked the vision of participants’ right upper arm so that the real right arm and hand were completely occluded; thus, only the two right rubber hands placed on the upper platform could be seen by the participants (Figure 1A). The participants were asked to keep their right hand relaxed at all times during all experimental trials (see below) and not to make any movements of the arm, wrist, thumb, or fingers. They were further instructed to look at and attend to both of the rubber hands.

We carefully applied two minutes of repeated paintbrush strokes to the index (Experiments 1 and 2) or middle (Experiments 3A-C) finger of the two rubber hands and real hand in the following conditions: (1) both synchronous (SS) – we applied synchronous strokes to both rubber hands and the real hand; (2) left synchronous and right asynchronous (SA) – we synchronously stroked the rubber hand on the left and the real hand while stroking the rubber hand on the right asynchronously; (3) left asynchronous and right synchronous (AS) – we synchronously stroked the right rubber hand and the real hand while stroking the left rubber

hand asynchronously; and (4) both asynchronous (AA) – we applied asynchronous strokes to the two rubber hands and the real hand. To apply brushstrokes in a well-controlled manner, we used a ‘brushstroke apparatus’ (Figure 1A) that we developed in our laboratory. Two small paintbrushes (length: 12.9 cm, width: 1.30 cm) (Penselset Hobby 7070, Habo Penslar AB, Bankeryd, Sweden) were attached to one rotating rod placed 10 cm above the index digits of the two rubber hands (middle finger in Experiments 3A-C). This rod was rotated by the experimenter’s left hand, which held the lateral end of the rod and continuously rotated the handle in a circular (360-degree) movement. The handle and the experimenter’s hand were out of sight of the participant; thus, the participant could see only the two rotating paintbrushes repeatedly stroking the two rubber hands. At the same time, the experimenter’s right hand applied the strokes with a paintbrush (identical to the brushes touching the rubber hands) to the corresponding section of the participant’s matching real right finger as synchronously as possible with the strokes applied to the rubber hands (SS) or one of the rubber hands (AS, SA). In the AA condition, these strokes were applied with a one-second delay (see Figure 1B). The procedure of stroking the real hand took place under the platform and was thus out of the participant’s view. Paintbrush strokes were applied to the finger from the metacarpophalangeal joint to the distal interphalangeal joint at a frequency of 0.5 Hz. During the entire experiment, the experimenter maintained this frequency and a steady velocity of the paintbrush strokes by rotating the handle that generated the rotation of the brushes at a regular speed so that an entire 360-degree rotation of the handle was completed every 2 seconds (the experimenter listened to an auditory metronome as a rotation cue) and matched this frequency and velocity for the strokes manually applied to the real right hand. For all asynchronous conditions, we adjusted

1 the alignment of one (AS and SA) or both (AA) of the paintbrushes seen by the participants by
2 180 degrees in relation to the hidden paintbrush touching the real hand to achieve a one-second
3 delay between the seen and felt touches.

4
5 In Experiment 1, the real right hand was placed directly under the vertical midline of the two
6 rubber hands (Figure 1C, top left panel) so that the distance between the real hand and each of
7 the two rubber hands was identical [as in Ehrsson (H. H. Ehrsson, 2009)]. In contrast, in
8 Experiments 2 and 3, the real hand was placed directly under the more laterally placed right
9 rubber hand (Figure 1C, lower left panel) to augment the dual-hand ownership illusion (see
10 Results for details).

11
12 Before each experimental trial commenced, we reminded the participant to keep looking at both
13 rubber hands and to attend to them equally. The participants were explicitly instructed not to
14 fixate on only one of the rubber hands. The experimenter regularly checked the participants'
15 gaze throughout the experiment to ensure that the participant followed these instructions. We
16 wanted to avoid participants looking at and attending to only one rubber hand owing to the
17 concern that such behavior might bias the questionnaire ratings or SCR responses towards a
18 particular rubber hand.

Figure 1. Illustration of experimental setup, procedures and conditions. (A) Participant's real right hand was hidden under a platform, while two identical right rubber hands were placed adjacent to one another on the platform in full view of the participant. The brushstrokes to the rubber hands and the real hand were applied with a "brushstroke apparatus" that allowed for the delivery of well-controlled stimuli (see Methods section). Skin conductance responses (SCRs) were recorded with the participant's real left hand (through surface electrodes attached to the middle finger and index finger). (B) Main conditions used in the study. The two rubber hands were stroked at 0.5 Hz at the index (Experiments 1-2) or middle finger (Experiments 3A-C) by two small paintbrushes in the following conditions: both rubber hands synchronously (SS) with the real hand; both asynchronously (AA) with the real hand; left synchronously and right asynchronously (SA) with the real hand; and left asynchronously and right synchronously (AS) with the real hand. (C) In Experiment 1, the participant's right hand was placed precisely between the two rubber hands. In Experiments 2 and 3, the participant's real right hand was placed directly under the right rubber hand.

1 Procedures

2 Experiments 1 and 2 focused on the quantification of the subjective experience of the illusion
3 by using a questionnaire (the first part of these experiments). Each of the four conditions was
4 repeated once in separate trials. Each trial took two minutes, during which sixty individual
5 paintbrush strokes were applied to each hand. The orders of the four conditions across
6 participants were pseudorandomized. All participants were asked to complete a questionnaire
7 after each trial. In this questionnaire, the participants were asked to rate on a Likert scale how
8 much they agreed or disagreed with ten statements that referred to possible feelings that they
9 may have experienced during the preceding trial. The rating scales consisted of 7 points from -
10 3 to +3, where -3 means “completely disagree”, 0 means “neither agree nor disagree, i.e., not
11 sure” and +3 means “totally agree”.

12
13 We constructed the questionnaire based on statements adopted from previous rubber hand
14 illusion studies (Botvinick & Cohen, 1998; Folegatti et al., 2012; Guterstam et al., 2011;
15 Newport et al., 2010) (see Table 1). In this questionnaire, two statements were used to describe
16 the illusion for the rubber hand on the left (medial position) (S1 and S2); two statements were
17 related to the illusion for the rubber hand on the right (lateral position) (S3 and S4); and two
18 statements specifically described the rubber hand illusion for both rubber hands at the same
19 time (S5 and S6). These illusion-related questions included separate statements regarding
20 sensing touch on the rubber hand(s) where they were being stroked (“referral of touch”; S1, S3,
21 and S5) and explicit feelings of ownership of the hand(s) (S2, S4, S6), which are the two most
22 prominent perceptual features of the rubber hand illusion (H.H. Ehrsson, 2012). Statements S5

and S6 are the most important in this study because they directly assess the explicit senses of duplicated referral of touch (S5) and dual-rubber hand ownership (S6). The last four questions were control statements (S7-S10) that were included to control for possible effects related to suggestibility and task compliance.

