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Original Reports

Rubber Hand Illusion Increases Pain Caused by Electric Stimuli

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Abstract: The rubber hand illusion (RHI) has been shown to alter the experience of pain, although studies have yielded inconsistent results. In this experiment we tested the influence of the RHI on the intensity of pain caused by electric stimuli. Electric stimuli were delivered to participants' experimental and control hands before RHI induction (control condition) and afterward (experimental condition), in a procedure that was double-blind with respect to location and strength of noxious stimulation. All hands were covered during the stimulation to avoid the analgesic effect of seeing one's own body part. The perceived location of the hand and of pain were measured after each trial in the experimental condition. The results showed that noxious stimuli were experienced as more painful on the hand under the illusion. In addition, in the experimental condition the perceived location of noxious stimulation applied to the experimental hand drifted toward the rubber hand. Our data suggest that the link between bodily illusions and pain could be modulated by uncertainty about location of pain and the affected body part. Future studies should aim to determine which aspects of altered body awareness lead to pain sensitization.

***Perspective:* We show that the RHI can change the perceived location of pain and increase pain ratings caused by electric stimuli. Our data suggest that the link between bodily illusions and pain could be modulated by uncertainty about location of pain and the affected body part.**

Key words: *Rubber hand illusion, pain, body awareness, expectations, electric stimuli.*

Pain has the important biological function of preparing an organism to defend itself from potentially dangerous stimuli, or to protect tissue that has already been damaged.[26] However, studies show that pain experience is not always directly connected to the state of tissues, but can be modulated by other somatic, psychological, and even social factors.[29] In this article we focus on body awareness, which has been shown to influence the intensity or threshold of pain,[15,18,24,35,50] experienced location of pain,[50] discomfort,[47] and also physiological responses to noxious stimuli.[43,44,46]

The relationship between different aspects of body awareness and pain has been observed in a number of neuropsychological disorders. For example, it has been suggested that patients suffering complex regional pain syndrome might also have altered body awareness[14,23,25,40]: they perceive a painful limb as being enlarged[28] and a reduction in the perceived size of a limb decreases pain.[31] It has also been shown that patients suffering long-term disruptions of body awareness, such as somatoparaphrenia (delusion that one's own limb belongs to somebody else) and body integrity identity disorder (desire to have one or more limbs amputated) show decreased anticipatory skin conductance response (SCR) to noxious stimulation approaching affected areas.[46] At the same time, in patients with body integrity identity disorder, noxious stimuli contacting an unwanted limb induced a stronger SCR compared with the healthy limb.[46]

The influence of body awareness on pain experience in healthy participants is often experimentally studied by inducing bodily illusions.[5] During such experiments,

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participants receive conflicting sensory information about their body, for example, they are being touched on their back while watching a mannequin or virtual avatar being synchronously touched on its back. This procedure usually makes participants "feel" the touch at the seen location and experience the avatar's body as their own.[17,24] It has been shown that experiencing a sense of ownership over an alien body or body part decreases the intensity of pain and increases pain thresholds in a participant's real body. For example, experiencing virtual body ownership elevates the pressure pain threshold[17] and feeling as if a virtual hand were one's own increases thermal pain threshold.[17,24] Gaining the ownership over an avatar's body has also been shown to reduce SCR to painful stimuli applied to the participant's physical body.[45] Another experimental manipulation called "out-of-body experience" has been shown to decrease chronic pain[34] and to reduce SCR when a participant's body was threatened.[16]

The most common method for experimentally manipulating the sense of ownership is the rubber hand illusion (RHI).[6] In a typical RHI protocol, a participant's experimental hand is hidden from view and stroked synchronously with a visible rubber hand. As a result, participants often report that they feel ownership over the rubber hand and experience tactile sensations as originating from this hand.[2,6] RHI-induced alterations in bodily awareness are typically probed by first-person reports and behavioral measures. The former is tested with a questionnaire[6] and the latter by quantifying changes in experienced limb location after the RHI induction (so-called proprioceptive drift,[49] and proprioceptive localization error[20]).

Studies using physiological measures have shown that during the illusion participants can temporarily gain sense of ownership over the rubber hand, analogous to virtual/manikin body ownership under full body illusion. It has been also suggested that during the illusion, the real hand is to some extent disowned.[22,30,48] For example, participants might report a feeling of ownership of the rubber hand as well as disownership of their own hand.[18,50] Studies have also reported a limb-specific temperature decrease and a slower processing of tactile information in the affected hand.[13,20,31] Moreover, it has been shown that histamine reactivity (a response observed in autoimmune disorders) is higher in the hand under the illusion.[3]

How does the RHI affect the experience of pain? A few studies have investigated this issue, yielding inconsistent results. Mohan and colleagues[27] did not find differences in pain threshold, intensity of pain, or thermoception between the experimental (synchronous stroking) and control (asynchronous stroking) conditions. Valenzuela-Moguillansky and colleagues[50] ran 2 experiments with 2 different types of control condition and obtained contrasting results. Pain ratings were higher under the RHI compared with a control condition in which asynchronous stroking was used, but lower when no stroking was applied. A few other studies showed that the RHI increases pain threshold and decreases discomfort. Hegedüs and colleagues[18] observed a higher thermal pain threshold under the illusion compared with the control condition (asynchronous stroking). Similarly, Giummarra and colleagues[15] used a cold pressor test and reported increased pain tolerance after the RHI compared with pre-RHI, but no change in pain intensity ratings. Our previous study[47] showed that participants after the RHI had increased tolerance for discomfort caused by cold stimulation (compared with asynchronous stroking).

