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The Role of Body Awareness in Pain

An Investigation Using the Rubber Hand Illusion

Abstract: *In this article, we explore the effect of a modification of one aspect of body awareness, the so-called sense of body-ownership, on pain perception. In order to do so, we modify body-ownership in healthy participants by using a visuo-tactile illusion called the 'rubber hand illusion' (RHI). We combine the classical experimental paradigm of the RHI with a method to induce pain by thermal stimulation. We present and discuss two experiments that show interesting but conflicting results. In the first experiment our results show the RHI has the effect of* ***decreasing*** *pain estimations, whereas in the second experiment the RHI has the effect of* ***increasing*** *pain estimations. We discuss the different factors that could be involved in this difference, and suggest that different types of changes in participants' body schema might have been involved in the two experiments. We propose that an approach that considers participants' subjective experience of the illusion will help us to solve this puzzle.*

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1. Introduction

In this article we will explore the relationship between body awareness and pain perception. To do so, we will use the experimental paradigm of the rubber hand illusion (RHI) that modifies one aspect of body awareness, the so-called 'sense of body-ownership'. We will additionally use a method to induce pain through thermal stimulation.

1.1 Body Awareness

The concept of 'body awareness' involves different facets of the experience of *being* a body: for instance, the knowledge necessary to move our body through space; to relate to and interact with other objects and bodies; to know that our body is ours and not someone else's. Body awareness also concerns how we imagine our body, how we feel it, and how we feel *about* it. In everyday life, all these aspects combine, and the fact that our body is there, and that we experience *through* it, becomes almost transparent to us. Most of the time, it is obvious to us that our arm is our arm; we don't need to think about the position or the movements of our arm in order to lift it and reach for a glass or scratch our head.

Among the many concepts that researchers have defined referring to the different facets of body awareness, the most commonly used are the 'body schema' and 'body image' (see, e.g. de Vignemont, 2010). Different researchers propose different definitions for these concepts, but for the purpose of this article we will use the definitions given in the context of pain research. We will refer to the body schema as 'A real time-time dynamic representation of one's own body in space, which is derived from sensory input and is integrated with motor systems for the control of action' (Moseley, 2004). We will refer to the body image as 'A conscious representation of the body, thought to be maintained by ongoing tactile, proprioceptive, and visual input. It can be modulated by memory, belief, and psychosocial factors' (Lotze and Moseley, 2007).

Crucial for the present study is another concept regarding body awareness that has been introduced in recent years: the 'sense of body-ownership'. This refers to the sense that it is *my* body that is undergoing a certain experience (Gallagher, 2000). Lately, the term has been widely used in empirical and theoretical research, since it seems to designate an aspect of the minimal experience of the self that can be dissociated and studied in certain pathological and non-pathological cases (for a review see Tsakiris, Hesse *et al.*, 2007; Tsakiris, 2010).

In this article we will mainly talk about the body image, the body schema and the sense of body-ownership. We will use the general term ‘body awareness’ to refer to all these facets together.

1.2 Body Awareness and Pain

Recent findings suggest that in several pain states, such as chronic pain, complex regional pain syndrome (CRPS), and phantom limb pain, some of the aspects of body awareness mentioned above are altered.

1.2.1 Body Schema

Schwoebel *et al.* (2001; 2002) showed that patients with CRPS pain have longer response times in tasks involving mental rotation of their painful hand in comparison with the contralateral healthy hand, suggesting an alteration of **body schema** in these patients. Moseley *et al.* (2005) performed a study with a similar task in two groups: CRPS patients and healthy participants with experimentally induced pain. The results confirmed Schwoebel *et al.*’s findings for the CRPS group, but no change in response time was found for the experimentally induced acute pain group, suggesting that body schema alteration depends on the type of pain state that the person is undergoing. Another study showed a similar disruption caused by chronic back pain: Bray and Moseley (2010) found that patients with bilateral back pain made more mistakes on a left/right trunk rotation task than patients with unilateral back pain, who in turn made more mistakes on that task than healthy subjects.

1.2.2 Body Image

Several studies corroborate that the **body image** is also affected by pain states. For instance a study by Moseley (2005) on CRPS patients shows that, when asked to estimate the size of their affected body part using different-sized pictures of their hand, patients estimate the size of the painful hand as being larger than it really is. Another example is illustrated by phantom limb phenomena. Phantom limbs, by their very existence, involve a disruption in the body image which can go as far as the missing phantom feeling heavy, swollen, or placed in an awkward position (Flor *et al.*, 2006; Giummarra *et al.*, 2007; Lotze and Moseley, 2007; Ramachandran and Altschuler, 2009). This disruption is accompanied with pain in 50–80% of cases (Flor *et al.*, 2006).

A final example involving body image concerns chronic pain. Moseley (2008), studying lower back pain patients, found that most of his patients were unable to complete drawings that involved their painful body part. In addition, the patients had higher tactile thresholds and decreased tactile discrimination ability in their painful body part. The author interpreted these results in terms of a disruption of the body image.

1.2.3 Body-Ownership

Several studies indicate that CRPS patients express a feeling of 'foreignness' towards the affected body part (Bultitude and Rafal, 2010). Some researchers relate this feeling to 'neglect-type' symptoms (Galer *et al.*, 1995; Galer and Jensen, 1999; but see Förderreuther *et al.*, 2004; Lewis *et al.*, 2007). Whether or not this is the case, certainly the feeling of foreignness can reasonably be related to the sense of **body-ownership**.

An interesting study that goes in this direction is Moseley, Parsons *et al.* (2008). In this study the investigators asked a group of chronic arm pain patients to evaluate the intensity of their pain after doing a set of standardized movements. When looking through magnifying or minifying binoculars, patients felt respectively more or less pain than when they looked directly at their arm. Physically measured swollenness of the hand followed the same pattern. The authors interpreted these results in terms of a bi-directional link between pain and body tissues on the one hand, and the body image on the other hand. They proposed that the decrease in pain intensity found while looking through the minifying binoculars could be due to reduced body-ownership of the limb.

The possibility that pain and sense of body-ownership could be related is also compatible with Craig's view of pain (Craig, 2003; 2002). Craig suggests that pain is part of the 'interoceptive system' that senses the physiological state of the whole body and provides the foundations for the experience of subjective sensations and emotions. In this sense, the subjective experience of the limits of our body could be related to the system that regulates the physiological limits in the functioning of our organism, and thereby its integrity.

In another study, Moseley, Olthof *et al.* (2008) showed that transferring ownership onto a rubber hand can generate a slight decrease in temperature of the unseen real hand and a decrease in the ability to do temporal discrimination of pairs of tactile stimuli delivered to the unseen hand, suggesting the interesting possibility that a modification in the sense of body-ownership can affect physiological parameters.

Following Craig's view of pain as a physiological parameter and Moseley's suggestion that reduced ownership modifies a physiological parameter, it is plausible to ask whether a modification in the sense of body-ownership might modify pain.

2. Pain and the Rubber Hand Illusion

In order to further investigate the possibility that body-ownership might have an impact on pain, we studied the effect of modifying the sense of body-ownership on the evaluation of experimentally induced pain in healthy subjects.

An experimental paradigm known to modify the sense of body-ownership is the 'rubber hand' illusion (RHI) (see, e.g. Botvinick and Cohen, 1998; Longo *et al.*, 2008; Tsakiris and Haggard, 2005; Kammers *et al.*, 2009). In the RHI, a person watches a rubber hand being stroked synchronously in the same location and at the same time as his or her own hidden hand is stroked (Figures 1 and 2). After a few minutes, the person gets the curious impression that the rubber hand belongs to them. There are two requisites for this illusion to work; first, the rubber and the real hand have to be stroked at the same time and in the same place; and second, the rubber hand has to be placed in an anatomically plausible position. The most common measures used to evaluate this phenomenon are a behavioural measure, consisting in a displacement of the felt position of the hidden index finger in the direction of the rubber hand, termed 'proprioceptive drift', and the person's response to a questionnaire (Botvinick and Cohen, 1998; Kammers *et al.*, 2009; Tsakiris, Hesse *et al.*, 2007).