Table 1. The statements of the questionnaire used in Experiments 1 and 2

Statements	
S1	It seemed as if I were feeling the touch of the paintbrush in the location where I saw the rubber hand furthest to the left touched.
S2	I felt as if the rubber hand furthest to the left were my hand.
S3	It seemed as if I were feeling the touch of the paintbrush in the location where I saw the rubber hand furthest to the right touched.
S4	I felt as if the rubber hand furthest to the right were my hand.
S5	It seemed as if I were feeling the touches of the paintbrushes in the locations where I saw both rubber hands touched.
S6	I felt as if both rubber hands were my hands.
S7	It felt as if my (real) hand was turning “rubbery”.
S8	It no longer felt like my (real) hand belonged to my body.
S9	It appeared (visually) as if the rubber hands were drifting towards the left.
S10	It appeared (visually) as if the rubber hands were drifting towards the right.

In Experiment 3 (A-C), concerned the objective physiological measure of the illusion by registering SCRs evoked by physical “threats” towards the rubber hands. The SCR reflects increased sweating attributable to the activation of the autonomic nervous system (Dawson, Schell, & Filion, 2007). When the body is physically threatened, the threat triggers feelings of fear and pain anticipation and the associated autonomic arousal that can be registered as an SCR some seconds after the threat event. The difference in “threat-evoked SCR” between two well-matched conditions has been shown to be a reliable index of body ownership in the rubber hand

illusion paradigm (Gentile et al., 2013; Guterstam et al., 2013; Petkova & Ehrsson, 2009). In the current experiments the threat-stimuli consisted of sting of a needle [‘needle sting’; based on (H. H. Ehrsson et al., 2008)] to the middle finger of one of the rubber hands (right rubber hand in Experiment 3A and left in Experiments 3B and 3C). For the needle sting, the experimenter makes a small movement of a needle attached to a syringe (diameter 0.8 mm, length 160 mm) directly towards the middle finger of one of the two rubber hands and so that the needle slightly touches the rubber skin and stings it gently. This procedure provided a threat that was spatially restricted and precise, and that targeted the central area of each rubber hand. In line with this, we also applied the brushstrokes to the middle fingers of the rubber hands and the participant’s real right hand (instead of the index fingers, as in Experiments 1 and 2). The total number of trials in each SRC experiment was 9, and we included the three most important conditions in each experiment [Experiments 3A, 3C (SS, SA and AA conditions), and 3B (SS, AS and AA conditions)]. SCRs are subjective to attenuation effects over repeated threats, so minimizing the number of conditions in each experiment is important to ensure quality of the data. The needle sting was delivered immediately at the end of each one-minute trial in the three experimental conditions. The needle sting procedure took approximately 4 seconds in total (presentation of the syringe, stinging the middle finger and retracting the syringe). All three conditions were repeated 3 times. The order of the conditions was counterbalanced among the participants. From an ethics perspective, it should be pointed out that the threat procedure was completely risk-free. Moreover, we informed the participants that we would never threaten their real hands, and they were familiarized with the needle and the needle-sting procedure before the actual experiment commenced.

1
2 SCRs were recorded with a Biopac System MP150 (Goleta, USA). Two electrodes were
3 attached to the index and middle fingers of the participant's left hand. We collected the data at
4 a sample rate of 100 Hz. The experimenter flagged the exact timing of the "needle-sting" event
5 in the recording data file by pressing a foot pedal. Participants who did not display detectable
6 SCRs ($< .1 \mu\text{S}$ peak amplitude from preceding baseline, 10-second time window from the onset
7 of syringe presentation) in more than two-thirds of the threat trials were excluded from the SCR
8 data analysis (Petkova & Ehrsson, 2009). Considering the large variability in SCR amplitudes
9 across individuals, each SCR amplitude value was divided by the maximum SCR amplitude
10 detected for that individual during the experiment (Dawson et al., 2007; Lykken, Rose, Luther,
11 & Maley, 1966). The average of all responses for each participant, including those in which no
12 increase in amplitude could be identified, was separately calculated for each condition, and this
13 value was taken as the SCR magnitude (Dawson et al., 2007). This normalized SCR magnitude
14 was then compared statistically across the different conditions.

15 Data analysis

16 We set the significance threshold to $p < .05$ for the statistical analysis. All comparisons are
17 planned based on our hypotheses and in line with the experimental design of the study. We
18 therefore corrected for the number of critical illusion-related questionnaire items in
19 Experiments 1 and 2 (S1-S6) only when contrasting the conditions of interest, resulting in a
20 significance level of $p = .05/6 = .0083$ for these results (all reported p-values are "uncorrected"
21 values). The questionnaire results for Experiments 1 and 2 are not normally distributed

1 (Shapiro-Wilks test p values always $< .05$). We therefore applied nonparametric tests, the
2 Friedman test and Wilcoxon signed-rank test (two-tailed, Bonferroni correction, significance
3 level $p = .05/6 = .0083$), to the critical questionnaire statements (S1-S6). To test the differences
4 in the questionnaire responses between Experiments 1 and 2, we used a two-tailed Mann-
5 Whitney U-test (see Supplementary Figure 1 and Supplementary Results). The SCR results
6 from Experiments 3A, 3B and 3C are normally distributed and passed the Shapiro-Wilks
7 normality test (p values $> .05$). We used the paired sample t-test (two-tailed) to analyze the SCR
8 results in accordance with our planned comparisons in Experiment 3 (A-C).