It is important to note that the methodologies of the aforementioned experiments differed in many ways. First, different experimental setups were used (eg, type of control conditions, stroking session duration, etc) that may have resulted in a difference in relative degree of real hand disownership and rubber hand ownership.[50] Moreover, the experiments differed in the way the strength of the illusion was measured. For example, behavioral measures (eg, proprioceptive drift) were sometimes collected directly after a stroking session and before noxious stimulation,[15,18] but at other times they were completely omitted and only subjective reports were taken at the end of blocks or the whole experiment.[27,50] Therefore, it is not clear whether participants experienced the illusion during all trials of noxious stimulation. Third, in some experiments participants saw the rubber hand and the stimuli at the moment of stimulation,[18,27,50] whereas in some the rubber hand remained hidden.[47] It has been shown that seeing one's own body part[21] or body part experienced as one's own[24,33] has an analgesic effect. Therefore, assuming that participants experience the rubber hand as their own, they "feel" the touch and pain as being located on this hand.[2,6,11,50] When a participant sees noxious stimuli being applied to this "own" rubber hand, the pain could be experienced as less intense compared with the control condition (no ownership over the rubber hand).

In this article, we present a study aiming to further investigate the effect of the RHI on pain experience. We introduced several methodological changes to control for the aforementioned possible sources of the differences of results. First, we compared pain intensity ratings before (control condition) and after the illusion (experimental condition), and, although we induced the RHI only for 1 hand, we applied painful stimuli to both hands (experimental and control hand). Typically, RHI experiments involve control conditions in which a participant's hand and a rubber hand are stroked asynchronously. However, it has been shown that asynchronous stroking might also induce the illusion (eg, Valenzuela-Moguillansky et al[50]). Second, we controlled the successful induction of illusion and its strength by measuring proprioceptive localization error: the mismatch between real and perceived position of the hand[20] after each stroking session. We also included 7 additional questionnaire items addressing the sense of disownership of the experimental hand. Third, to avoid analgesic effects of seeing one's own body part,[21] all hands (2 real and 1 rubber) were hidden during the noxious stimulation. There were a few other important changes compared with the previous studies. Instead of thermal stimulation we used electric stimuli; to our knowledge this has not yet been used in

RHI experiments, although it is commonly used in pain research.[34] We applied a double-blind procedure in reference to the strength and location of noxious stimuli, therefore neither the participant nor the experimenter collecting the pain ratings knew whether electric stimulus would be applied on the left or on the right hand and how strong it would be. Finally, we measured perceived pain location after each noxious stimulation to find out whether the experienced displacement of the real hand might alter experienced pain location. To our knowledge, the degree to which participants mislocate their experimental hand has not been analyzed in relation to pain experience.[18,50]

On the basis of previous results that mostly suggest an analgesic effect of body or body part disownership, we hypothesized that inducing the RHI would reduce the intensity of pain experience in the hand under the RHI. We also expected that changes in experienced location of a real hand and perceived locus of pain would negatively correlate with pain experienced in the experimental hand.

Methods

Participants

After approval by the Ethics Committee in the Institute of Psychology, 22 participants (as in similar studies on RHI and pain, eg, Mohan et al,[27] and Valenzuela-Moguillansky et al[50]) took part in the experiment. Participants were healthy, right-handed volunteers. There were 14 women and 8 men, aged 19 to 24 (mean = 21.52, SD = 1.34) years. Participants were naive to the purpose of the experiment and some parts of the procedure: they were informed that the study concerned the effect of perceiving body parts on pain experience. They all gave written consent and were informed that they could withdraw from the study at any moment.

Materials

Rubber Hand Experimental Setup

We used a natural-looking hand prosthesis (male and female) and a wooden framework (78 × 37 × 23 cm) with 2 compartments (Fig 1). The participant's left hand and the rubber hand were placed in the left compartment, which was larger and open at the top (58 × 37 cm), whereas the right hand was inserted into the right compartment, which was smaller and covered (20 × 37 cm). The framework cover was made of cardboard (120 × 52 cm) and was longer than the framework to minimize the risk of participants using it to estimate the position of their hands. Three electrodes were attached to the bottom of the framework: 1 in the right compartment (for the right hand), and 2 in the left one (for the left and the rubber hand).