In order to test the possibility that a modification in the sense of body-ownership could affect pain intensity, we performed two experiments that combined the rubber hand illusion with a method to induce pain perception by thermal stimulation of a participant's real (hidden) hand. We used a range of temperatures ranging from non-painful to very painful, and gathered verbal reports of participants' estimation of their pain. Our initial reasoning was that through the effect of the RHI, participants would lose ownership of their own hand, and might therefore experience less pain on their 'disowned' real hand.

We shall see that although we confirm this expectation in Experiment 1, Experiment 2 will reveal that the situation is not so simple. In what follows we will explain the methodology of the experiments, present the results, and discuss possible factors that could give rise to the discrepancy and that could help in the interpretation of further studies interested in sense of body-ownership, body awareness, and pain.

Experiment 1

Participants

Following approval by a local Ethics Committee, the experiment included nineteen (ten females and nine males; mean age 28.3 ± 2.6 years) paid participants informed about the experiment's procedure but not about the hypothesis of the study.

Materials

The thermal stimulation was given with a contact thermode of Peltier elements measuring 25x50mm (Somedic AB, Stockholm, Sweden). The apparatus continuously measured the induced temperature and modified the applied current so that the local skin temperature remained constant at the target value throughout stimulation.

Procedure

The experiment was carried out in a quiet room at constant temperature (21°C) and lasted about 75 minutes.

Participants were seated in front of a table, with their right, stimulated arm placed through a hole cut in the front of a specially constructed cardboard box (Figure 1); another hole on top of the box allowed the participant to see the rubber hand; most of the back of the box was removed, allowing the experimenter to stimulate both hands. On the table inside the box a small cardboard marker indicated where the tip of the participant's right index finger should be placed. A cardboard cover was placed on top of the box. When the cover was removed, the participant saw the rubber hand; when the cover was placed over the box, the participant could not see the rubber hand. Ruled lines on the cover spaced at 1 cm intervals and marked by numbers in a random order allowed participants to verbally indicate the felt position of their index finger.

Each session was composed of six blocks: three identical SYNCHRONOUS blocks, and three identical NON-STROKING blocks. The SYNCHRONOUS and NON-STROKING conditions were undertaken in alternate order; half of the participants began with the SYNCHRONOUS condition and the other half with the NON-STROKING condition.

In the SYNCHRONOUS condition, the tactile stimuli were applied synchronously on the rubber and real hands (Figure 2). Here we expected the rubber hand illusion to occur, with the accompanying transfer of ownership to the rubber hand. In the NON-STROKING condition we asked participants to look at the rubber hand while we delivered tactile stimulation only to their real hand. In this condition we did not expect to induce ownership of the rubber hand because it is known that the illusion is strongly reduced when there is no coherence between the tactile and visual sensations (Armel and Ramachandran, 2003; Botvinick and Cohen, 1998; Ehrsson *et al.*, 2004; Longo *et al.*, 2008; Tsakiris, Schütz-Bosbach *et al.*, 2007). Since participants nonetheless continuously fixated the rubber hand, this condition controlled for the amount of attention given to the rubber hand. The condition also controlled for the amount of tactile stimulation given to the real hand of the participants, since this was the same as in the SYNCHRONOUS condition.

Each block began with the cover of the box closed. The experimenter placed the participant's right hand on the marker inside the box. Participants were requested not to move their own hand and to look attentively at the rubber hand throughout the duration of the whole experimental block. Participants were asked to indicate verbally the position of their right index finger by saying which of the randomly labelled ruled lines marked on the top of the box corresponded to the location of their finger (pre-block estimate of index finger location). Then the following procedure was repeated six times: the experimenter measured the temperature of the participant's right hand using an infrared thermometer. In the SYNCHRONOUS condition blocks, the experimenter stroked the rubber hand and the participant's right hand in a synchronous manner. The stroking was delivered for one minute (two minutes in the case of the first of the six repetitions) using two identical brushes. Immediately afterwards, a thermal stimulus was applied to the dorsum of the real hand. The thermal stimulus was one of the following six temperatures: 38°C, 40°C, 42°C, 44°C, 46°C, 48°C. The duration of each stimulus was 6 seconds. At the same time the rubber hand, which was being observed by the participant, was 'stimulated' with a similar thermode but which was not connected to the power source. Immediately after the thermal stimulus, participants were asked whether the sensation was painful or not. If the sensation was painful, they were asked to verbally evaluate pain intensity on a numerical scale graduated from 0 ('no pain') to 10 ('worst possible pain'). They were then asked to evaluate the warmth sensation, also on a numerical scale graduated from 0 ('not warm') to 10 ('very warm'). This warmth evaluation was only taken into account in the data analysis if the observers' pain evaluation was 0. This procedure was repeated six times in all in order to complete the six temperatures (38°C, 40°C, 42°C, 44°C, 46°C, 48°C). The order of stimulation was balanced across the blocks and different for each participant. When the judgment of the last thermal stimulation was completed, the cover was placed over the box. The offset of the cover was changed randomly. The participant was asked to indicate verbally which of the ruled lines corresponded to the location of the felt pain. Then the cover was randomly moved again and the participant was asked to judge the position of the hidden index finger (post-block estimate of index finger location). Participants did not receive feedback concerning the estimation of their index finger position either in the pre-block estimate of index finger location or in the post-block estimate of index finger location. Because blocks were repeated three times each, and to reduce total experiment duration, we used no training runs.

Once the judgment of pain location and of the right index finger position were completed, participants were allowed to take their right hand out of the box, and were asked to freely describe their experience. In order to quantify and categorize participants' experience of the RHI, at the end of each block they were asked to indicate their degree of agreement with ten statements (Figure 4). Participants were asked to utilize a scale from 0 to 10, 0 being 'not agreed at all' and 10 'totally agree'. The questionnaire was based on Botvinick and Cohen (1998) and Kammers *et al.* (2009), but modified according to the specific issues addressed in the present study. In particular, during pilot experiments we had noted that the phenomenon of the RHI was experienced differently depending on whether the experienced sensation was tactile, heat, or pain. Therefore, in addition to the standard statement (Statement 5) used in previous studies to measure the RHI (Armel and Ramachandran, 2003; Botvinick and Cohen, 1998; Kammers *et al.*, 2009), we included three new statements that evaluated how the RHI depended on the type of felt sensation (Statements 6, 7, and 8 — see Figure 4 for the exact statements). An additional statement (Statement 4: 'I felt as if my right hand had melted') was included as a control to exclude the possibility that participants were just acquiescing to the experimenter's questions. We expected no effect of the RHI on responses to this statement. Finally, in order to test the nature of the possible modifications in body representation that underlie the RHI, we considered two of the three alternatives proposed by Schütz-Bosbach *et al.* (2009); (a) the rubber hand displaces or substitutes for the participant's hand, and (b) an extra limb is incorporated as an additional part of the body. Statements 2 and 3 tested alternatives (a) and (b) respectively. Statements 9 and 10 relate to the spatial location of the sensations of heat and pain.

In the NON-STROKING blocks the same procedure was performed with the differences that only the real hand, and not the rubber hand, was stroked, and that the thermode was placed only on the real hand at the moment of thermal stimulation.

Figure 1. Experimental set-up, seen from experimenter's viewpoint. Participants placed their right hand inside the cardboard box; they placed their index finger on a mark. They could see the rubber hand (here on the right part of the figure) but not their real hand.

