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The rubber hand illusion increases heat pain threshold

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Abstract

Background: Accumulating evidence shows that manipulations of cortical body representation, for example, by simply viewing one's own body, can relieve pain in healthy subjects. Despite the widespread use of the rubber hand illusion (RHI) as an effective experimental tool for the manipulation of bodily awareness, previous studies examining the analgesic effect of the RHI have produced conflicting results.
Method: We used noxious heat stimuli to induce finger pain in 29 healthy subjects, and we recorded the participants' pain thresholds and subjective pain ratings during the RHI and during the control conditions. Two control conditions were included in our experiment – a standard one with reduced illusion strength (asynchronous stroking control) and an additional one in which the participants viewed their own hand.
Results: Raw data showed that both the RHI and the vision of the own hand resulted in slightly higher pain thresholds than the asynchronous stroking control (illusion: 47.79 °C; own-hand: 47.99 °C; asynchronous: 47.52 °C). After logarithmic transformation to achieve normality, paired *t*-tests revealed that both increases in pain threshold were significant (illusion/asynchronous: $p = 0.036$; own-hand/asynchronous: $p = 0.007$). In contrast, there was no significant difference in pain threshold between the illusion and the own-hand conditions ($p = 0.656$). Pain rating scores were not log–normal, and Wilcoxon singed–rank tests found no significant differences in pain ratings between the study conditions.
Conclusion: The RHI increases heat pain threshold and the analgesic effect of the RHI is comparable with that of seeing one's own hand. The latter finding may have clinical implications.

1. Introduction

In recent years, some studies have revealed that manipulations of cortical body representation can reduce pain in healthy subjects (Moseley, 2011). Longo et al. (2009) found that the observation of one's own hand receiving painful stimuli compared with viewing a neutral object produced significant decrease in the subjective intensity and unpleasantness of laser-evoked acute pain. In another study, the vision of the own hand was shown to effectively increase heat pain threshold (Mancini et al., 2011). The change in body perception can reduce pain also when the cortical multisensory integration is disturbed, for example, when crossing the arms impairs the localization of hand pain (Gallace et al., 2011).

To better understand how to affect bodily awareness for the management of acute pain, it has become necessary to test the analgesic potentials of such commonly studied bodily illusions as the rubber hand illusion (RHI). In the classical experimental paradigm of the RHI introduced by Botvinick and Cohen (1998) the subject sees that brush strokes are applied to an artificial hand while the subject's real hand, which is hidden out of view, is also stroked by a paintbrush. The congruence between the visual and tactile stimuli

What's already known about this topic?
Pain can be modulated by manipulations of cortical body representation. Viewing one's own body reduces pain. The rubber hand illusion (RHI) modifies bodily awareness. Previous studies examining the analgesic effect of the RHI have produced conflicting results.

What does this study add?
We provide two converging lines of evidence that the rubber had illusion increases heat pain threshold. The analgesic effect of the RHI is shown to be comparable with that of viewing one's own hand. We confirm that the vision of the own hand reduces pain.

arising from the synchronized strokes leads to an illusory sense of ownership over the artificial hand, and also to the loss of the feeling that the unseen real hand is a part of the participant's body (Longo et al., 2008). The illusion also modifies the subjects' capacity to localize their affected hand resulting in the so-called proprioceptive drift, when subjects perceive the position of their hidden hand to be closer to the prosthetic hand than it really is. The illusion is reduced or does not occur when the posture of the artificial and real hand is incongruent (Tsakiris and Haggard, 2005), or when there is a phase shift between the two series of brush strokes, i.e., when the stroking is asynchronous.

Previous studies examining the analgesic effect of the RHI have produced mixed results. Hänsel et al. (2011) used a modified version of the RHI called the out-of-body illusion and found weak evidence that evoking the sense of ownership towards a virtual body increased the pressure pain threshold. Another study reported conflicting results as to whether the classical RHI decreases or increases thermal pain ratings (Valenzuela-Moguillansky et al., 2011). A more recent study with rigorous design observed neither an effect of the RHI on thermal pain threshold nor an effect on heat pain ratings (Mohan et al., 2012). Here, we also used the classical paradigm of the RHI and we hypothesized that higher heat pain thresholds and lower heat pain ratings would be detected when the illusion is elicited than when an asynchronous stroking is applied. To gain insight into the potential clinical relevance of RHI-induced analgesia, we decided to test whether the RHI has an antinociceptive effect comparable with that of viewing one's own hand. For this reason, in a third condition, participants viewed their hand during painful stimulation.