Pain Stimulation

Electric stimuli were delivered using the Constant Current High Voltage Stimulator (model DS7AH; Digitimer, Welwyn Garden City, England) through 2 durable stain-

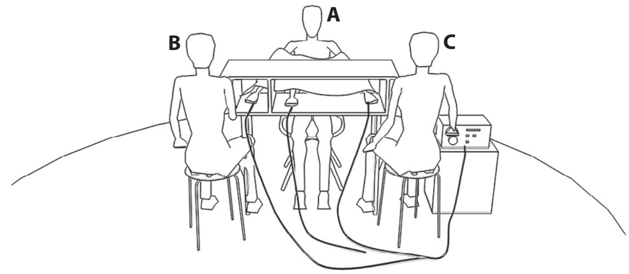

Figure 1. Experimental setup during noxious stimulation in experimental condition. (**A**) Participant sits with both hands and a rubber hand placed in the wooden framework and covered from view. All hands are placed on electrodes mounted to the bottom of the framework. (**B**) Experimenter 1 induces the illusion and collects the measures of hand and pain location as well as pain intensity. (**C**) Experimenter 2 delivers painful stimuli. The strength of the stimuli and the hand on which it is delivered is not known to experimenter 1.

less steel disk electrodes 8 mm in diameter with 30-mm spacing. Each stimulus lasted 200 μs. We used Nuprep (Weaver) conductive gel.

RHI Questionnaire

The questionnaire was created by Botvinick and Cohen[6] to measure subjective RHI strength. It includes 9 items with a scale ranging from "disagree strongly" (−3) to "agree strongly" (+3). We added 6 statements to explore the experience of real hand disownership. The statements related to the feeling of the right hand disappearing, going numb, or not belonging to a participant. To avoid suggestions about expected experience, the questions referred to the experimental as well as the control hand. The final question explored whether participants felt like having more or less than 2 hands, and if so, to specify which (right or left) hand was missing or added.

Pain measures. We used two 11-point numeric rating scales to assess the intensity of pain and discomfort caused by electrical stimulation.[4,19] The pain experience scale ranged from 0 = "no pain" to 10 = "worst imaginable pain" with a yellow to red color gradient from left to right. The discomfort scale ranged from 0 = no discomfort to 10 = maximum discomfort ("I don't want any more").

Procedure

General Information

Participants were tested individually in the laboratory. They were told that they would receive repeated harmless electrical stimuli and were asked to rate pain intensity and discomfort after each stimulus application. They were also informed that they could withdraw from participation at any moment. The experimental session lasted approximately 2 hours. We implemented a within-subjects design of pain stimulation with a randomized order of pain location and strength. Two experimenters conducted each session in the study: one induced the illusion and collected pain and discomfort ratings, whereas the other delivered painful stimuli (Fig 1).

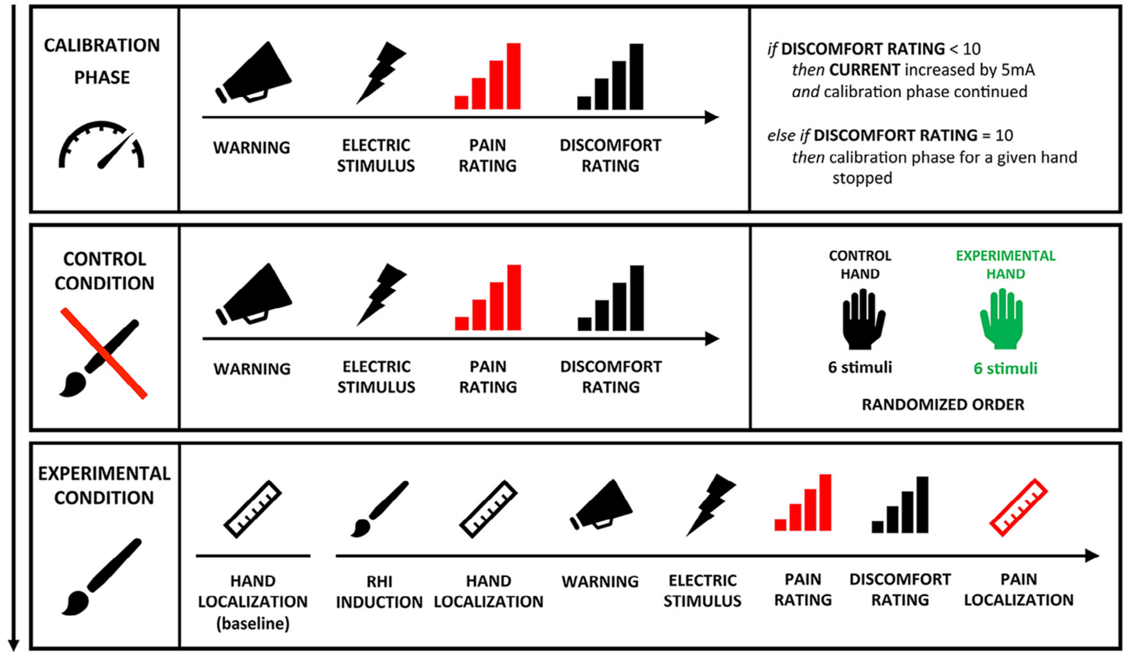

Figure 2. Outline of the procedure. In the first (calibration) phase, the strength of the stimuli associated with maximal discomfort was estimated for each hand separately. In the control phase, noxious stimuli were applied to both hands in a random order. In the experimental condition, the RHI was induced for the right (experimental) hand at the beginning of each trial and followed by noxious stimulation applied randomly to one of the participant's hands.