Results

Experiment 1

Questionnaire

An overview of the questionnaire results from the first experiment (N = 40), including all statements, is provided in Figure 2A and Table 2. As expected, the participants gave higher ratings of hand ownership and referral of touch for the rubber hand(s) that received synchronous visuotactile stimulation than for those that received asynchronous stimulation. Furthermore, they provided negative ratings for the four control statements, meaning that they rejected these statements and that their overall questionnaire responses should therefore be reliable. Notably, the participants also gave higher ratings for the statements (S5 and S6) related specifically to the supernumerary hand illusion in the SS condition than in the other conditions, although the ratings for dual-hand ownership (S6) were not clearly affirmative, as we had hoped (see further below). In the statistical analysis, we separately analyzed the rating scores for the illusion-related statements (S1-S6) and present the results in the following paragraphs and in Figure 3.

Table 2. Median values and interquartile ranges of questionnaire statements in Experiment 1

Questionnaire	Experiment 1 rating median (interquartile ranges)			
	SS	SA	AS	AA
S1	1.5 (-1 ~ 2.75)	2 (1.25 ~ 3)	-3 (-3 ~ 1)	-1 (-2.75 ~ 1)
S2	1 (-2 ~ 2)	2 (1 ~ 3)	-2 (-3 ~ 1)	-2 (-3 ~ -0.5)
S3	0 (-2 ~ 2)	-3 (-3 ~ -1.25)	2 (1 ~ 3)	-2 (-3 ~ 0)
S4	-0.5 (-2 ~ 1)	-3 (-3 ~ -2)	1 (-1 ~ 2)	-2 (-3 ~ -1)
S5	1 (0 ~ 3)	-2 (-3 ~ -1)	-2 (-3 ~ 0)	-2 (-3 ~ 1)
S6	-0.5 (-3 ~ 1)	-3 (-3 ~ -1.25)	-2 (-3 ~ -0.25)	-2.5 (-3 ~ -2)
S7	1 (-3 ~ 2)	-1 (-3 ~ 1)	-0.5 (-3 ~ 1)	-2 (-3 ~ 0)
S8	-1.5 (-3 ~ 1)	-1.5 (-3 ~ 1)	-1.5 (-3 ~ 0.75)	-2.5 (-3 ~ -1)
S9	0 (-2.75 ~ 1)	0 (-3 ~ 1)	-2 (-3 ~ 0)	-1.5 (-3 ~ 0)
S10	-1 (-3 ~ 0)	-2 (-3 ~ 1)	-0.5 (-3 ~ 1.75)	-2 (-3 ~ -1)

Figure 2. Overview of questionnaire results from Experiments 1 and 2. (A) Questionnaire results from Experiment 1. (B) Questionnaire results from Experiment 2. The rating scales consist of 7 points from -3 to +3, where -3 means “completely disagree”, 0 means “neither agree nor disagree, i.e., not sure” and +3 means “totally agree”. For display purposes and for consistency with previous studies, mean values are presented; the error bar represents the standard error.

Illusion for medial (left) rubber hand

For referral of touch and ownership over the rubber hand on the *left* (S1 and S2), there was a statistically significant difference in the rating scores of agreement among the four conditions (SS, SA, AS and AA) (S1: $\chi^2(3) = 53.173, p < .001, W = .443$; S2: $\chi^2(3) = 40.916, p < .001, W = .341$). As expected, the participants rated significantly stronger referral of touch (S1) and ownership (S2) for the left rubber hand in the SS condition than in the AS condition (S1: $Z = -3.947, p < .001, r = -.441$; S2: $Z = -3.963, p < .001, r = -.443$) and in the SS condition than in

the AA condition (S1: $Z = -3.120$, $p = .002$, $r = -.349$; S2: $Z = -3.824$, $p < .001$, $r = -.428$) (see Figure 3A and B). The median rating scores indicated that the participants felt the rubber hand on the left much like their own hand when the two rubber hands were synchronously stroked (S1: median = 1.5; S2: median = 1, SS condition) and rejected these statements when the two hands were asynchronously stroked (S1: median = -1; S2: median = -2, AA condition) or just the rubber hand on the left was stroked (S1: median = -3; S2: median = -2, AS condition). We further noted (post hoc) that the ratings for the illusion of the left model hand were somewhat higher in the SA condition (S1: median = 2; S2: median = 2) than in the SS condition (S1: median = 1.5; S2: median = 1) (S1: $Z = -2.485$, $p = .013$, $r = -.278$; S2: $Z = -1.975$, $p = .048$, $r = -.221$), although this difference did not reach statistical significance after Bonferroni correction for multiple comparisons ($p < .0083$).

Illusion for lateral (right) rubber hand

For the illusion of the rubber hand on the *right* (S3 and S4), there was a statistically significant difference in the rating scores of agreement among the four conditions (SS, SA, AS and AA) (S3: $\chi^2(3) = 51.372$, $p < .001$, $W = .428$; S4: $\chi^2(3) = 49.234$, $p < .001$, $W = .410$) (see Figure 3C and D). In line with our hypothesis, the ratings for referral of touch and right hand ownership were significantly greater in the SS condition than in the SA condition (S3: $Z = -3.759$, $p < .001$, $r = -.420$; S4: $Z = -3.707$, $p < .001$, $r = -.414$) and in the SS than in the AA condition (S3: $Z = -3.042$, $p = .002$, $r = -.340$; S4: $Z = -2.878$, $p = .004$, $r = -.322$). In terms of absolute rating scores, the participants were uncertain whether they felt the illusion for the right rubber hand when both artificial hands received synchronous strokes (S3: median = 0; S4: median = -0.5, SS

condition), but they firmly denied both ownership and referral of touch sensations when asynchronous strokes were applied to the rubber hand on the right (S3: median = -3; S4: median = -3, SA condition; S3: median = -2; S4: median = -2, AA condition). We further noted (post hoc) that the feeling of touches on the right rubber hand (S3) tended to be stronger in the AS condition (S3: median = 2) than in the SS condition (S3: median = 0) (S3: $Z = -2.480$, $p = .013$, $r = -.277$), although this effect did not survive the Bonferroni correction ($p = .0083$). Similarly, the ratings of right rubber hand ownership were significantly stronger in the AS (S4: median = 1) than in the SS condition (S4: median = -0.5) (S4: $Z = -2.947$, $p = .003$, $r = -.329$).