2. Methods

2.1 Participants

The study was conducted according to the principles of the Declaration of Helsinki and was approved by the Regional Research Ethics Committee of the Medical Center, Pécs. Thirty healthy, right-handed volunteers (17 women, 13 men, mean age: 22.36 ± 2.25) were recruited among the students of the University of Pécs. Handedness was assessed by the Edinburgh Inventory (Oldfield, 1971). All participants had no previous experience with RHI and were blind to the hypothesis tested by the study. We excluded volunteers taking any pain-modulating substance 1 week prior to the experiment. Additionally, we had to exclude one participant whose pain threshold was higher than the safety limit of the heat stimulator device. Participants received a small fee for taking part in the study.

2.2 Experimental set-up

The study was conducted in April and May 2012, and the experiments took place in a separate room at the Neurology Department of the University of Pécs. The set-up is shown in Fig. 1. Participants wearing a green laboratory coat sat on a chair, and their arms rested on a table with their palms facing down. The left index or little finger was placed on the contact area of a heat probe inserted into the tabletop. At the right hand there was a computer mouse by means of which subjects could terminate receiving heat stimuli. The experimenter stood opposite the participant. Three experimental conditions were used in our study: illusion condition (syn-

Figure 1 Experimental set-up in the rubber hand conditions. A prosthetic left hand was placed to the right of the participants' left hand that was hidden out of view. A finger of the unseen hand rested on a heat probe inserted in the tabletop. By a computer mouse subjects could terminate receiving heat stimuli.

chronous stroking), asynchronous control condition (asynchronous stroking) and own-hand control condition (no stroking, but the participants viewed their own hand during the pain measurements). In the illusion and the asynchronous conditions, a realistic-looking prosthetic left hand was placed to the right of the participants' real left hand. The distance between the index finger of the prosthetic hand and the index finger of the real hand was 20 cm. Additionally, the proximal end of the artificial hand and the participants' shoulder was connected by a laboratory coat sleeve that looked the same as the sleeve of the coat worn by the participants. In order to prevent subjects from seeing their own left hand a standing screen was positioned between the prosthetic and the real hand. In the asynchronous condition the posture of the rubber hand was slightly incongruent with the real hand, though anatomically possible (rotated by 20–30°).

2.3 Procedure

Before starting the experimental phase, subjects went through a short training session containing a proprioceptive drift and two pain threshold measurements, and a series of pain intensity assessments. The experimental phase consisted of three blocks corresponding to the three experimental conditions (illusion, asynchronous and own-hand). The sequence of all three blocks was randomized and counterbalanced across subjects. Both the synchronous and the asynchronous block started with a 2-min stroking period (induction phase), during which all fingers (except the thumb) of the rubber and the unseen left hand were at the same time stroked by two brushes either synchronously to induce the RHI or asynchronously. After the induction phase, the proprioceptive drift was measured, and participants reported their perceptual experiences associated with stroking by answering a questionnaire. Then, following a 1-min stroking period (top up phase) the pain threshold measurements were performed. Finally, after a further top up phase of stroking, participants rated the intensity of heat-induced pain using a visual analogue scale (VAS). The predetermined pattern and the frequency (0.9 Hz) of stroking were the same in both conditions due to the use of a metronome that governed the experimenter through an earphone. In the own-hand block, only the proprioceptive drift, the pain threshold and the pain ratings were measured without placing a rubber hand and a standing screen on the table, and without applying brush strokes. There were 5-min pauses between the experimental blocks. The experiments were video recorded.