The experiment consisted of 3 parts. First, in the calibration phase, we estimated the value of electric stimuli (in milliamps) at which participants felt maximum discomfort (10 on the discomfort scale). In the 2 subsequent parts a series of electrical stimuli was applied to both hands, first without RHI induction (control condition) and then with RHI induction (experimental condition). The procedure was double-blind with respect to the location and exact strength of noxious stimuli. The middle fingers of the left and right hand were stimulated during the calibration phase; however, during the control and experimental conditions, stimulus was delivered to index fingers to avoid habituation. During all stimulation trials, the hands were hidden from participants' view. The phases of the procedure are presented in Fig 2.

Calibration Phase

Because of individual differences in pain sensitivity, the experiment started with a calibration session to establish the highest strength of stimuli that was still tolerable for each participant, rather than equivalent intensity of stimulation.[51] The procedure was applied separately for right and left hand, allowing for a different strength for each hand. Participants were informed that they would receive a series of stimuli of increasing intensity until they reported maximum discomfort (10 on the discomfort scale—"I don't want any more"). We explicitly told participants that we did not expect them to withstand all levels of pain up to the maximum (10 on the pain scale—"worst imaginable pain").

Participants placed their right and left hand middle fingers on the electrodes in the left and right compartments of the box with the center of their body located between the leftmost electrode and the right electrode designated to the rubber hand. The experimenter then applied a series of stimuli of ascending intensity, starting with 1 mA and increasing the current in steps of 5 mA. Participants were verbally warned before stimulus application and saw the experimenter pressing the button. After each stimulus, the participant's pain and discomfort were assessed on the scales. Stimuli were delivered on each hand until maximum discomfort was reported. During the calibration phase, we identified, for each hand separately, stimuli values (in milliamps) corresponding to the maximum discomfort rating (10) and the previous, lower value. Therefore, after this phase for each participant we determined 4 current (milliamp) values corresponding to: 1) discomfort rating of 10 (the highest discomfort) for the experimental hand, 2) preceding discomfort rating (value for the highest discomfort minus 5 mA) for the experimental hand, 3) discomfort rating of 10 for the control hand, and 4) preceding value for the control hand.

Control Condition

During control and experimental conditions, we used an individually adjusted stimuli strength corresponding to current values at which discomfort ratings of 9 and 10 were given during the calibration phase by each participant for each hand. Participants placed both index fingers onto the electrodes and the framework was covered during this part of the experiment. The stimuli were applied 6 times (3 highest and 3 next-to-highest discomfort values) to each hand. The order of hand and the strength of the stimulation were randomized and neither the participant nor the experimenter collecting pain

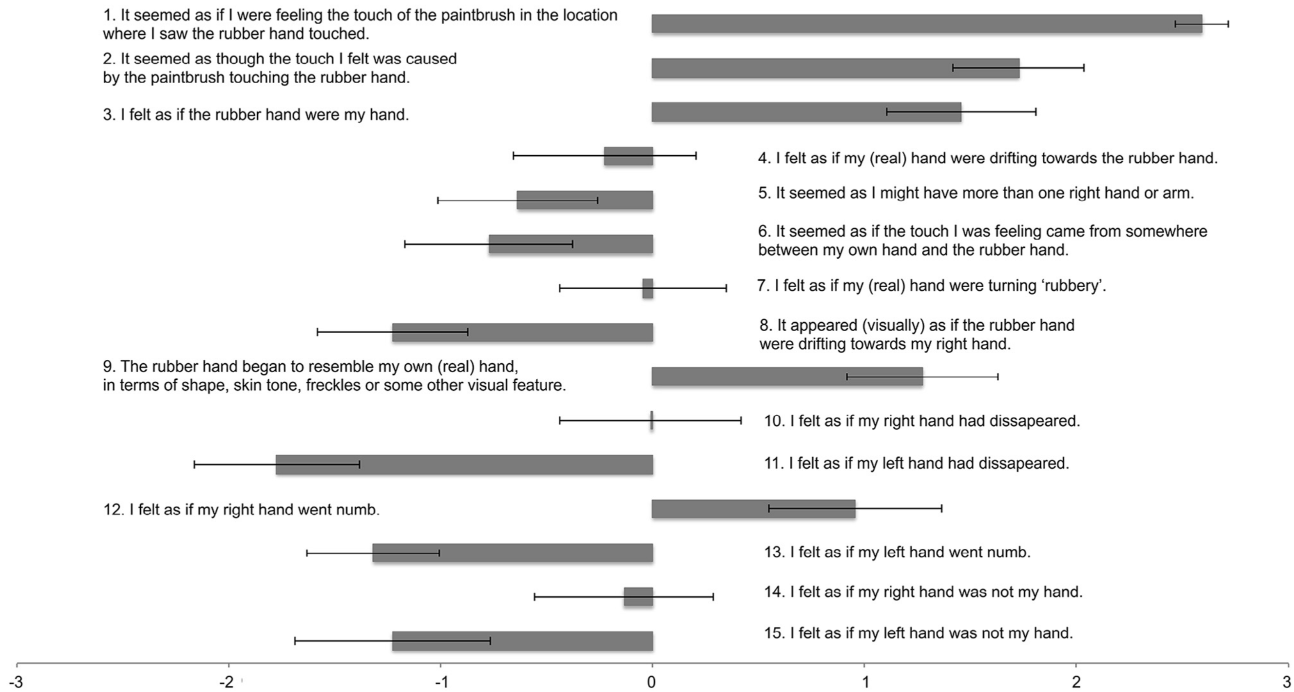

Figure 3. Average agreement for each questionnaire statement.

ratings knew about them before the stimulus was delivered. After each stimulus application, participants were asked to rate their pain and discomfort, just as they did during the calibration phase.