Supernumerary rubber hand illusion

For referral of touch and ownership of *both* rubber hands (S5 and S6), there was a statistically significant difference among the four conditions (SS, SA, AS and AA) (S5: $\chi^2(3) = 37.471$, $p < .001$, $W = .312$; S6: $\chi^2(3) = 23.751$, $p < .001$, $W = .198$) (see Figure 3E and F). In support of our hypothesis, the ratings of duplicated referral of touch (S5) and dual-rubber hand ownership (S6) were significantly higher in the SS condition (S5: median = 1; S6: median = -0.5) than in the SA condition (S5: median = -2; S6: median = -3) (S5: $Z = -4.422$, $p < .001$, $r = -.494$; S6: $Z = -3.193$, $p = .001$, $r = -.357$), the AS condition (S5: median = -2; S6: median = -2) (S5: $Z = -4.208$, $p < .001$, $r = -.470$; S6: $Z = -2.633$, $p = .008$, $r = -.294$), or the AA condition (S5: median = -2; S6: median = -2.5) (S5: $Z = -3.523$, $p < .001$, $r = -.394$; S6: $Z = -3.675$, $p < .001$, $r = -.411$). On the basis of the median scores, we can conclude that the participants affirmed feeling the touches on both rubber hands (S5: median = 1), while they were uncertain about the ownership of the two artificial hands (S6: median = -0.5) when both rubber hands were synchronously

1 stroked (SS). Importantly, although the supernumerary hand illusion was associated with clearly
2 affirmative ratings only for referral of touch to both rubber hands, the dual-hand ownership
3 ratings were still statistically significantly stronger in the SS condition than in all other
4 conditions in our design (SA, AS and AA; see above), which provides evidence for a significant
5 perceptual effect in line with our hypothesis.

Figure 3. Boxplots of questionnaire results from Experiment 1. (A) Questionnaire results regarding sensing touch on the left rubber hand (S1). The rating scores in both the SS and SA conditions confirmed referral of touch to the left rubber hand in these conditions, while the AS and AA conditions were associated with a denial of such illusory tactile experiences. (B) Questionnaire results regarding the feeling of ownership of the left rubber hand (S2). The rating scores in both the SS and SA conditions were significantly higher than those in the AS and AA conditions. (C) Questionnaire results regarding the tactile feeling on the right rubber hand (S3). Only the rating scores in the AS condition confirmed that the participants sensed touch on the right rubber hand, while in the SA and AA conditions, the subjects rejected this statement, and in the SS condition, the participants' median score indicated uncertainty. (D) Questionnaire results regarding body ownership of the right rubber hand (S4). Only the rating scores in the AS condition confirmed the ownership of the right rubber hand, while in the SA and AA conditions, the participants rejected this statement, and in the SS condition, the participants were uncertain. (E) Questionnaire results regarding sensing touches on both rubber hands at the same time (S5). Only the scores in the SS condition positively confirmed the touch feeling of the two rubber hands. (F) Questionnaire results regarding body ownership of both rubber hands (S6). The SS condition was not associated with a clear positive confirmation of the dual-hand ownership statement, although the participants expressed a degree of uncertainty. Importantly, however, the rating scores on both S5 and S6 were significantly higher in the SS condition than in the other three conditions (AS, SA and AA), which provides evidence for a significant supernumerary hand effect even if the illusion of dual-hand ownership was not vivid for the majority of the participants. The boxplots depict the data based on their median (think black line) and quartiles (upper and lower ends of boxes). The vertical lines, the whiskers, indicate the minimum or maximum and illustrate variability outside the upper and lower quartiles (* $p < .05$; ** $p < .01$; *** $p < .001$).

Experiment 2

Questionnaire

A summary of the questionnaire results for all statements is provided in Figure 2B and Table 3. The most notable differences in comparison to the first experiment was that the participants now gave affirmative ratings for sensing ownership of both rubber hands (S6) in the SS condition and that the single-hand illusion strength was more balanced between the left and the right rubber hands (see Supplementary Figure 2 for details). As expected, and highly consistent with the results from the first experiment, the participants provided higher ratings of ownership and referral of touch for the synchronously stroked rubber hand(s) than for the asynchronously

stroked ones; furthermore, they gave negative ratings for the control statements. The statistical results for the illusion-related statements (S1-S6) are presented below and in Figure 4.

Table 3. Median values and interquartile ranges of questionnaire statements for Experiment 2

Questionnaire	Experiment 2 rating median (interquartile ranges)			
	SS	SA	AS	AA
S1	2 (0 ~ 3)	3 (2 ~ 3)	-2.5 (-3 ~ -0.25)	-1.5 (-3 ~ 1)
S2	1 (-1.75 ~ 2)	2 (1 ~ 3)	-3 (-3 ~ -2)	-2 (-3 ~ 0.75)
S3	2 (1 ~ 3)	-2.5 (-3 ~ 0)	3 (2 ~ 3)	0 (-2 ~ 2)
S4	1 (-0.75 ~ 2.75)	-3 (-3 ~ -1)	2 (1 ~ 3)	-1 (-3 ~ 1)
S5	2 (1 ~ 3)	-2 (-3 ~ 1)	-0.5 (-3 ~ 1)	-0.5 (-2.75 ~ 2)
S6	2 (-1 ~ 3)	-3 (-3 ~ -1)	-3 (-3 ~ -1)	-2 (-3 ~ 1)
S7	-2 (-3 ~ 1)	-1 (-3 ~ 1)	-2 (-3 ~ 1)	-2 (-3 ~ 0)
S8	0 (-3 ~ 1)	-2 (-3 ~ 0)	-2 (-3 ~ 0)	-2 (-3 ~ 0)
S9	-3 (-3 ~ 0)	-2.5 (-3 ~ 1)	-3 (-3 ~ -1.25)	-3 (-3 ~ -1.25)
S10	-2 (-3 ~ 0)	-3 (-3 ~ -1)	-2 (-3 ~ 0.75)	-3 (-3 ~ -1.25)