2.4 Measurements

2.4.1 Pain threshold

Pain threshold measurements were made through the method of limits performed by gradually increasing the intensity of heat stimuli using the Medoc Pathway Pain and Sensory Evaluation System (Medoc, Ramat Yishai, Israel). Heat stimuli were delivered to the ventral surface of the distal phalanx of the index or little finger via a contact heat-evoked potential stimulator thermode with a round contact area of 573 mm^2 (27 mm in diameter). In cases, when in the training session the pain threshold of the index finger was higher than 49 °C, the little finger was used in the subsequent experimental blocks in order to reduce sensitization and thereby the chance of reaching the safety limit of the thermal stimulator device. The thermode was placed on the tabletop so the subjects could comfortably rest their finger on the surface of the thermode without receiving unusual mechanistic stimuli. Care was taken to prevent the participants from moving their hand or fingers. In each block three measurements were performed with 25-s intervals, and the mean values were used for statistical analysis. In the illusion and the asynchronous control condition, the intervals contained a 20-s stroking period (top up minor phases) in order to counterbalance the loss of the vividness of the illusion due to heat stimulation (Kammers et al., 2011). Each measurement started at 37 °C, and the temperature was increased by 0.5 °C/s until participants first experienced pain and stopped the stimulus. The verbal instruction given to the participants was the Hungarian translation of the standardized instruction of the quantitative sensory testing protocol elaborated by the German Research Network on Neuropathic Pain (see Supporting Information Appendix S1). Additionally, subjects were asked to focus their attention to the hand seen in front of them on the left area of the laboratory table.

2.4.2 Subjective pain ratings

Participants rated the intensity of heat-induced pain using a 100 mm VAS in which 0 corresponded to no pain and 100 to maximum pain. In each experimental block, one VAS measurement was performed. The duration of painful stimulus was 3 s, and the participants were asked to rate the pain intensity at the end of the stimulus by drawing a vertical line on the VAS.

The temperature of the noxious heat stimulus was individually determined for each subject in the pre-test training session. A series of thermal stimuli with increasing temperature (started at 41 °C) was given to the participant, and the temperature of the first stimulus rated as highly painful (VAS > 50 mm) was used in all the subsequent experimental blocks. We did not set an upper limit, but the safety limit of the heat stimulator device was 51 °C. Due to the method we used, the temperature at which participants rated the intensity of pain varied across the subjects, but not across the conditions.

2.4.3 Proprioceptive drift

The change in the perceived position of the participants' left hand was measured by a method that is known from experiments involving non-visual variant of the RHI (Lopez et al., 2012). The steps of the measurement are shown in Fig. 2.

Figure 2 The measurement of the perceived position of the hand. Participants put their right index finger on the initial part of a ruler (A), and then they closed their eyes and indicated the location where they felt it was exactly above their left index finger (B).

First, a ruler was placed in an angular position in front of the participants, who were asked to put their right index finger somewhere on the initial part of the ruler. Then, after having instructed the subjects to close their eyes, the experimenter removed the standing screen and positioned the ruler 13 cm above the table. Finally, the participants were asked to indicate the perceived position of their left index finger by drawing their right index finger on the ruler to the location where they felt it was exactly above the tip of their left index finger. The subjects were instructed to answer as spontaneously as possible. The outcome of the proprioceptive drift measured in the own-hand condition was taken as the baseline value.

2.4.4 RHI questionnaire

In the illusion and the asynchronous stroking condition a questionnaire was administered consisting of nine statements in order to measure the main characteristics of how the participants subjectively experienced the RHI (see Table 1). We adopted seven questions from Longo et al. (2008), referring to the two main components of the subject's experience: (Q1–4) items were about the embodiment of the rubber hand, and (Q5–7) items were about the loss of own hand. The eighth question (Q8) was adopted from Ehrsson et al. (2004) and Zopf et al. (2011) in order to measure the duration of the experienced ownership over the rubber hand. Finally, we used one statement (Q9) as a control question considered to be unrelated to the RHI and therefore to be a good tool for identifying any response bias (Kammers et al., 2011). Participants answered each statement by choosing a number from an 11-point Likert scale ranged from 0 ('strongly disagree') to 10 ('strongly agree'), with the exception of Q8 in which 0 corresponded to 'never', and 10 corresponded to 'all through the stroking period'. The questions were presented in a random order.

2.5 Statistical analysis

Data were analysed using the Statistical Package for the Social Sciences (SPSS) statistical software package (version 20.0.0; SPSS Inc., Chicago, IL, USA). The level of significance was set at $p < 0.05$. To verify that the RHI was present, we examined the proprioceptive drift data and the data of the 9-item questionnaire. Our hypothesis was tested by comparing pain threshold values and VAS scores between the asynchronous and the synchronous conditions. Additionally, to see whether the analgesic effect of the RHI is comparable with that of viewing one's own hand the comparisons of pain values were made also between the own-hand and each of the rubber hand conditions (own-hand/asynchronous and own-hand/synchronous). Prior to data analysis, the normal distribution of pain thresholds and VAS scores was tested by Kolmogorov–Smirnov tests. The tests indicated significant deviations from Gaussian distribution in both sets of data.