Experimental Condition

In this phase, participants were again given 6 electrical stimuli in a randomized order on the right and 6 stimuli on the left hand, but this time each stimulus application was preceded by the RHI induction. The right rubber hand and the real left (control) hand were placed in the left compartment in natural-looking positions, whereas the real right hand (experimental hand) was hidden in the right compartment. The center of the participant's body was placed between the left hand and the rubber hand. Participants were asked to put their index fingers on the electrodes. There was 16 cm between the index fingers of the rubber hand and the right hand and 40 cm between the rubber hand and left hand.

At the beginning of the experimental condition, we informed participants that in this session, apart from experiencing electric stimuli, they would be stroked on the right, hidden hand while watching the rubber hand being stroked at the same time. First, we measured the perceived position of the participant's right hand. The experimenter covered the box, placed the ruler randomly on the cover, and asked participants to estimate the position of their right middle finger. The box cover was removed and the experimental trials followed, each starting with the RHI induction. Participants were asked to look at the rubber hand and to not move their real hands. Two small brushes were used to synchronously stroke the fingers and dorsum of the participant's right hand and rubber hand in accordance with a previously developed protocol. The position and tempo of stroking were delivered to the experimenter's ears through headphones. At the end of each stroking session, the perceived position of the right hand was measured. Participants were asked to close their eyes and the whole box was covered. When participants opened their eyes, they were asked to indicate the position of their right middle finger with the help of a ruler placed on the cover in a random position. Afterward, an electric stimulus was delivered to 1 of the (still covered) hands. Participants were asked to rate pain and discomfort. Then, they were asked to locate the pain, again using the ruler placed on the box cover.

This procedure was repeated 12 times. There were 2 experimental blocks of 6 trials each with a short break in between. The first stroking in each block lasted for 4 minutes to establish a solid illusion; in the subsequent trials, stroking was applied for 2 minutes.[18,27,50]

Questionnaires

At the end of the experiment, participants were asked to complete the questionnaire measuring subjective RHI strength.

Data Analysis

Measures

Subjective experience related to the illusion was measured using the questionnaire (Fig 3). We assumed that affirmative answers to statements 1, 2, 3, and 9 (the mean over 1,[8,36]) indicated successful induction of the illusion (rubber hand ownership). The sense of disownership of the experimental and control hand was measured using the items 10 to 15 of the questionnaire. The objective measures of illusion included hand localization error and proprioceptive drift. Hand localization error was measured as the distance between the indicated position of the right hand middle finger and the real position of the finger. Proprioceptive drift was calculated as the mean difference between the position of the middle finger reported at the beginning of the experimental condition (before RHI) and positions at the end of illusion induction in each trial. Pain localization error was measured as the difference between the real position of the middle finger of the hand to which the electrical stimulation was delivered and the reported location of experienced pain. Pain intensity was measured using the numeric rating scale described in the *Materials* section.

Analysis Plan

The data were analyzed using standard statistical methods in IBM SPSS Statistics version 24 software. We set α level at 5%. First, to understand whether and how participants were affected by induction of the RHI, we analyzed the data concerning subjective and objective measures of the RHI. To estimate whether the illusion resulted in a sense of experimental hand disownership, we compared average agreement with statements that refer to the experimental and the control hand (items 10–15) using the Wilcoxon test. We ran Pearson correlations between questionnaire statements of interest (1, 2, 3, and 9–15); localization error and proprioceptive drift. We decided that participants who reported that they did not experience the illusion at all (the mean agreement with statements 1, 2, 3, and 9 $\leq$1) were excluded from further analyses. Then we compared pain localization error between the experimental and control hand with the Student t-test and ran Pearson correlation to estimate the relation between pain localization error and hand localization error.

Our main analysis, which was intended to test the effect of the illusion on pain ratings, was a repeated measure analysis of variance with 2 factors: hand (experimental/control) and condition (experimental/control). If an interaction was detected, planned comparisons between pain ratings in the control and experimental conditions for each hand would be conducted. Additionally we ran Pearson correlations not only between pain ratings and subjective and objective measures of RHI, but also between pain ratings and pain localization error.

Results

RHI—Subjective Measures

The subjective experience accompanying the illusion was not the same for all participants. All but 3 of them agreed with statement 3 ("I felt as if the rubber hand was my hand"), but they gave very diverse answers when asked how many hands they experienced during the experimental condition and at what location (question 10). Six participants declared that they felt as if they had 2 right hands, 1 participant reported having just 1 hand between the right hand and the rubber hand, and only 2 participants declared that they felt as if their right hand had disappeared. Finally, 3 participants felt as if their left hand had disappeared (1 of them experienced having 2 right hands instead).

To find out whether the RHI induction was successful, we averaged the answers to questionnaire items 1, 2, 3, and 9 (see Fig 2), which differentiate between control and experimental conditions in RHI studies (see eg, Botvinick and Cohen[6] and Siedlecka et al[47]). The average mean for those 4 items was 1.76 (SD = .89). One participant reported not experiencing the illusion at all (average score on questionnaire items 1, 2, 3, and 9 were below zero) and was excluded from further analysis.