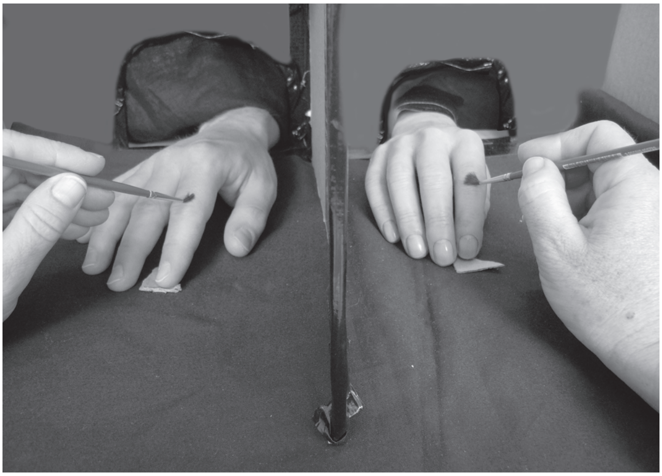

Figure 2. Stroking in the SYNCHRONOUS condition. Stroking was applied synchronously on the real (left of photo) and rubber (right of photo) hand.

Results

1. Occurrence of the RHI

As expected, the experimental setup succeeded in eliciting the rubber hand illusion. In fact the illusion was present not only in the SYNCHRONOUS but also, to a lesser extent, in the NON-STROKING condition. This can be seen first from the existence of a generally positive proprioceptive drift. Out of 19 participants, 16 had medians with positive proprioceptive drift in the SYNCHRONOUS condition, and 13 in the NON-STROKING condition. Second, the existence of an illusion is confirmed from the responses to Statement 5 of the questionnaire ('I felt as if the rubber hand was my hand') (see Figure 4). If we arbitrarily say that participants had an illusion when they responded with more than a median level of '5' to this statement, then 16 out of 19 participants had an illusion in the SYNCHRONOUS condition, and 3 in NON-STROKING condition. A similar pattern is observed for Statement 6 ('I felt as if the rubber hand was my hand when I felt the brush'), which also globally measures the strength of the illusion. Out of 19 participants, 17 had the illusion in the SYNCHRONOUS condition and 4 in the NON-STROKING condition. As a control, we note that the answers to Statement 4 'I felt that my right hand had melted' were close to zero: out of 19 participants, 14 had a median of zero and 5 participants had medians between zero and '6' in the SYNCHRONOUS condition. In the NON-STROKING condition, 16 participants had median of zero and 3 had medians between zero and '5'. These results for Statement 4 show that positive answers to Statement 5 were not simply the result of participants acquiescing to the experimenter's questions.

In what follows we look at differences in the strength of the illusion in the two conditions.

1.1 Proprioceptive drift

Figure 3 shows that mean proprioceptive drift was greater in the SYNCHRONOUS (3.18 ± 1.16 cm) than in the NON-STROKING (1.20 ± 0.67 cm) condition. A two-tailed paired t-test shows that difference was significant, $t(18)=2.54$, $p<0.05$. Note that simply looking at the rubber hand in the NON-STROKING condition is already sufficient to induce a displacement of the felt position of the participants' index finger. Such an effect has also been found in other studies (Holmes and Spence, 2005; Holmes *et al.*, 2006).

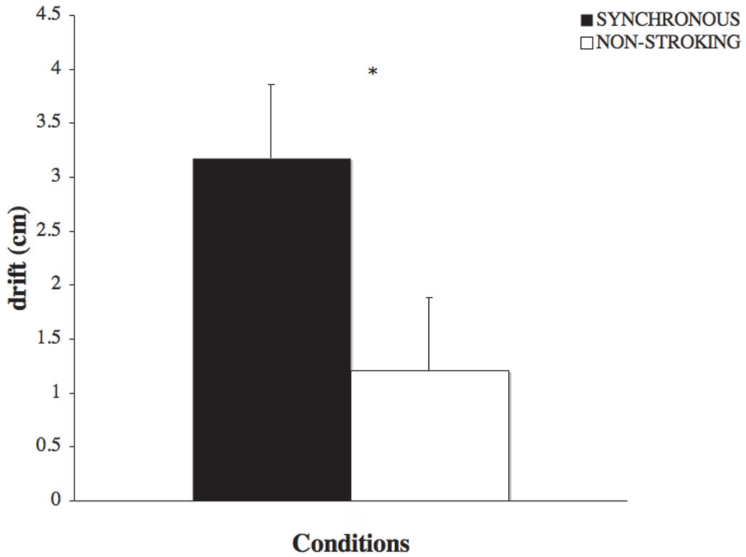

Figure 3. Means and standard errors for NON-STROKING (white) and SYNCHRONOUS (black) conditions of proprioceptive drift defined as the difference between the post- and pre-block estimations of finger location. Zero on the ordinate scale indicates no difference between post- and pre-block finger position estimates; positive values indicate displacement towards the rubber hand. The asterisk indicates a statistically significant difference at $p<0.05$.

1.2 Questionnaire

Since the questionnaire evaluates qualitative variables with non-normal distributions, we used medians and non-parametric statistics to analyse the results, presented in Figure 4.

1.2.1 Presence of the illusion while feeling the thermal stimulation

The level of agreement to Statements 7 and 8, which measure the strength of the illusion during thermal stimulation, show that the illusion was experienced while feeling heat and pain on the hand. However, as seen from Figure 4, the medians for Statements 7 and 8 were lower than for Statements 5 and 6, suggesting that the illusion was less intense while feeling heat and pain than while feeling only the brush.

1.2.2 Effect of condition on the strength of the illusion

The answers to Statements 5 and 6 globally assess the strength of the RHI. In both cases, Wilcoxon tests show a significantly stronger illusion in the SYNCHRONOUS than in the NON-STROKING condition (Statement 5: z=-3.634, p<0.01; Statement 6: z=-3.832, p<0.01). Statements 7 and 8 also measure the strength of the illusion, but this time during the thermal stimulation. Here also the illusion is significantly stronger in the SYNCHRONOUS than in the NON-STROKING conditions (Statement 7: z=-3.186, p<0.01; Statement 8: z=-3.420, p<0.01).

1.2.3 RHI and change in body representation

As concerns the type of modification in body representation that occurred as a consequence of the RHI, levels of agreement between 1 and 4 indicate that neither of the possibilities proposed by Statements 2 and 3 apply. However, the difference of agreement between the SYNCHRONOUS and the NON-STROKING condition for Statement 2 (z=-3.066, p<0.01), suggests that in the SYNCHRONOUS condition participants' experience is closer to feeling a disappearance of the real hand from the body representation than the incorporation of the rubber hand as a supernumerary limb.

1.2.4 Localization of the felt heat and pain

The medians around 4 for Statements 9 and 10 indicate that participants in that condition felt heat and pain sensations somewhat displaced onto the rubber hand in the SYNCHRONOUS condition, but not for the NON-STROKING condition where medians were around 0 (Statement 9: z=-3.422, p<0.01; Statement 10: z=-3.190, p<0.01).

2. Perception of Pain Intensity

We performed a 2x6x3 repeated measures analysis of variance with three factors: condition (NON-STROKING *vs.* SYNCHRONOUS), temperature (38°C, 40°C, 42°C, 44°C, 46°C, and 48°C), and repetition (first, second, and third). Effects are reported as significant when p<0.05 at least. The analysis showed a significant main effect of condition $F(1, 18)$=5.234; of temperature $F(5, 90)$=130.789; and of repetition $F(2, 36)$=6.831. There was a significant interaction effect between condition and temperature $F(5, 90)$=2.957; and between temperature and repetition $F(10, 180)$=2.207. The main effect of stroking condition corresponds to a mean decrease of pain estimation of 0.34 ± 0.14 in the SYNCHRONOUS condition compared to the NON-STROKING condition.