Illusion for medial (left) rubber hand

For the illusion of the *left* rubber hand (S1 and S2), there was a statistically significant difference in the rating scores for ownership and referral of touch statements in the four main conditions (SS, SA, AS and AA) (S1: $\chi^2(3) = 61.7$, $p < .001$, $W = .514$; S2: $\chi^2(3) = 56.116$, $p < .001$, $W = .468$) (see Figure 4A and B). For both illusory sensations – in line with our predictions – the ratings were significantly higher in the SS condition than in the AS condition (S1: $Z = -4.241$, $p < .001$, $r = .474$; S2: $Z = -4.380$, $p < .001$, $r = .490$) and the AA condition (S1: $Z = -3.050$, $p = .002$, $r = .341$; S2: $Z = -3.464$, $p = .001$, $r = .387$). In terms of the magnitude of ratings, the participants affirmed feeling that the rubber hand on the left was their own when the left rubber hand was synchronously stroked in the SS condition (S1: median = 2; S2: median = 1) and the SA condition (S1: median = 3; S2: median = 2); conversely, they denied this illusory experience

1 when the left hand was asynchronously stroked in the AS (S1: median = -2.5, S2: median = -3)
2 and AA conditions (S1: median = -1.5; S2: median = -2). In addition, we found that the
3 affirmative ratings of left hand ownership and referral of touch were significantly higher in the
4 SS condition than in the SA condition (S1: $Z = -3.506$, $p < .001$, $r = .392$; S2: $Z = -2.428$, p
5 $= .015$, $r = .271$), although the left rubber hand received synchronous strokes in both of these
6 conditions.

8 Illusion for lateral (right) rubber hand

9 For referral of touch and ownership of the *right* rubber hand (S3 and S4), there was a statistically
10 significant difference in the rating scores of agreement depending on the four conditions (SS,
11 SA, AS and AA) (S3: $\chi^2(3) = 49.718$, $p < .001$, $W = .414$; S4: $\chi^2(3) = 51.216$, $p < .001$, W
12 $= .427$) (see Figure 4C and D). Importantly, these ratings were significantly higher in the SS
13 condition than in the SA condition (S3: $Z = -4.833$, $p < .001$, $r = .540$; S4: $Z = -4.100$, $p < .001$,
14 $r = .458$) and the AA condition (S3: $Z = -3.601$, $p < .001$, $r = .403$; S4: $Z = -3.098$, $p = .002$, r
15 $= .346$). The participants felt the rubber hand on the right much like their own hand when both
16 rubber hands were synchronously stroked in the SS condition (S3: median = 2; S4: median = 1)
17 and denied this feeling when the right rubber hand was asynchronously stroked in the SA (S3:
18 median = -2.5; S4: median = -3) and AA conditions (S3: median = 0; S4: median = -1). The
19 relatively small differences in ratings between the SS (S3: median = 2; S4: median = 1) and AS
20 conditions (S3: median = 3; S4: median = 2) for referral of touch (S3: $Z = -2.285$, $p = .022$, r
21 $= .255$) or ownership of the right rubber hand (S4: $Z = -1.685$, $p = .092$, $r = .188$) did not survive
22 Bonferroni correction ($p = .008$).

Supernumerary rubber hand illusion

For the supernumerary rubber hand illusion involving both rubber hands (S5 and S6), there was a statistically significant difference between the four conditions (SS, SA, AS and AA) (S5: $\chi^2(3) = 43.629, p < .001, W = .364$; S6: $\chi^2(3) = 56.867, p < .001, W = .474$) (see Figure 4E and F). Importantly, for both sensing touch on both rubber hands and dual-hand ownership, there were significantly higher ratings for SS (S5: median = 2; S6: median = 2) than for SA (S5: median = -2; S6: median = -3; S5: $Z = -5.036, p < .001, r = .563$; S6: $Z = -4.670, p < .001, r = .522$), for SS than for AS (S5: median = -0.5; S6: median = -3; S5: $Z = -4.606, p < .001, r = .515$; S6: $Z = -4.960, p < .001, r = .555$), and for SS than for AA (S5: median = -0.5; S6: median = -2; S5: $Z = -3.746, p < .001, r = .419$; S6: $Z = -4.229, p < .001, r = .473$). Furthermore, the participants affirmed both dual-hand ownership (S6) and referral of touch to both artificial hands (S5) in the SS condition (S5: median = 2; S6: median = 2, SS condition) and provided negative median rating scores for these statements in the other conditions. Collectively, these questionnaire results suggest that the participants experienced a vivid supernumerary hand illusion in the SS condition in Experiment 2.

Figure 4. Boxplots of questionnaire results from Experiment 2. (A) Questionnaire results regarding referral of touch to the left rubber hand (S1). The rating scores in both the SS and SA conditions confirmed the tactile sensations on the left rubber hand, while in the AS and AA conditions, participants denied this experience. (B) Questionnaire results regarding ownership of the left rubber hand (S2). Affirmative rating scores were higher in both the SS and SA conditions than in the AS and AA conditions, which were both negative. (C) Questionnaire results regarding referral of touch to the right rubber hand (S3). The rating scores in both the SS and AS conditions confirmed the participants' referral of touch to the right rubber hand. (D) Questionnaire results regarding the feeling of ownership of the right rubber hand (S4). (E) Questionnaire results regarding referral of touch to both rubber hands at the same time. Only in the SS condition did the rating scores positively confirm that the participants sensed touches located on both rubber hands. (F) Questionnaire results regarding body ownership of both rubber hands. Only the scores in the SS condition positively confirmed that the volunteers experienced ownership of both rubber hands. The rating scores for referral of touch and ownership were both significantly higher in the SS condition than in the other three conditions (n.s., not significant; * $p < .05$; ** $p < .01$; *** $p < .001$). The boxplots depict the data based on their median (think black line), the upper and lower quartiles (upper and lower ends of boxes) and the whiskers that indicate the minimum or maximum (thus illustrating variability outside the quartiles).

Experiment 3

SCRs

In Experiment 3A ($N = 36$), we applied the needle sticks to the right rubber hand (Figure 5A), and, in line with our hypothesis, we observed significantly greater SCRs in the SS condition than in the SA condition ($t(35) = 3.027, p = .005$, Cohen's $d = .535$, 95% $CI = [.040, .204]$) and in the SS condition than in the AA condition ($t(35) = 3.0429, p = .004$, Cohen's $d = .625$, 95% $CI = [.044, .220]$). These results provide objective physiological evidence for the supernumerary hand illusion and indicate that this effect can be differentiated from single-hand ownership with the current threat-evoked SCR approach.