To estimate subjective disownership of the experimental hand, we compared the average agreement with the questions concerning the loss of the experimental and control hands (questions 10–15; see Fig 3). The Wilcoxon test revealed that participants agreed more often with the statement that their right (experimental) hand had disappeared than with the statement that their left hand had disappeared (questions 10 and 11, $Z = 2.76$, $P = .006$), and that their right hand, rather than left hand, had gone numb (questions 12 and 13, $Z = 3.47$, $P = .001$). We found no statistically significant difference between agreement to the questions "I felt as if my right hand was not my hand" and "I felt as if my left hand was not my hand" (questions 14 and 15, $Z = 1.67$, $P = .09$).

Perceived Location of Experimental Hand

Localization error, which before the RHI equaled .55 cm (SD = 3.26), during the RHI was on average 3.72 cm (SD = 5.67). The proprioceptive drift was 3.18 cm (SD = 5.67), which was significantly different from 0 ($t = 2.63$, $P = .02$). The positive drift value means that on average participants rated position of their experimental hand as having drifted toward the rubber hand.

We did not detect correlation between average localization error and proprioceptive drift with any questionnaire item concerning rubber hand ownership or real hand disownership, apart from question 10: "I felt as if my right hand had disappeared" (localization error: $r = .45$, $P < .04$; proprioceptive drift: $r = .53$, $P = .01$).

Perceived Location of Pain

Pain localization error was higher for the experimental (mean = 3.55, SD = 5.57) than for the control hand (mean = .3, SD = 3.47) and this difference was statistically significant ($t_{21} = (-2.59$, $P = .02$, $d = .7$). The magnitude of pain localization error for the experimental hand correlated with localization error for this hand ($r = .95$; $P < .001$). In trials in which the control hand was stimulated, we did not find any correlation between localization error of the experimental hand and pain localization error ($r = .18$, $P = .43$).

The Influence of the RHI on Experienced Pain

The average strength of electric stimuli in the control and experimental conditions were mean = 71.77 mA

Table 1. **The Average Stimulus Strength and Pain Ratings for Each Hand and Each Condition**

	Mean Stimulus Strength (SD), mA	Mean Pain Rating (SD)	
		Control Condition	Experimental Condition
Control hand	56.42 (37.62)	5.70 (1.32)	5.87 (1.47)
Experimental hand	56.13 (38.29)	5.57 (1.29)	6.21 (1.37)

(SD = 66.5) for the left hand and mean = 66.75 mA (SD = 52.4) for the right hand. Exceptionally high stimulus values (above 1 SD on each hand: over 180 mA) were applied to the 2 participants who either had extremely high discomfort thresholds, or were not holding their fingers correctly on the electrodes. Their data were excluded from further analysis. The average strength of electric stimulus applied in the control and experimental conditions (after removing extreme cases) and the average pain ratings in each condition for the remaining participants are shown in Table 1.

Analysis of variance showed no main effect of Hand ($F_{1,18}$ = 3.6, P = .07, η^2 = .17), nor Condition ($F_{1,18}$ = .31, *P* = .58, η^2 = .02). However, the test showed a statistically significant interaction between the 2 variables ($F_{1,18}$ = 4.82, *P* = .04, η^2 = .21). Contrast analysis revealed that participants reported stronger pain on the experimental hand during the RHI than in the control condition ($F_{1,18}$ = 8.94, *P* = .008). We detected no such difference for the control hand ($F_{1,18}$ = .40, *P* = .53). The results are presented in Fig 4.

Additionally, for exploratory purposes, we used behavioral criterion of RHI strength and repeated the analysis after excluding the data of 5 participants whose proprioceptive drift was below zero (localization error smaller after RHI induction than in the pretest). The results were consistent with the previous analysis. Neither the effect of Hand on pain rating ($F_{1,14}$ = 1.46, *P* = .25, η^2 = .09), nor Condition ($F_{1,14}$ = .05, *P* = .83, η^2 = .003) were statistically significant. The test revealed a statistically significant interaction between Hand and Condition ($F_{1,14}$ = 7.08, *P* = .02, η^2 = .34). Contrast analysis showed that participants reported stronger pain on the experimental hand in the experimental condition than in the control condition ($F_{1,14}$ = 6.28, *P* = .02). We found no significant difference for the control hand ($F_{1,14}$ = .001, *P* = .98).

We also analyzed correlations between subjective and objective measures of the RHI and reported pain intensity. We did not find a relation between subjective report of rubber hand ownership (item 3: "I felt as if the rubber hand were my hand" and pain intensity (r = –.04, *P* = .87), disownership of the experimental hand (item 10: "I felt as if my right hand had disappeared") or pain intensity: (r = –.16, *P* = .49). Similarly, we found neither correlation between localization error of the experimental hand and pain intensity on this hand (r = –.17, *P* = .47), nor between pain localization error and pain intensity on the experimental hand (r = –.15, *P* = .53).