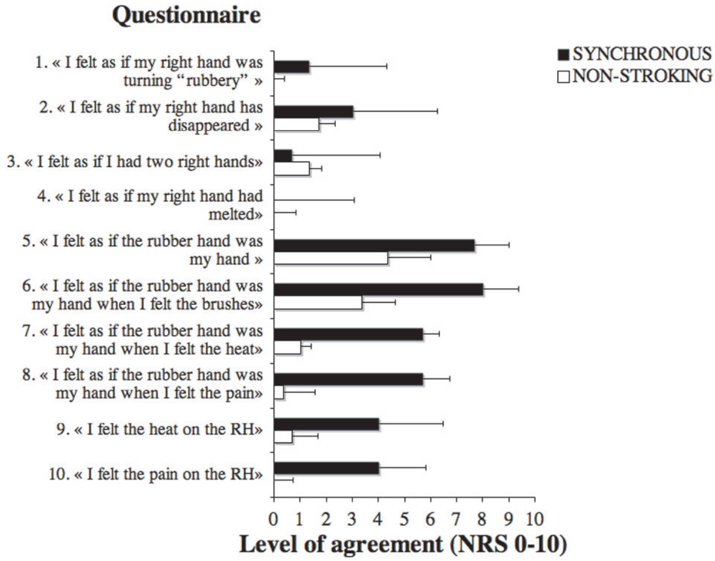

Figure 4. Medians of agreement scores for each statement of the questionnaire. White bars indicate the NON-STROKING condition and black bars the SYNCHRONOUS condition. The error bars indicate one quartile above the median. The questionnaire consisted in ten statements that participants evaluated on a 10-point numerical scale (NRS) after each experimental block. Statements 5 and 6 directly assess the feeling of ownership of the rubber hand.

The origin of the condition x temperature interaction is visible in Figure 5, which shows the means and standard errors of pain ratings for the imposed temperatures. As can be seen from the graph, the difference between SYNCHRONOUS and NON-STROKING conditions is stronger at 46°C. A post-hoc test revealed that pain estimations were significantly lower in the SYNCHRONOUS condition comparing the NON-STROKING condition only at 46°C (p<0.05).

We shall not further discuss the effects and interactions with the repetition factor, which are due to pain being perceived as stronger later in the experiment.

3. Perception of Warmth Intensity

We restricted the analysis of the perception of warmth to 18 participants due to the fact that one participant misunderstood the instruction for distinguishing warmth and pain, making his warmth judgments unusable. There was no difference in warmth estimations between the

NON-STROKING and SYNCHRONOUS conditions. There remains an effect of temperature $F(3, 51)=87.343$, $p<0.001$.

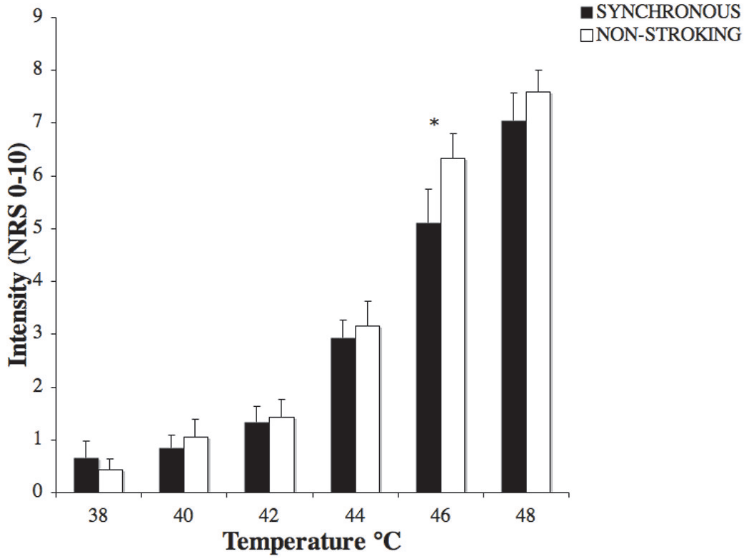

Figure 5. Means and standard errors across participants of pain estimations as a function of temperature. White bars indicate the NON-STROKING condition and black bars indicate the SYNCHRONOUS condition. Pain was estimated on a 10-point numerical rating scale (NRS). The asterisk points to a significant difference at $p<0.05$ indicated by an analysis of contrast.

4. Locus of Pain

Figure 6 shows that the mean of the location of pain as measured at the end of each block of six temperatures in the SYNCHRONOUS condition (9.12 ± 1.41 cm) is shifted towards the rubber hand as compared to the NON-STROKING condition (5.95 ± 0.91 cm). This effect of more than 2 cm is confirmed by a two-tailed paired t-test, $t(18)=3.34$, $p<0.01$.

5. Correlation

In order to evaluate the relation between the intensity of the illusion for each participant and pain estimation differences, the means (by participant) of the responses to Statement 5 in the questionnaire (which evaluates the feeling of ownership of the rubber hand) and the means (by participant) of the difference between SYNCHRONOUS and NON-STROKING conditions on pain estimations were entered into a linear regression analysis. The Pearson regression coefficient showed no correlation (r=0.098). Note, however, that it is statistically not strictly justified to look at correlations calculated from questionnaire data in this way (*cf.* Svensson, 2001).

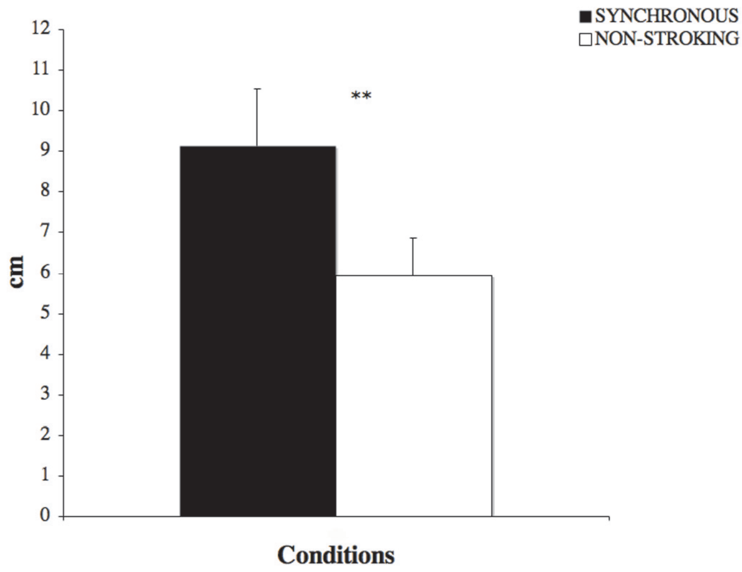

Figure 6. Means and standard errors of pain localization. The white bar indicates the NON-STROKING condition and the black bar indicates the SYNCHRONOUS condition. The value zero corresponds to the position where the thermode was placed over the dorsum of the participants' hand. Positive values indicate locations towards the rubber hand. Double asterisks indicate a statistically significant difference at p<0.01.

6. Participants' Hand Temperature

Our measurements confirmed that participants' right hand temperature at the beginning of the experimental session and before each thermal stimulation remained approximately stable. The mean of the standard deviations across the experimental blocks and across participants was 0.7°C.

Discussion for Experiment 1

The result of our first experiment showed that the RHI overall slightly decreases participants' estimation of pain for thermal stimulations, but with a statistically significant effect only being found at 46°C. The fact that at the lower temperatures there is no significant difference can be explained by a floor effect caused by the fact that at the lower temperatures most participants felt no pain, often giving estimates of '0'. This is coherent with the literature that shows that thermal pain is elicited at temperatures from about 45°C upwards (Bushnell *et al.*, 1985; Miron *et al.*, 1989). The fact that the RHI did not significantly alter pain estimations for the 48°C stimulation could be explained by a ceiling effect: at 48°C the intensity of pain may be so high that participants always give the highest pain ratings. Another possibility is that the strong attention-grabbing nature of intense pain (Crombez *et al.*, 1994; 1997; Eccleston *et al.*, 1997) might have weakened the rubber hand illusion, so weakening the difference found between conditions at this temperature. But this argument is questioned by the results of Capelari *et al.* (2009), who found that using painful stroking instead of normal stroking did not diminish the RHI. Our result (see Figure 4) for Statement 8 of the questionnaire ('I felt as if the rubber hand was my hand when I felt the pain') also shows that the RHI can be induced even while participants feel pain. Still, these findings could apply only within a certain range of pain intensity.