1 In Experiment 3B ($N = 36$), we changed the target of the needle threat to the left rubber hand
2 and tested the SS, AS, and AA conditions (see Figure 5B). As hypothesized, we observed
3 significantly greater SCRs in the SS condition than in the AS condition ($t(35) = 2.802, p = .008$,
4 Cohen's $d = .499$, 95% $CI = [.025, .157]$) and significantly greater SRCs in the SS condition
5 than in the AA condition ($t(35) = 2.508, p = .017$, Cohen's $d = .429$, 95% $CI = [.015, .139]$).
6 These results were consistent with the findings from Experiment 3A and thus corroborate the
7 psychophysiological evidence for the supernumerary hand illusion.

8
9 In Experiment 3C ($N = 36$), we used the same three conditions as in Experiment 3A (SS, SA,
10 and AA conditions) but threatened the left rubber hand (Figure 5C). Consistent with our
11 hypothesis and the above results, we observed significantly greater SCRs in the SS condition
12 than in the AA condition ($t(35) = 2.28, p = .029$, Cohen's $d = .390$, 95% $CI = [.009, .150]$) and
13 significantly greater SCRs in the SA condition than in the AA condition ($t(35) = 2.690, p = .011$,
14 Cohen's $d = .511$, 95% $CI = [.025, .182]$). These results provide further support for our main
15 conclusion and additionally confirm the effectiveness of the single-hand ownership
16 manipulation in the current paradigm (AS versus AA).

Figure 5. Skin conductance response (SCR) results from Experiment 3A-C. The normalized SCR magnitude (mean ± SE) is displayed for each of the three conditions that was included in each of the three experiments. (A) SCR results from Experiment 3A. The middle finger of the right rubber hand was stung by a needle after a period of synchronous brushing eliciting the supernumerary hand ownership illusion (SS condition) or asynchronous brushing when experiencing ownership only of the left hand (SA condition) or no illusion for either rubber hand (AA condition). (B) SCR results from Experiment 3B. The middle finger of the left rubber hand was stung by the needle after the SS, AS or AA condition. In these two experiments, we observed a significantly stronger magnitude of SCRs in the SS condition compared to the two other conditions for needle threats applied to either model hand, which provides physiological evidence in support of our main hypothesis regarding the existence of the supernumerary rubber hand illusion. (C) SCR results from Experiment 3C. The left rubber hand was stung by the needle after the SS, SA and AA conditions. As expected, we observed a significantly greater SCR magnitude after the two conditions with synchronous stimulation applied to the left hand (SS and SA) than after the AA condition. Asterisks indicate a significant difference between conditions (* $p < .05$; ** $p < .01$; n.s., not significant).

Discussion

In the current study, we revisited the question of whether it is possible to elicit a supernumerary rubber hand illusion. To this end, we developed a modified version of the original setup with two right rubber hands (H. H. Ehrsson, 2009) and used an experimental design that allowed us to isolate supernumerary hand ownership from single-hand ownership. Both the questionnaire results and the threat-evoked SCRs demonstrated that the application of synchronous strokes to both rubber hands (SS) induced ownership over *both* artificial hands compared to the conditions in which we applied asynchronous strokes to one rubber hand and the real hand (SA and AS) or asynchronous strokes to both fake hands (AA). These results are important because they resolve a discussion in the literature about whether the rubber hand illusion is restricted to one model hand by establishing that the supernumerary rubber hand illusion is a genuine body illusion. Conceptually, this finding is significant because first, it shows that the dynamic flexibility of body representation goes beyond the constraints of the human body plan in terms of number; second, it indicates that the everyday experience of having four limbs that most people have is not an automatic “default” but the result of active integrative processes in the brain that are binding together visual, tactile, proprioceptive signals into a coherent multisensory bodily experience that is most consistent with current sensory inputs; and third, it suggests that the process of causal inference in multisensory own-body perception (H. H. Ehrsson & Chancel, 2019; Fang et al., 2019; Kilteni et al., 2015; Samad, Chung, & Shams, 2015) is highly influenced by the spatiotemporal pattern of bottom-up sensory information and allows for highly unusual causal structures that apparently violate prior experience of the human body. From an applied perspective, our results are relevant for emerging technologies and

1 applied research into embodiment of supernumerary prostheses and wearable robotic extra arms
2 by providing a proof-of-principle that it might be possible for users to experience such devices
3 as part of their own body.

4 5 Evidence supporting the existence of the supernumerary rubber hand illusion.

6 The current experiments were designed to address the critical points raised by Folegatti, Farne,
7 Salemme & de Vignemont (Folegatti et al., 2012) and to overcome the inherent limitations of
8 the Ehrsson (H. H. Ehrsson, 2009) study. In the latter, Ehrsson revealed a significant difference
9 in threat-evoked SCRs between a condition where synchronous strokes were applied to the two
10 rubber hands and the real hand (SS) and a condition with asynchronous strokes (AA) delivered
11 to the two model hands. However, no control condition with ownership of one of the two rubber
12 hands was included, and no questionnaire data were collected, which left open the possibility
13 that only one of the two rubber hands was perceived as owned and that the “spatial resolution”
14 of the SCRs was too low to differentiate between threats applied to each of the two rubber hands
15 (Folegatti et al., 2012). This latter concern is not unreasonable given that both model hands are
16 presented within a perihand space from the real hand, which is a “safety zone” around the body
17 in which threatening stimuli elicit augmented emotional defense reactions (Brozzoli, Ehrsson,
18 & Farne, 2014; H.H. Ehrsson, Weich, Weiskopf, Dolan, & Passingham, 2007; Graziano &
19 Cooke, 2006). Importantly, the questionnaire results – especially those from Experiment 2 –
20 together with the SCR results from Experiment 3A–C refute these previous concerns. The latter
21 experiments show that the threat-evoked SCR approach has sufficient spatial resolution to
22 differentiate between the illusion for two adjacently placed rubber hands, as is evident from the

significant differences in SCRs for the AS vs. AA conditions and SA vs. AA conditions. More importantly, by threatening the asynchronously stimulated rubber hand in the SA and AS conditions in Experiment 3A (right) and 3B (left), respectively, and comparing these SCRs to those evoked when the corresponding rubber hand was threatened in the SS condition, we could eliminate any possible “spreading effect” of the SCRs between the two rubber hands and thus reveal SCR increases that are specific to ownership of the two right rubber hands. Our questionnaire results from Experiment 2 are also very important in this respect because they demonstrate significantly greater affirmative ratings for the statements we designed to directly describe dual-hand ownership (Q6) and dual referral of touch (Q5) in the SS condition compared to the conditions in which only one rubber hand is stroked synchronously (AS, SA). Finally, our study has a larger sample size than previous studies, which reduces the risk of false positive and false negative findings. Based on the sample size calculation, the valid number of participants would be 34 (effect size = .5, two-tailed, significance level = .05, power = .8). Our sample size was 36 in Experiment 3A, 3B and 3C, which suggests that our statistical results should be reliable. Thus, based on the considerations discussed above, we conclude that a genuine supernumerary rubber hand illusion can be identified.