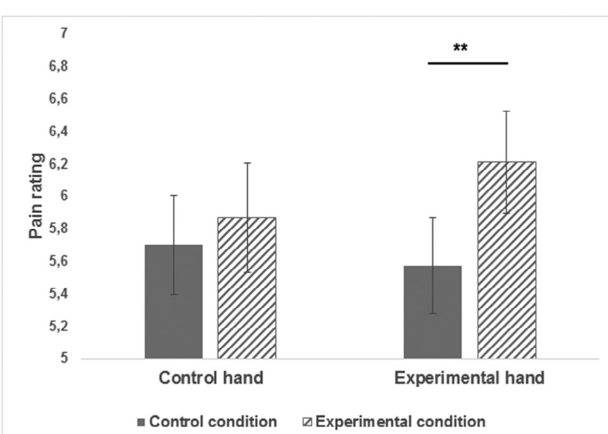

Figure 4. Reported intensity of pain felt on the right (experimental) and left (control) hand during experimental (with RHI) and control conditions. (** P < .01)

Discussion

In the experiment, we tested the effect of the RHI on the intensity of pain caused by electrical stimuli. We expected that the synchronous visuotactile stimulation would decrease experienced pain in the experimental hand. We also hypothesized that the reduction of pain in the experimental hand would be related to the magnitude of pain localization error and hand localization error. The results did not confirm our hypotheses. Although participants under the RHI perceived their experimental hand and the locus of pain as being shifted toward the rubber hand, they reported increased pain in their experimental hand.

Our hypotheses were on the basis of the results of previous studies suggesting that pain is reduced when the location of noxious stimulation is attributed to a body part that is not felt as one's own.[17,18,50] To our knowledge, only 1 experiment on the RHI reported an increase in pain experience under the illusion (Valenzuela-Moguillansky et al,[50] experiment 2). The authors attributed this result to a relatively high sense of ownership over the rubber hand during the illusion compared with the control condition (no stroking). They suggested that experienced pain intensity is not necessarily reduced when painful stimulation is applied to a rubber hand that the participant perceives as his or her own. Among the possible causes of the increase in pain, the authors listed interaction between the illusion and other factors such as anxiety and control over pain related to experimental setup (eg, ability to withdraw from the painful stimulation).

This line of reasoning only partially helps to explain our results. Although we cannot compare it directly, in our experiment, as in the experiment of Valenzuela-Moguillansky and colleagues[50] (experiment 2), participants' feeling of ownership over the rubber hand seemed stronger than the disownership of their experimental hand (ie, the average agreement to statements "I felt as if my right hand was not my hand" and "I felt as if my right hand had disappeared" was below zero). Therefore, in both experiments, participants expected that pain could occur in the rubber hand that was perceived as their own. However, because participants in our experiment did not know which hand (control or experimental) would be simulated next, they could expect to feel pain either in the location of the control hand or the rubber hand. Additionally, because no visual cues about the location of the rubber hand were available during noxious stimulation, the stimuli applied to the experimental hand caused pain that was experienced neither in the experimental nor in the rubber hand, but "between hands." This mislocation of pain possibly resulted from a compromise between the real and one of the expected locations of painful stimulus. We think that the illusion-evoked incorrect expectations and increased uncertainty about the location of stimulation could increase the intensity of experienced pain.

Expectations considering the occurrence of pain and its location are linked to the experienced body boundaries. For example, it has been shown that bodily awareness affects the way that an incoming threat is processed. Riemer and colleagues,[42] in a threat-of-shock paradigm, investigated whether the RHI could modulate defense response to the expected noxious stimulation applied to the experimental hand. They reported that participants who experienced a stronger feeling of rubber hand ownership also showed stronger anticipatory response measured according to startle reflexes (*orbicularis oculi* muscle) and SCR when expecting electric stimuli. It is likely that the elevated defense response to the threat of a hidden experimental hand was caused by a temporal change of body boundaries together with uncertainty about the location of incoming threat (there was no noxious stimulus attached or approaching the visible rubber hand). Patients suffering long-term disruptions of body awareness such as somatoparaphrenia and body integrity identity disorder show a reduced SCR to noxious stimuli approaching affected, disowned areas[43,46] and increased SCR to the noxious stimulation in these areas.[7,46] This suggests that stimulation outside of experienced body boundaries is unexpected and not preceded by the defense response. There are data that suggest that uncertainty about the occurrence of pain and unexpected stimulation induces stronger pain sensation.[9,10,38,39] This was possible in our experiment when participants expected electric stimulus to occur either on the control hand or rubber hand (or somewhere between the rubber hand and experimental hand where they localized their right hand). When the electric stimulus was delivered to the experimental hand, it was surprising and therefore could be experienced as more intense than the noxious stimulation applied to the control hand. However, it is important to note that although participants generally mislocated their experimental hand and experienced pain as being between hands, we did not detect the relation between pain ratings and pain localization errors nor between pain ratings and hand localization error. Similarly, the degree of rubber hand ownership and real hand disownership did not vary with reported pain intensity. Therefore a possible explanation for the increase of pain during the RHI is that the synchronous visuotactile stimulation induced general uncertainty about the location of the experimental hand and perceived pain, which in turn strengthened the pain experience.