Table 1 Questions measuring how participants subjectively experienced the rubber hand illusion.

Embodiment (location and ownership) statements
Q1. It seemed like I was feeling the touch of the paintbrush in the location where I saw the rubber hand being touched.
Q2. It seemed like the touch I felt was caused by the paintbrush touching the rubber hand.
Q3. It seemed like the rubber hand was my hand.
Q4. It seemed like the rubber hand belonged to me.
Disownership statements
Q5. It seemed like I was unable to move my hand.
Q6. It seemed like my hand had disappeared.
Q7. It seemed like my hand was out of my control.
Duration
Q8. Please indicate how much of the time the feeling that the rubber hand is your hand was present during stroking in this block.
Control
Q9 It seemed like I couldn't really tell where my hand was.

Pain threshold data were negatively skewed and – after reflection – normally distributed in logarithmic space. In order to achieve secondary normalization and to minimize outlier effect, pain threshold data were reflected (by subtracting all values from the maximum value plus one) and transformed using natural logarithmic transformation. After log–transformation, pain thresholds were analysed by paired samples t-tests. For each t-test we calculated the Cohen d_z value (Lakens, 2013). In case of VAS scores, data transformation were not applicable, so Wilcoxon's signed–rank tests were performed for statistical analysis.

3. Results

3.1 Proprioceptive drift

The baseline value of perceived hand position was obtained in the own-hand condition, in which no rubber hand was present. The proprioceptive drift (error in hand localization) was calculated by subtracting the baseline value from the values of perceived hand position measured in the synchronous and in the asynchronous conditions. We used paired samples t-test for statistical analysis (see Supporting Information Fig. S1). This showed that the difference between the synchronous and asynchronous conditions was significant [$t(28) = -2.415$, $p = 0.023$]. The perceived position of the participant's left hand was closer to the rubber hand after synchronous than asynchronous stroking.

3.2 Questionnaire data

According to the statistical analysis – paired samples t-tests – in the synchronous condition subjects gave significantly higher ratings for five questions: Q1, Q3, Q4, Q6 and Q8 (statistical parameters are described in Supporting Information Table S1). Synchronous and asynchronous conditions did not differ for questionnaire item Q9, which is unrelated to the RHI, designed to detect response bias ($p = 0.722$). Both the embodiment of the rubber hand and the loss of own hand (disownership) were experienced by the subjects as was shown by the statistical analysis of the component scores (see Fig. 3). Component scores were calculated by taking the average of each subject's ratings for Q1–4 (embodiment) and for Q5–7 (disownership) in each condition. Paired samples t-tests revealed that both the embodiment and the disownership component scores were significantly higher in the illusion condition than in the asynchronous condition [$t(28) = 3.436$, $p = 0.002$ and $t(28) = 2.076$, $p = 0.011$].

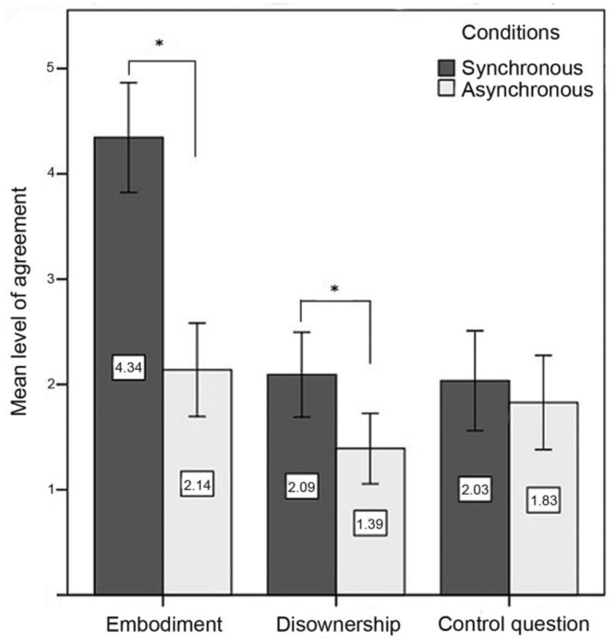

Figure 3 Questionnaire. Mean level of agreement with statements about the embodiment of the rubber hand (Q1–4) and about the disownership of the unseen real hand (Q5–7). The control question (Q9) was designed to detect response bias. Asterisks denote statistically significant difference ($p < 0.05$). Horizontal bars represent standard error to the mean.