Multisensory processes that mediate the supernumerary hand illusion.

The classical rubber hand illusion is often explained within a theoretical framework of multisensory integration in which a coherent multisensory representation of one’s own arm is dynamically formed based on the available visual, tactile, proprioceptive and other sensory signals (H.H. Ehrsson, 2012, 2020; H. H. Ehrsson & Chancel, 2019; Fang et al., 2019; Kiltner

et al., 2015; Samad et al., 2015). According to such theories, multisensory perception involves determining which sensory signals to combine and which to not combine, i.e., solving the multisensory binding problem by inferring the causal structure responsible for generating the multisensory signals (causal inference) (Dokka, Park, Jansen, DeAngelis, & Angelaki, 2019; H. H. Ehrsson & Chancel, 2019; Fang et al., 2019; Kayser & Shams, 2015; Kording et al., 2007) and then combining the relevant sensory signals according to relative reliability (optimal integration) (Ernst & Banks, 2002; van Beers, Sittig, & Gon, 1999). These processes are dynamic and influenced both by prior information (previous experience and innate factors) and information derived from the afferent sensory signals in terms of temporal and spatial correlations and other forms of multisensory congruence patterns. From this perspective, the rubber hand illusion thus happens as a consequence of the brain inferring that the rubber hand is the most likely cause of the tactile, visual, proprioceptive and other sensory impressions one is experiencing, which leads to the fusion of the unisensory signals into a coherent multisensory perception of a single own hand (H.H. Ehrsson, 2012, 2020; H. H. Ehrsson & Chancel, 2019). However, how does the supernumerary rubber hand illusion fit in this multisensory framework of body ownership? We argue that supernumerary limb illusions can be elicited due to a striking flexibility in the causal inference process that allows for causal structures that involve “duplicated” limbs. Thus, tactile and proprioceptive (or other somatic) sensations from the hidden real hand are perceptually fused with the visual impressions of the two rubber hands being stroked, which leads to the sensation of both model hands as one’s own and duplication of the visuotactile stroking events. Given that supernumerary limbs constitute an unrealistic scenario that presumably violates strong prior knowledge about the human body plan and the

1 assumption that a specific body part can only be located at a single place at any given moment,
2 our findings underline the importance of the pattern analysis of afferent multisensory signals in
3 the causal inference of body ownership, a conclusion that has a bearing on theoretical work
4 regarding the importance of prior information and top-down constraints in the process of causal
5 inference in own body perception (H. H. Ehrsson & Chancel, 2019; Fang et al., 2019; Kilteni
6 et al., 2015; Samad et al., 2015) and multisensory causal inference more generally (Cao,
7 Summerfield, Park, Giordano, & Kayser, 2019; Dokka et al., 2019; Rohe, Ehlis, & Noppeney,
8 2019). The findings of illusory “arm duplication” are similar to the famous cross-modal illusion
9 often referred to as the “sound-induced flash illusion” (or “double flash illusion”), in which
10 participants mistakenly perceive one flash accompanied by multiple auditory beeps as multiple
11 flashes (Shams, Kamitani, & Shimojo, 2000; Shams, Ma, & Beierholm, 2005). In this
12 audiovisual illusion, participants experience an illusory duplication of visual flashes,
13 presumably due to a causal inference process in which two audiovisual events are inferred by
14 the brain. In the present study, the participants similarly perceived duplication of their right
15 hands and visuotactile stroke events on the model hands, which might indicate that the same
16 probabilistic principles determine multisensory perception of the external world and one’s
17 bodily self.

19 Possible neural mechanism

20 What could be the neuronal mechanism of the supernumerary hand illusion? In the rubber hand
21 illusion and similar paradigms, the sense of ownership of a single hand has been associated with
22 increases in BOLD activation (Brozzoli, Gentile, & Ehrsson, 2012; H. H. Ehrsson, Spence, &

1 Passingham, 2004; Gentile et al., 2013; Guterstam et al., 2013; Limanowski & Blankenburg,
2 2016) and high gamma activity (Guterstam et al., 2019) in the premotor cortex and the cortices
3 lining the intraparietal sulcus (IPS). Moreover, in the brains of macaque monkeys, these regions
4 contain neurons that integrate visual and somatosensory information from the upper arm (Fang
5 et al., 2019; Graziano, 1999; Graziano, Cooke, & Taylor, 2000), and activity in the premotor
6 cortex seems to reflect visuo-proprioceptive causal inference in hand ownership (H. H. Ehrsson
7 & Chancel, 2019; Fang et al., 2019). Therefore, we theorize that the supernumerary rubber
8 hands illusion can also be implemented by active neuronal populations within these
9 interconnected premotor-parietal areas. We theorize that single-cell recordings in nonhuman
10 primates and human fMRI studies employing multivariate pattern analysis should be able to
11 identify the specific neural signatures of the supernumerary rubber hand illusion in the premotor
12 cortex and (perhaps) the intraparietal cortex, and future neuroimaging investigations should
13 examine this hypothesis.