Before concluding that the overall results confirm that the RHI can decrease pain on the 'disowned' hand, several questions need to be addressed.

In the first place, our hypothesis was that it was loss of ownership of the participant's hand that was decreasing pain. Another hypothesis, however, is possible; namely that the effect was simply caused by the distraction effect induced by the RHI, which might have globally decreased pain impressions over the whole body. To dismiss this hypothesis we need to show that diminished pain sensations are confined to the limb which undergoes the illusion: no pain reduction should be found for noxious stimuli given to other parts of the body, e.g. to the foot.

A second issue with our experiment also relates to the hypothesis that the pain decrease is caused by loss of ownership. If this hypothesis holds, then we would have expected to find a correlation between the evaluations of the sense of body-ownership and the strength of the observed pain decrease (as measured by the subjective pain difference between the NON-STROKING and SYNCHRONOUS conditions). Unfortunately we did not find such a correlation (Results — section 5). This might simply be because the measure for ownership of the rubber hand and the measure of pain were taken at different moments:

ownership measures were at the end of each block of six trials, and pain measures were at the end of each trial.

A third issue concerns participants' subjective experience of the RHI. The questionnaire allowed us to obtain a quantifiable measure of certain general aspects of participants' experience in relation to the illusion. It did not, however, allow us to clarify whether the illusion actually involved a subjective loss of ownership of the real hand. An alternative might simply have been that the illusion involved the rubber hand being somehow incorporated into participants' body schema, without the real hand being 'lost'.

A fourth issue concerns the choice of control condition in our experiment. Often, in experiments using the rubber hand paradigm, an *asynchronous* stroking condition is used as control. We chose to use a NON-STROKING control condition instead, since in our pilot experiments we observed that an asynchronous stroking condition induced some ownership over the rubber hand, and we wanted to ensure the strongest possible difference in ownership between our test and control conditions. Unfortunately this had the consequence that there was a difference in visual input in the test and control conditions at the moment of the thermal stimulation. In the test condition the participant was looking at the rubber hand being stroked; in the control condition, the participant saw no stroking. This difference might be invoked as the cause of our observed effect. Indeed, a recent study shows that visual input can modulate pain estimations (Longo *et al.*, 2009). The difference in the visual input at the moment of receiving the thermal stimuli might somehow affect pain estimations, either due to the visual stimuli itself (looking at the source of noxious stimulation versus not seeing it) or by affecting how much attention participants allocated to the rubber hand at the moment of receiving the noxious stimulus.

A final point concerns hand temperature. Moseley, Olthof *et al.* (2008) have shown that the RHI induces a reduction in hand temperature of about ¼ of a degree. This change in temperature might in some way interact with the induction of pain using thermal stimulation. It would be interesting to confirm this effect and understand its interaction with the illusion. Unfortunately, however, our temperature measurements were done only before each trial and using a hand-held infrared thermometer. To improve reliability it would be advantageous to have continuously measured temperature throughout the experiment and to use more accurate equipment.

The purpose of Experiment 2 was to address these issues.

Experiment 2

This experiment had the main aim of demonstrating that the effect of the RHI on pain found in Experiment 1 was specific to the body part involved in the ownership transfer. Thus, in addition to using the previously used condition where painful stimulation was given to the hand, we added a condition into Experiment 2 in which we applied painful stimulation to the foot. Finding an effect on the hand but not on the foot would make more plausible our hypothesis that the phenomenon is really caused by a loss of ownership of the hand, rather than by a global attentional effect.

To further confirm that the effect involved loss of ownership of the hand, we needed a measure of ownership concomitant with the measure of pain. We obtained this in Experiment 2 by requesting ownership judgments after every trial instead of after every block.

In addition, we asked for ownership judgments not only of the real hand but also of the rubber hand. In this way we could check to what degree participants experienced not only loss of their own hand, but also incorporation of the rubber hand into their body schema.

Another issue we needed to rectify in Experiment 2 was that there should be the same type of visual input in the test and control conditions. We did this by using a classic ASYNCHRONOUS stroking condition, rather than the NON-STROKING control condition used in Experiment 1.

Finally we continuously monitored participants' skin temperature in order to check whether Moseley's finding of a temperature decrease in the RHI can be invoked to explain our results.

Participants

Following approval by a local Ethics Committee, the experiment was performed on eighteen (thirteen females and five males; mean age 30.1 ± 2.01 years) paid participants different from the ones who took part in Experiment 1. The participants were informed about the experiment's procedure but not about the hypothesis of the study.

Materials

Throughout the whole experiment, skin temperature was measured continuously using contact sensors attached to participants' hands, forearms, and feet. The sensors were Cu-CuNi thermocouples interfaced to a computer (apparatus constructed by Ellab A/S, Compiègne). A sensor was attached to each of the participant's two index fingers, one to the dorsum of the hand involved in the illusion (right hand), a sensor on left and on right forearms, and a sensor on each foot. The sampling rate was 1 measure every 10 seconds and the accuracy of the measures was ±0.1°C. The sensor response times were 13.5s, except on the fingertips where smaller sensors with faster response times (0.15s) were used.

The thermal stimulation was given with thermodes of Peltier elements measuring 25x50mm (Somedic AB, Stockholm, Sweden). The thermodes were constantly attached: one to the dorsum of participants' right hand and the other to the dorsum of participants' right foot. A third thermode not connected to the power source was attached to the rubber hand.

Procedure

The experiment had two parts: a first part in which we induced the RHI without painful stimulation that we will call 'RHI alone', and a second part in which we combined the RHI with the use of painful thermal stimulation that we will call 'RHI and pain'.

RHI Alone

Participants were seated in front of a table as described for Experiment 1. This section started with a familiarization period of five minutes of synchronous stroking, during which participants could give their subjective impressions if they desired. After this five minute period, participants were explicitly asked to describe their experience. Then participants were familiarized with the method to evaluate limb ownership, as follows. For three minutes we synchronously stroked the participants' hand and rubber hand. Every 45 seconds during this three minute period we asked participants to verbally evaluate their feeling of ownership of the rubber hand and also of their real hand on a scale from 0 ('I feel it does not belong to me at all') to 10 ('I feel it completely as mine'). At the end of the three-minute period, participants were asked to describe their experience. Next, we repeated a three-minute stroking but this time it was asynchronous. Every 45 seconds, participants were again asked to verbally evaluate on a scale from 0 to 10 their feeling of ownership of the rubber hand and also of their real hand, and at the end of the three-minute period, they were again asked to describe their experience.

RHI and Pain

This section was composed of four blocks: two identical SYNCHRONOUS blocks, and two identical ASYNCHRONOUS blocks. The

SYNCHRONOUS and ASYNCHRONOUS conditions were undertaken in alternate order; half of the participants began with the SYNCHRONOUS condition and the other half with the ASYNCHRONOUS condition.

Each block was composed of eight trials; in four of them the thermal stimulation was given to the dorsum of right hand (hand trial) and in the other four they were on the dorsum of the right foot (foot trial). The hand and foot trials were alternated. The temperatures of the thermal stimulations were 40°C, 44°C, 46°C, and 48°C. The order of the temperatures was balanced across the blocks and different for each participant.