3.3 Sensitivity to pain

Higher pain thresholds were measured following synchronous stroking than following asynchronous stroking in 20 of the 29 subjects studied (69%). The mean and the median scores also showed an increase of pain threshold in the synchronous condition as compared with the asynchronous condition (see Table 2 for descriptive statistics). After log–transformation paired samples t-test was employed for the analysis of pain threshold data. As is shown in Fig. 4 the difference between the synchronous and the asynchronous conditions was found to be statistically significant [$t(28) = -2.197$, $p = 0.036$, Cohen's $d_z = 0.407$].

Table 2 The descriptive statistics for pain-related raw data.

	Pain threshold		VAS	
Condition	Median	Mean (SD)	Median	Mean (SD)
Asynchronous	47.93	47.52 (2.20)	33.00	36.12 (22.36)
Synchronous	48.55	47.79 (2.95)	28.25	35.74 (22.07)
Own-hand	48.73	47.99 (2.46)	30.50	37.21 (28.55)

The median, the mean and the SD of pain thresholds (in °C) and of subjective pain ratings (in VAS mm). SD, standard deviation; VAS, visual analogue scale.

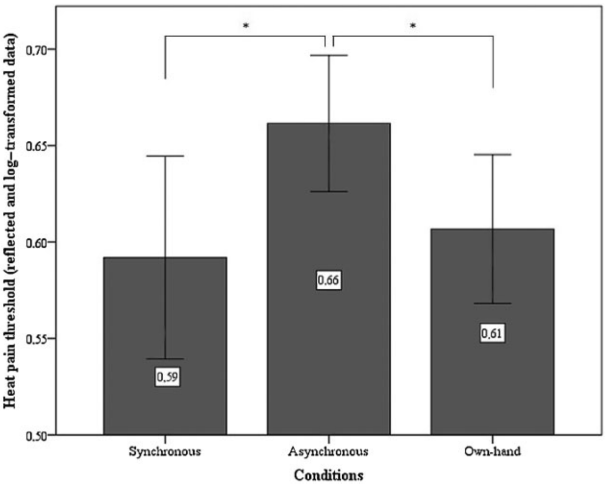

Figure 4 Pain thresholds. The mean of reflected and log–transformed values measured in the synchronous, asynchronous and own-hand conditions. Lower values correspond to higher pain thresholds. Asterisks denote statistically significant difference ($p < 0.05$). Horizontal bars represent standard errors to the mean.

To compare pain thresholds between the own-hand and each of the rubber hand conditions, we performed two paired samples *t*-tests on the log–transformed data (see Table 3 for pairwise comparisons). The analysis revealed that significantly higher pain thresholds were measured in the own-hand condition than in the asynchronous condition [$t(28) = -2.919$, $p = 0.007$, Cohen's $d_z = 0.542$]. In contrast, as compared with the synchronous stroking condition pain thresholds did not significantly change when subjects were viewing their own hand during painful stimulation [$t(28) = 0.451$, $p = 0.656$, Cohen's $d_z = 0.083$].

Wilcoxon's signed–rank tests did not show any significant differences between conditions in VAS scores ($p > 0.9$).

4. Discussion

Our study shows that that the RHI has an analgesic effect. The data of the questionnaire measuring how the subjects experienced the illusion as well as the proprioceptive drift data verify that the illusion was successfully evoked by the synchronous stroking of the rubber hand and the participants' own hand. Although we observed no effect of the RHI on pain ratings, our results provide two converging lines of evidence suggesting that the RHI increases heat pain threshold. Firstly, synchronous stroking resulted in slightly higher pain thresholds than asynchronous stroking, and this difference was significant. Secondly, pain thresholds did not differ significantly between the synchronous stroking and the own-hand conditions, although asynchronous stroking resulted in lower pain thresholds than viewing one's own hand. It also implies that synchronous stroking increased the pain threshold compared with the asynchronous stroking control.