15 Possible midline bias and placement of rubber hands

16 One of the key ideas behind the paradigms developed in both Ehrsson (H. H. Ehrsson, 2009)
17 and Newport, Pearce & Preston (Newport et al., 2010) is that each of the two rubber hands
18 should be equally effective in inducing an ownership illusion [from Ehrsson (H. H. Ehrsson,
19 2009), “two equally probable locations of the right arm,” and from Newport, Pearce & Preston
20 (Newport et al., 2010), “were equidistant from the location of the real hand”]. These authors
21 assumed that the best way to achieve this illusion is to place the two artificial hands at an equal
22 distance from the real hand, which was the setup we used in Experiment 1 [the distance between

the two rubber hands were 10 cm in Ehrsson (H. H. Ehrsson, 2009), 12 cm in Newport, Pearce & Preston (Newport et al., 2010) and 11 cm in our manipulation]. However, in Experiment 1, we observed that the rubber hand closest to the midline received significantly ($p < 0.05$) stronger ownership ratings than the more laterally placed rubber hand when stroked synchronously and that the median ratings for the lateral (right) rubber hand ownership (Q4) and dual-hand ownership (Q6) in the SS condition were not clearly affirmative, although they were still significantly higher than the median ratings in the asynchronous condition (AA) (see Results and Figure 3D and F). Based on this observation and earlier reports that the classical rubber hand illusion is stronger for hands placed closer to the body midline than for more lateral locations (Newport et al., 2010; Preston, 2013; Zopf, Savage, & Williams, 2010), we made changes in the spatial arrangement of the hands in Experiment 2 to counteract this bias. Specifically, we changed the position of the real right hand so that it was placed more laterally, directly under the right rubber hand. This spatial manipulation worked well, as in Experiment 2, the median questionnaire ratings for the supernumerary rubber hand illusion (Q6) and ownership of the most laterally placed rubber hand (Q4) were affirmative (positive scores > 1). Moreover, the difference in general illusion strength between the left and right rubber hands [Midline Bias Index: $(S1 + S2) - (S3 + S4)$] was significantly ($p < 0.05$) smaller in Experiment 2 than in Experiment 1, providing evidence that our experimental manipulation was effective in reducing the effect of midline bias and achieving a better balance in probabilities of ownership between the two fake limbs (see Supplementary Figure 1 and Supplementary Results).

1 The mechanism behind the “midline bias” is still unclear and could relate to several factors.
2 One factor could be prior experience that one’s hand is more often in front of the trunk and head
3 than in more lateral locations. This prior knowledge could bias the multisensory integration
4 process of hand ownership in the former part of space. Indeed, we know that the relative
5 weightings of vision and proprioception in visuo-proprioceptive integration for hand location
6 differ in different parts of space (van Beers, Wolpert, & Haggard, 2002), and similarly, the
7 strength of the rubber hand illusion varies in different parts of space (Kalckert et al., 2019;
8 Preston, 2013). The midline bias could also reflect potential influence by head-centered
9 (Duhamel, Colby, & Goldberg, 1998) and trunk-centered (Hyvarinen, 1981) reference frames
10 in addition to multisensory integration in arm-centered coordinates (Brozzoli et al., 2012;
11 Graziano, Hu, & Gross, 1997). Finally, it is also relevant to consider the degree of anatomical-
12 postural congruence between the rubber hand and the participant’s real arm and shoulder: the
13 relative postural congruence between the real shoulder and upper arm and the “extrapolated”
14 position of the unseen illusory upper arm that is connected to the seen rubber hand changed
15 between Experiments 1 and 2. When the real hand was placed directly under the laterally placed
16 rubber hand in Experiment 2, greater postural congruence was achieved in terms of shoulder
17 and upper-arm postures for the lateral rubber hand than in Experiment 1. Our data cannot
18 differentiate between these different explanations for the spatial “midline” bias, and further
19 studies are needed to unveil the factors that contribute to variations in rubber hand illusion
20 strength in different parts of space.

21

Conclusion

In summary, the present study presents conclusive evidence that the supernumerary rubber hand illusion does exist and provides new information about the optimal setup for its successful induction. Importantly, our results disambiguate ownership of two right rubber hands from ownership of a single right rubber hand and demonstrate that a subjectively experienced supernumerary limb illusion can arise beyond the perceptual experiences associated with the classical rubber hand illusion. This finding is important because it solves the ongoing debate in the literature and has important theoretical implications for body representation research and work on causal inference in multisensory perception. Additionally, the results bear on current studies of supernumerary robotic limbs and advanced prostheses for amputees and paralyzed individuals because they reveal the conditions under which it could be possible to design such a system with ownership of the extra artificial limb.

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Supplementary materials

Supplementary Figure

Supplementary Figure 1. Comparisons midline bias index in Experiments 1 and 2. Body midline bias index based on the questionnaire data $[(S1 + S2) - (S3 + S4)]$ displayed per condition (mean $\pm$ SE) in Experiments 1 and 2. We observed significant differences in midline bias index between experiments in the SS, AS, and AA conditions but not in the SA condition. Asterisks indicate a significant difference between conditions (* $p < .05$; n.s., not significant).

Supplementary Results

Midline bias index: comparing the questionnaire ratings across Experiments 1 and 2

We theorized that the change in real hand position between the experiments (from a more lateral position in Experiment 1 to closer to the body midline in Experiment 2) had significant effects on the supernumerary hand illusion. To test for a significant effect of the hand position manipulation with respect to the body midline, we computed a “midline bias index” (MBI) based on our questionnaire data $[(S1 + S2) - (S3 + S4)]$. S1+ S2 equals the general illusion feeling (tactile feeling + ownership feeling) on the left rubber hand, while S3+ S4 refers to the feeling on the right rubber hand. A positive MBI value suggested that participants had a stronger illusion for the left rubber hand than for the right rubber hand, and a negative MBI value indicated the opposite, a relatively stronger illusion for the right rubber hand.

In this post hoc analysis we directly compared the MBI between Experiments 1 and 2 for the four main conditions (Supplementary Figure 1). We applied the Mann-Whitney U-test to the MBI ($N = 80$). We found a significantly greater MBI in experiment 1 than in experiment 2 in our main SS condition ($N = 80, W = 1006, p = .043, r = .227$) as well as in the AS condition ($N = 80, W = 1018, p = .036, r = .235$) and the AA condition ($N = 80, W = 995, p = .044, r = .228$). No significant difference was found in MBI between the two experiments in the SA condition ($N = 80, W = 865, p = .532, r = .070$). Collectively, these results suggest that our manipulation

- 1 of hand position towards the midline in Experiment 2 successfully reduced the midline bias in
- 2 Experiment 1 that was evident in the data from the SS, AS and AA conditions.
- 3