Each block started with the tactile stimulation. In the SYNCHRONOUS condition, the tactile stimuli were applied synchronously on the rubber and real hand. In the ASYNCHRONOUS condition participant's hand and the rubber hand were stroked at different places and at different times. When one minute had passed, the experimenter asked the participant to verbally evaluate their feeling of ownership of the rubber hand and also of their real hand on a scale from 0 to 10. Immediately afterwards the thermal stimulus was applied, either on the hand or on the foot. The time-course of the thermal stimulation was the following: the temperature increased from a baseline (32°C) up to the desired temperature (one of 40°C, 44°C, 46°C, and 48°C) in 4 seconds, then the desired temperature was held for two seconds, after which it dropped back to baseline at the same rate. Immediately after the thermal stimulus, participants were asked whether the sensation was painful or not. If the sensation was painful, they were asked to verbally evaluate pain intensity on a numerical scale graduated from 0 ('no pain') to 10 ('worst possible pain'). If the stimulus was not painful participants were asked to evaluate the warmth sensation, also on a numerical scale graduated from 0 ('not warm') to 10 ('very warm'). This procedure was repeated eight times in all in order to complete the four temperatures (40°C, 44°C, 46°C, and 48°C) on the hand and on the foot. The order of stimulation was balanced across the blocks and different for each participant.

Results

The results and the discussion of Experiment 2 will concentrate on the second part of the experiment, particularly on ownership and pain estimations. The results of the participants' descriptions of the illusion and the details of temperature measurements go beyond the scope of this article and will not be included.

1. Occurrence of the Illusion

In order to assess the occurrence of the illusion we looked at participants' evaluations of ownership of the rubber hand and of their own hand on the numerical rating scale from 0 to 10. If we assume that an evaluation of the feeling of ownership of the rubber hand over 5 indicated the presence of the illusion, then eighteen participants out of eighteen experienced the illusion in the SYNCHRONOUS condition and four participants experienced it in the ASYNCHRONOUS condition.

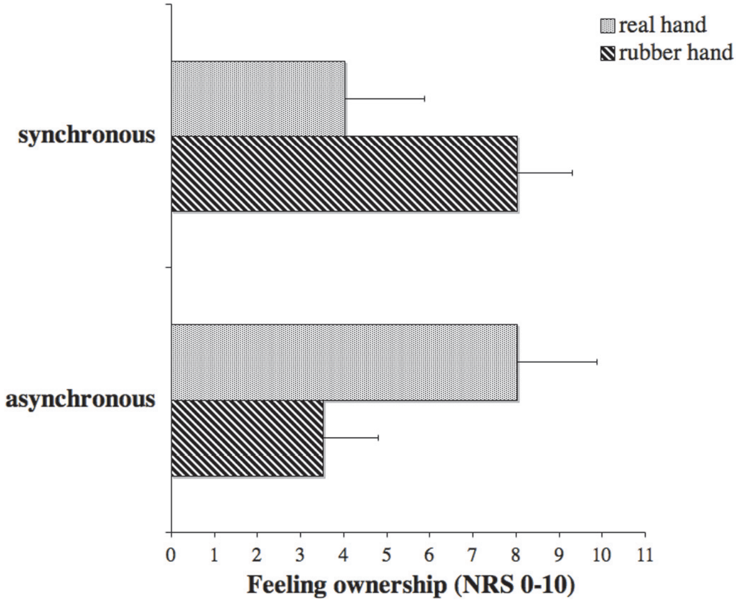

Figure 7. Feeling of ownership of the rubber and real hand in the SYNCHRONOUS and ASYNCHRONOUS conditions. The bars indicate the median across participants; error bars indicate one quartile above the median. Feelings of ownership towards the rubber and real hands were assessed after each one-minute stroking period and estimated on a 10-point numerical rating scale (NRS).

The results indicate that in the SYNCHRONOUS condition participants incorporated the rubber hand and partially lost their own hand from their body representation. On the other hand, in the ASYNCHRONOUS condition, participants partially incorporated the rubber hand into their body representation, but did not lose their hand from it (Figure 7).

2. Perception of Pain Intensity

As in Experiment 1, we found that the RHI modified the estimations of pain, but this time pain estimations *increased*.

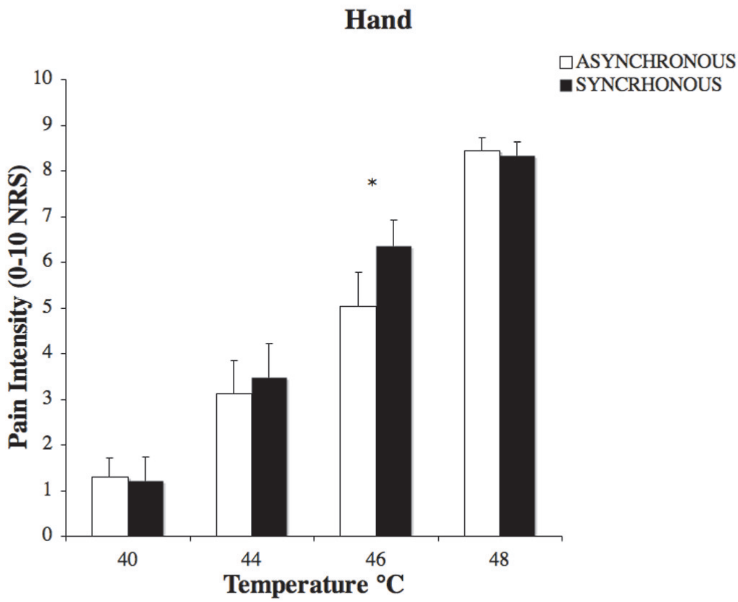

Figure 8. Means and standard errors across participants of pain estimations on the **hand** as a function of temperature. Black bars indicate the SYNCHRONOUS condition and white bars the ASYNCHRONOUS condition. The asterisk corresponds to a significant difference at $p<0.05$ indicated by the result of the post-hoc comparisons.

We performed a 2x2x4x2 repeated measures analysis of variance with four factors: condition (SYNCHRONOUS *vs.* ASYNCHRONOUS), body part (hand *vs.* foot), temperature (40°C, 44°C, 46°C, 48°C), and repetition (1, 2). Effects are reported as significant when $p<0.05$ at least. The analysis shows an effect of condition $F(1, 17)=6.210$; of temperature $F(3, 51)=85.08$; of repetition $F(1, 17)=6.49$, $p=0.021$; and an interaction of condition and temperature $F(3, 51)=4.335$. We performed a post-hoc test in order to compare the effect of condition on each temperature and of pain elicited on the hand and on the foot (see Figure 8 and Figure 9). The comparisons revealed that the effect of condition was only significant at 46°C and for pain estimations on the hand ($p<0.05$).

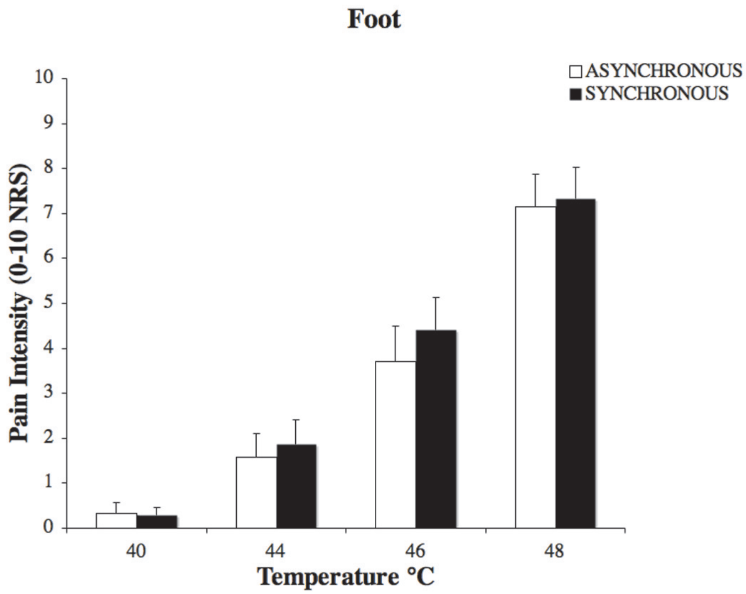

Figure 9. Means and standard errors across participants of pain estimations on the **foot** as a function of temperature. Black bars indicate the SYNCHRONOUS condition and white bars the ASYNCHRONOUS condition.