Furthermore, our data confirm that the observation of one's own hand receiving painful stimuli compared with viewing a neutral object increases heat pain threshold (Mancini et al., 2011). When asynchronous stroking is applied, there is only a slight alteration of bodily awareness, so viewing a rubber hand following asynchronous stroking is in some respects similar to when a neutral object is seen. In accordance with this, as was mentioned above, we observed significantly lower pain thresholds in the asynchronous condition than in the own-hand condition.

Accumulating evidence, including our present results, shows that seeing one's own body is a simple and effective method for manipulating body representation in order to reduce acute pain (Longo et al., 2009, 2012; Mancini et al., 2011). Taking these findings into account, our study yields insight into the potential clinical application of the RHI-induced analgesia. On the one hand, we found that the RHI cannot reduce pain more effectively than the vision of the body. Therefore, due to its practical simplicity, the use of the latter should be preferred in clinical pain management. On the other hand, our results suggest that the analgesic effect of the RHI is comparable with that of viewing one's own hand. Therefore, it follows that in cases in which the use of visually induced analgesia is contraindicated for some reason (e.g., when the vision of a seriously injured body part may exacerbate pain perception), the induction of the RHI

Table 3 Pairwise comparisons of mean pain thresholds between the study conditions.

Condition/condition	Mean	Standard deviation	*t* (28)	*p* (two-tailed)
Synchronous/asynchronous	–0.069	0.1702	–2.197	0.036*
Own-hand/asynchronous	–0.055	0.1009	–2.919	0.007*
Own-hand/synchronous	0.015	0.1763	0.451	0.656

The data were reflected and log–transformed before the analysis. Asterisk denotes statistically significant difference ($p < 0.05$).

for acute pain relief may be an option. It is important, however, to note that the application of visually induced analgesia supplemented with the mirror box technique may also be an option in the majority of such cases (Longo et al., 2009; Mancini et al., 2011).

Previous studies examining the analgesic potentials of the RHI, or of its extended form called the out-of-body illusion, have produced mixed results (Hänsel et al., 2011; Valenzuela-Moguillansky et al., 2011). Moreover, while our paper was in preparation, Mohan et al. reported a rigorously controlled study in which neither an effect of the RHI on thermal pain threshold nor an effect on heat pain ratings was observed (Mohan et al., 2012). Although our results are consistent with the pain assessment findings of Mohan et al., it is inevitable to reflect on some differences between the experimental protocols used by Mohan et al. and by us for suggesting some possible explanations for the conflicting outcomes of pain threshold measurements.

One obvious possible explanation is that in our experiment, the rubber hand was slightly rotated (by 20–30°) in the asynchronous stroking condition precisely because we wanted to maximize the reduction of the illusion in the control condition without eliminating any component of the multisensory experience necessary for the induction of the RHI. Additionally, two elements of the experimental protocol elaborated by us may have enhanced the bottom-up mechanisms underlying the RHI. Firstly, we built an experimental set-up allowing us to apply painful stimuli to a body part (a finger), which was also directly involved in the induction of the illusion. We decided to do so, because the RHI is highly sensitive not only to the timing, but also to the localization of strokes. As experiments show, if only one of the fingers (e.g., the index finger) is touched synchronously on the rubber and real hands, while another finger (e.g., the little finger) is not stroked at all, there will be a significant difference between the proprioceptive drifts of those fingers (Tsakiris and Haggard, 2005; Tsakiris et al., 2006). Since joints play a central role in the fine somatotopy of tactile representations (de Vignemont et al., 2009), we did not attach the heat probe on the dorsum of the subjects' hand, because by doing so, it would have been impossible to apply strokes and painful stimuli to exactly the same body part.

Secondly, with our set-up the participants did not have to receive an unusual and continuous tactile stimulation on the dorsal surface of their hand while seeing a salient heat probe on the rubber hand. We thought it was better to avoid this type of robust visuo-tactile congruence being present in all experimental blocks, because it might reduce the role of bottom-up mechanisms in making the illusion condition different from the asynchronous control condition. Additionally, as Mohan and his colleagues suggest, a heat probe on the rubber hand may facilitate the 'visual capture' of pain, and therefore the referral of pain to the owned rubber hand (see also Capelari et al., 2009). Since in our experiment, the heat probe was inserted into the tabletop, and only its round contact area was visually represented, it may have impaired the participants' ability to feel the painful stimuli on the rubber hand, and therefore pain localization may have been more disturbed by our protocol.