It is important to discuss the differences between our experiment and studies reporting the analgesic effect of bodily illusions. First, contrary to other studies,[18,27,50] participants did not see the rubber hand and the noxious stimuli at the moment of stimulation. Therefore, we should expect neither the analgesic effect of seeing one's own body part,[21] nor the visual capture of pain that occurs when participants have clear visual cues about the location of the painful stimulus.[27] It has been shown that pain can be referred to and felt on an alien limb (during the illusion[11]; and in patients[37]). In our experiment all hands were covered during painful stimulation, therefore no visual cues about the location of the rubber hand or noxious stimulation were available. This not only removed the possibility of an analgesic effect of seeing one's own body part, but could have also strengthened the uncertainty about the locations of the embodied rubber hand and pain delivered to this hand.

Second, to our knowledge, no previous study on pain during RHI has used electric stimulation. It has been shown that electrical stimuli are processed differently to other noxious stimuli. For example, the electroencephalogram (EEG) recorded from the somatosensory cortex during the application of noxious mechanical or thermal stimuli shows different cortical activation than with electrical noxious stimuli. An electrical stimulus indiscriminately activates nociceptive as well as non-nociceptive receptors, which results in greater activation of primary somatosensory cortex neurons.[32] Thermal and electrical stimuli also activate different fibers.[12] Moreover, electrical nerve stimulation evokes a rare sensation and, unlike other methods that typically stimulate nerve receptors, electrical stimuli bypass the receptor and stimulate the primary afferent axon. From a subjective perspective, electric stimuli tend to be perceived as more unpleasant than heat stimuli[41] and often result in stimulus-related fear.[1] However, despite these differences it is not clear why electric stimulation would interact with body awareness differently than with other methods of stimulation. One possible reason might be that the electric stimulation influenced muscle tension and thus could suddenly break the illusion.

Third, the difference between data from studies on pain during bodily illusions may have emerged as a consequence of using different pain measurements. Although intensity ratings are considered subjective or explicit measures, estimating pain thresholds and collecting physiological responses are thought to be implicit ways of assessing pain.[45] In RHI experiments, a decrease in pain threshold and increase in pain tolerance has been consistently observed,[15,18,24,47] whereas the data on intensity ratings are less coherent.[50] However, studies on illusions inducing the sense of ownership over virtual body have been shown to reduce SCR to noxious stimuli while leaving subjective ratings unaffected.[44,45] This dissociation opens a very interesting research question about the aspects of bodily illusions that differently affect implicit pain measures and judgements about pain experience.

Finally, we should discuss the limitations of our study. One of the shortcomings is that we cannot establish which aspect of the illusion is crucial for the altered experience of pain, because we neither found correlations between pain intensity nor objective or subjective aspects of the illusion (see also Giummarra et al,[15] and Tsakiris and Haggard[49]). It is worth noting, however, that participants reported very different experiences concerning the number of hands they perceived as their own, and the strength of the illusion measured according to proprioceptive drift varied from trial to trial. Perhaps more trials should be planned to analyze the influence of the illusion on pain ratings trial-by-trial; this would allow us to test which aspect of the illusion (ie, subjective sense of ownership over the rubber hand or uncertainty about the location of real hand) is crucial for the altered experience of pain.

Another limitation is the lack of incongruent (asynchronous) visuotactile stimulation in the control condition. We did not include such a condition because asynchronous stroking has been suggested to also elicit the illusion to some extent,[22,48] potentially diminishing the differences between conditions in terms of their effect on pain ratings. However, this experimental plan does not allow us to draw a firm conclusion about the role of sense of ownership in the pain experience. In future studies a control condition for the experimental hand should be included and proprioceptive drift on the control hand should be measured to ensure more accurate comparisons between conditions. Another concern might refer to whether the results are not influenced by a predetermined order of conditions, because the control condition was always performed first. This was necessary to keep participants naive about the purpose of the experiment as long as possible, and to avoid the control condition being affected by expectations related to the effects of the RHI on pain and potential long-term effects of the illusion on pain ratings. If sensitization or changes in pain anticipation had occurred, they would have only affected the experimental hand because we found no difference for the control hand. However, in the future studies we should randomize the order of conditions, provide more trials, and implement additional measures, such as pain localization error in the control condition, and proprioceptive drift for both hands, before and after each trial of experimental condition. A possible solution to the problem of prolonged experimental sessions (ie, potential sensitization and long-term effects of RHI) could be to conduct the experiment over a few days controlling for day-to-day pain sensitivity variations. Also, although the effect of the RHI on pain ratings was detectable in our sample, future replications of the results should involve a larger number of participants and manipulations designed specifically to test the effects of uncertainty about hand and pain locations.

Conclusions

The experiment has shown that synchronous visuotactile stimulation can influence the locus and intensity of experienced pain in the affected hand, and the effect does not generalize to the other limb. Interpreting the results together with other studies, we could speculate that bodily illusions could reduce pain if noxious stimulation is applied to a body or body part that is not perceived as one's own, or is perceived as one's own and visible at the moment of the stimulation, but not when body boundaries and the location of pain are uncertain. It is important for future studies to control the strength of illusion in each trial as well as to systematically manipulate all of the variables that could interact with altered body awareness, such as type of noxious stimulation, visibility of simulated body parts, and expectations about the location and intensity of pain. Taking into consideration that the results showed that the analgesic effect of bodily illusion could be reversed under some conditions, the study seem to have important consequences. Determining the conditions that increase experienced pain will not only contribute to understanding the mechanisms of pain experience but also lead to new clinical applications.

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