3. Correlation

In order to evaluate the relation between pain estimation differences on the hand and the intensity of the illusion for each participant, the means (by participant) of the evaluation of the feeling of ownership of the rubber hand and the means (by participant) of the difference between pain estimations in the SYNCHRONOUS and ASYNCHRONOUS conditions were entered into a linear regression analysis. Although not strictly applicable in cases where the evaluation scale is ordinal, the Pearson regression coefficient showed a tendency for a positive correlation, r=0.453, p=0.059, n.s., suggesting that when the feeling of ownership of the rubber hand was stronger, the difference in pain estimations were also greater (see Figure 10).

4. Temperature

Continuous measurement of temperature of the stimulated hand during the experiment showed that applying the painful thermal stimulation created an increase in hand temperature of approximately 0.015°C. Moseley's finding that synchronous stroking provokes a drop in hand temperature was confirmed in the first part of Experiment 2, where we found a drop of 0.21°C ± 0.067 going from ASYNCHRONOUS to SYNCHRONOUS conditions, $t(8)=3.11$, $p=0.014$. Interestingly, in the second part, where painful thermal stimulation was added, the effect, though in the same direction, was much smaller 0.045 ± 0.07 and not significant $t(17)=0.61$, n.s. We shall leave additional analysis of this difference for further work.

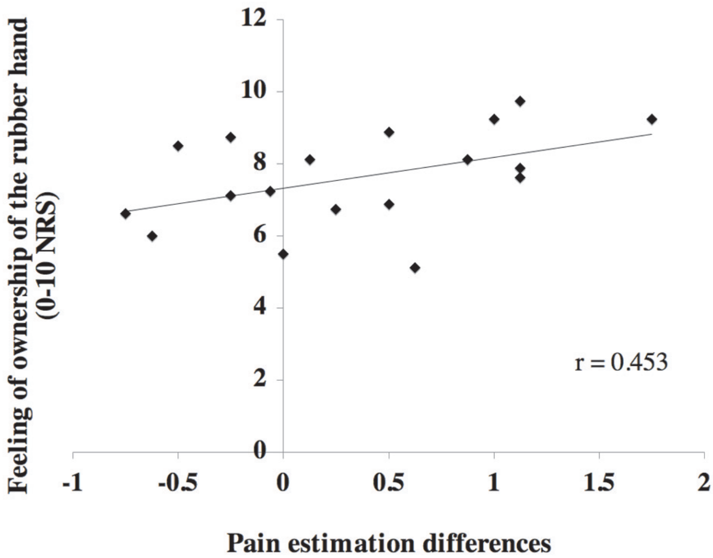

Figure 10. Correlation between the differences in pain estimations between the ASYNCHRONOUS and SYNCHRONOUS conditions and ratings to the feeling of ownership towards the rubber hand. Positive differences in pain estimation values indicate more pain in the SYNCHRONOUS condition.

Discussion of Experiment 2

This experiment had the aim of (a) demonstrating that the effect of the RHI on pain found in Experiment 1 was specific to the body part involved in the ownership transfer; (b) to obtain a measure of ownership that is concomitant with the measure of pain; (c) to clarify if this effect related to the participants' experience of loss of their real hand and/or incorporation of the rubber hand into their body schema; (d) to control for the type of visual input in the test and control conditions; (e) to monitor participants' skin temperature in order to check whether

Moseley's finding of a temperature decrease in the RHI can be invoked to explain our results.

Our results show that pain estimations increased for the 46°C thermal stimulations on the hand. Though very similar to the data for the hand, the pain estimations of stimulation on the foot did not differ significantly for SYNCHRONOUS and ASYNCHRONOUS conditions, which suggests that the effect of the RHI may be specific to the body part involved in the ownership transfer. We found a correlation of r=0.453, p=0.059, between the evaluations of the feeling of ownership of the rubber hand and the difference in pain estimations between the SYNCHRONOUS and ASYNCHRONOUS conditions. On the other hand, no correlation was found for the evaluations of the feeling of ownership of the real hand and the difference in pain estimations between the SYNCHRONOUS and ASYNCHRONOUS conditions, suggesting that the pain difference between the SYNCHRONOUS and ASYNCHRONOUS conditions is more related to the incorporation of the rubber hand into participants' body representation than to the loss of the real hand from participants' body representation.

The evaluations of the feeling of ownership of the rubber and real hands show that the ownership of the rubber hand increases and ownership of the real hand decreases in the SYNCHRONOUS condition compared to the ASYNCHRONOUS condition. It is noteworthy that the effect of condition on ownership is greater on the rubber hand than on the real hand, suggesting that the rubber hand illusion is more strongly affecting the incorporation of the rubber hand than the loss of the real hand.

3. General Discussion

The main objective of the two experiments presented here was to test the effect on pain estimations of a modification in body-ownership induced through the RHI.

In the first experiment we found that pain estimations *decreased* when the illusion was induced, and in the second experiment we found that pain estimations *increased*: the respective decrease and increase in pain estimations were of similar magnitude. Why do we find this discrepancy between the results of the first and second experiments? In what follows we analyse possible factors that might participate in contributing to the difference in results.

3.1 Control Conditions

The results presented here are always in terms of a comparison between a 'test' and a 'control' condition. In both experiments the test conditions were the same, that is, synchronous stroking. However, the control conditions were different. The control condition of the first experiment was NON-STROKING of the rubber hand, while the control condition of the second was ASYNCHRONOUS stroking. How can this difference have changed the effect of the illusion on the estimations of pain intensity?

3.1.1 Degrees of Ownership

It could be that the two control conditions induced different degrees of 'non-illusion'.

As can be seen from our results for proprioceptive drift in the NON-STROKING of the rubber hand control condition of Experiment 1, simply looking at the rubber hand without stroking was already sufficient to induce a displacement of the felt position of the participants' index finger (proprioceptive drift).

Concerning the ASYNCHRONOUS control condition of Experiment 2, we observed that several of our participants did express some feeling of ownership of the rubber hand. Such an observation has also been made in other studies (Longo *et al.*, 2008; Lewis and Lloyd, 2010). Another point is that some participants said that the ASYNCHRONOUS condition felt more disturbing than the synchronous condition because, although they noticed the incongruence between what they saw and what they felt, they could not avoid having very ambiguous sensations: some of them felt the touch where they saw the brush touching the rubber hand; others felt the touch on the rubber hand in the location where the brush was touching their real hand — even though they did not see the brush in that location. Lewis and Lloyd (2010) have also reported similar impressions in the asynchronous stroking condition of their study, they have called these feelings 'violation of expectation'.

These different degrees of illusion and possible differences in its nature between the NON-STROKING and ASYNCHRONOUS control conditions could possibly affect the comparison of these with the SYNCHRONOUS test condition in the two experiments.

3.1.2 Nature of Change in Body Awareness

A second point that might differentiate the two experiments concerns possible differences in body awareness. Here we have been assuming that the RHI induces a kind of 'disownership' of the participant's own hand. This is also the point of view of Moseley, Olthof *et al.* (2008); Armel and Ramachandran (2003); Ehrsson *et al.* (2007); and Tsakiris

(2010). However, an alternative hypothesis has been suggested in the literature, namely that there need be no real disownership or replacement of the participant's hand (Schütz-Bosbach *et al.*, 2009). The rubber hand could simply be incorporated into the body schema, in addition to the real hand.