Although experiments are required to test the speculations mentioned above, we are convinced that the observed elevation of pain threshold is not a chance finding, and that the RHI can modify pain perception. There are several mechanisms that may be responsible for such an analgesic effect. Firstly, as it is also discussed thoroughly by Mohan et al., the RHI brings into conflict the different reference frames needed to localize somatosensory inputs, which may disrupt nociceptive processing. Similarly to what was observed by Gallace et al. (2011) that crossing the arms over the body midline leads to a small but significant reduction of pain, the RHI may also be able to affect pain experience through the disruption of the processes by which brain localizes noxious sensation.

Another possible explanation for the detected elevation of pain threshold is that viewing an artificial hand perceived as one's own hand may affect pain experience through the same mechanisms that underlie the antinociceptive effect of viewing one's own body part (Longo et al., 2009; Mancini et al., 2011). The change in pain threshold, therefore, may have represented the different degrees to which the rubber hand was embodied due to the different types of stroking. Finally, the homeostatic control is decreased in the disowned hand as it is shown by the physiological changes of the hand (Moseley et al., 2008; Barnsley et al., 2011), and some indirect evidence suggests that sensory processing is also decreased in the unseen hand during the RHI (see f or a review Moseley et al., 2012). The latter effect of disownership may also serve as the basis of the illusion-induced analgesia. However, it is important to note that neither of the explanatory hypotheses mentioned above is confirmed by correlation data in our study, so the role of distraction in the increase of pain threshold cannot be excluded.

There are several limitations to our study. An important one is that for subjective pain assessment, we used only one VAS measurement in each block. The reliability of this simplified method is lower than when the mean of repeated measurements is calculated for statistical analysis. Another important limitation is that we did not use an object-view control condition. It follows that there is some uncertainty about whether our results show that both the RHI and viewing one's own body reduce pain, or instead, the data show that asynchronous stroking exacerbates pain. On the basis of Longo et al. (2008), Mancini et al. (2011) and Longo et al. (2012), it is reasonable to interpret our results as suggesting that the RHI is analgesic, but this conclusion cannot be drawn purely from our own data.

In conclusion, our study shows that the RHI increases heat pain threshold. It follows that the classical paradigm of RHI is an appropriate experimental tool for achieving a better understanding of how the manipulation of cortical body representations can be used for acute pain management. Furthermore, our results indicate that one or more components of the illusory experience involved in the RHI may be analgesic (mislocalization of pain, ownership over the rubber hand, disownership towards the real hand, the illusion-induced reorganization of attentional resources). However, further studies are needed to identify the mechanisms underlying the analgesic effect of the RHI, and also to clarify how to obtain more unambiguous results.

Author contributions

All authors discussed the results and commented on the paper.

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Supporting Information

Additional Supporting Information may be found in the online version of this article at the publisher's web-site:

Figure S1. Proprioceptive drift. Mean drift (in cm) measured after synchronous and asynchronous stroking ($p = 0.023$). Value zero represents the perceived position of the participant's left index finger in the own-hand condition (baseline). Lower values are shifts towards the fake hand. Horizontal bars represent standard error to the mean.

Table S1. Paired comparisons of how participants experienced the rubber hand illusion following synchronous and asynchronous stroking. Responses were on an 11-point Likert scale from 0 ('strongly disagree') to 10 ('strongly agree'), in case of Q8 from 'never' to 'all through the stroking period'. Asterisks denote statistically significant difference ($p < 0.05$).

Appendix S1. The standardized instruction for thermal pain threshold measurements in the protocol of quantitative sensory testing elaborated by the German Research Network on Neuropathic Pain (Rolke et al., 2006): *'The temperature of the skin will increase to "warm" and a few moments later to "hot". Eventually a painful component will be added to the sensation of "hot", and it will change in quality from "hot" to, for example, "burning" or "stinging hot". Please press the stop-button immediately at the first "burning" or "stinging hot" sensation'.*