If we consider the 'disownership' hypothesis, which was our initial hypothesis for Experiment 1, we would predict that participants should feel less pain in a condition where the illusion is induced, in comparison to a condition where the illusion is not induced, since when the illusion is induced, the participant does not feel their hand as being part of their body. This hypothesis could explain the results for Experiment 1. However, the hypothesis does not explain Experiment 2, since here pain *increases* when the illusion is induced.

Consider the second possibility, which is that the RHI induces an incorporation of the rubber hand into the participant's body schema. Here one would predict that since participants really felt the rubber hand as being their own, then pain seen as inflicted on the rubber hand should be perceived as more intense. This hypothesis could explain the results of Experiment 2 but not of Experiment 1.

A plausible possibility is that the RHI implies both: a degree of incorporation of the rubber hand into the person's body schema and, to some extent, a removal of the real hand from the person's body schema. The degree to which participants incorporate the rubber hand and the degree to which they remove their real hand from their body schema could together determine the sense in which pain estimations will be affected. From the body-ownership evaluations of Experiment 2, we observed that in many cases the SYNCHRONOUS and ASYNCHRONOUS conditions involve different degrees both of ownership of the rubber hand and ownership of the real hand. In Experiment 2 our result showed that the effect of inducing the rubber hand illusion was stronger on the ownership of the rubber hand than on the 'disownership' of the real hand. Thus one could suppose that, in Experiment 2, the change in participants' body awareness between the two conditions essentially concerned the rubber hand. But as we did not assess the degree of ownership of the real hand in Experiment 1, we cannot estimate the contribution of this component in Experiment 1. It is possible that the effect of a modification in body-ownership might depend on the precise type of ownership modification involved. It is therefore important to clarify the subjective nature of the change and consider the differences in types of body-ownership modification across participants.

3.1.3 Visual Input

Another possibility to explain the difference between Experiments 1 and 2 is that a difference in visual input at the moment of receiving the painful stimulus plays a role. A recent study by Longo *et al.* (2009) shows that pain elicited by an infrared laser is less intense when participants look at the part of their own body which is in pain than when they look at an object or at another person's body.

Although these results seem contrary to the everyday 'out of sight, out of mind' intuition that a pain (such as an injection) is less painful when you look away from it, it is worth considering our results in the light of Longo *et al.*'s idea.

In the SYNCHRONOUS condition of Experiment 1 participants transfer ownership to the rubber hand. Since the rubber hand feels like the participant's own hand, and since the participant is looking at it, we expect, by Longo's result, that there should be less pain. Conversely, in the NON-STROKING of the rubber hand condition, there is very little or no transfer of ownership to the rubber hand. Participants therefore feel that it is not their own hand they are looking at, and they should feel more pain. This reasoning allows us to explain the results of Experiment 1.

In the SYNCHRONOUS condition of Experiment 2, participants felt the rubber hand as their own, so, as in Experiment 1, we could say that they feel that it is their own hand they are looking at. In the ASYNCHRONOUS condition there is little transfer of ownership to the rubber hand, so participants feel that they are not looking at their own hand, and should feel more pain. This reasoning does not allow us to explain the results of Experiment 2.

It should be noted that this argument concerning the ASYNCHRONOUS condition of Experiment 2 can be questioned, because the ownership component in the ASYNCHRONOUS condition is more ambiguous than in the control condition of Experiment 1. Indeed, for some participants, the ASYNCHRONOUS condition actually does elicit ownership of the rubber hand. This observation is corroborated by the study performed by Lewis and Lloyd (2010); the authors found that 84% of participants still reported feeling ownership of the rubber hand in the ASYNCHRONOUS condition.

We see that if what is important is whether participants are looking at where on their own body they feel pain, then we need to better assess where in fact they feel their own body to actually be located throughout the illusion.

3.2 Evolution of the Illusion Over Time

Above we have considered differences linked to the control conditions used in Experiments 1 and 2 as a possible explanation for the differences in the results. Now we shall consider a possibility related to differences in the perceived nature of the illusion during the course of the experiments.

Preliminary analysis of participants' descriptions of the illusion in Experiment 2 suggests that there are different phases of the illusion; for some persons the illusion goes from experiencing the rubber hand as an external object unrelated to their body, passing through an intermediate phase in which participants start to feel the touch on the rubber hand — but the real hand remains present in their body schema — up to a phase, for those who have a strong illusion, in which their real hand is completely removed from their body schema and the rubber hand is felt as their own hand. For others, these different phases shift, for instance, depending on their focus of attention.

Even if these observations are only preliminary, they are coherent with what has been found at an experiential and neurological level. Lewis and Lloyd (2010) have recently published a study whose aim was to characterize the experience of the RHI using first-person reports. The authors confirm that the experience of the illusion is composed of several components, including 'ownership of the rubber hand' and 'loss of the real hand'. In addition, the authors found that there was an evolution of the experience over time. Neurophysiological findings also suggest an evolution in the neural activity related to the establishment of the illusion. fMRI studies conducted by Ehrsson *et al.* (2004; 2005) show activation in areas of the premotor and parietal cortex in a temporal window that corresponds to the onset of the illusion (from 11 ± 7s up to 45s after the start of stimulation). On the other hand Tsakiris, Hesse *et al.* (2007) in a PET study show activation in the right posterior insula and the right frontal operculum in a later temporal window (from 45s up to 105s after the beginning of the stimulation). Tsakiris and collaborators proposed that the sensory event that 'causes' the rubber hand illusion might be different from the phenomenal 'effects' of ownership induced by the illusion. Tsakiris suggest that the activity in the parietal and premotor cortex found by Ehrsson might be related to the multi-sensory integration that causes the illusion, and that the activity of the posterior insula and operculum is related to the sense of owning the rubber hand. If this is true, it is plausible that pain estimation is modulated differently depending the phase of the illusion.

3.3 Control Over Pain

Another factor which we think is important to consider in understanding the difference between Experiments 1 and 2 is participants' perceived sense of control over the painful stimuli. Several experimental studies have shown that providing participants with some level of control over painful stimulation can increase pain tolerance (Staub *et al.*, 1971; Weisenberg *et al.*, 1985). In our Experiment 1, the thermodes were placed on participants' hands only at the moment of giving the thermal stimulation; in our Experiment 2, thermodes were constantly attached to participants' right hand, right foot, and to the rubber hand. Furthermore, participants had seven temperature sensors attached to their hands, forearms, and feet. In comparison to Experiment 1, this considerably reduced their mobility, and their potential capacity to withdraw from the painful stimulation. We observed that, contrary to Experiment 1, in Experiment 2 several participants were very anxious about the experimental set-up. This factor could have caused a global decrease in pain tolerance in Experiment 2, which could in turn interact with one or other of the factors mentioned above and affect the direction of the results.

4. Conclusion

The motivation of our experiments was to explore the possibility that the sense of owning our body has an impact on pain perception. Indeed we did find that an illusion that modifies the sense of body-ownership modulates pain estimations. Nonetheless, our results show that the relationship between the illusion and pain perception is not a simple one. The direction of this modulation seems to be determined by one or more up-to-now unknown variables.

We believe that a key issue will be a better understanding of the nature of the change in participants' body awareness induced by the illusion, in particular to what degree the illusion involves replacement of the real hand or merely incorporation of the rubber hand. It will also be important to understand the evolution of this change during the course of induction of the illusion. We think that in future an approach should be used that takes account of the subjective experience of the participants, and that includes a method to categorize and measure each of the experiential components of the illusion. A protocol should also be used that controls for visual input and participants' sense of control over the painful stimuli.

The complexity of our results illustrates the complexity of pain experience: many factors need to be considered in order to understand its nature and modulation. We believe that clarification of the effects of the RHI on pain can contribute to the understanding of the relationship between body awareness and pain.

Acknowledgments

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