

1 **RUNNING HEAD: virtual body ownership and pain threshold**

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3 **Modulation of pain threshold by virtual body ownership**

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- 27 • Realistic sensorimotor correlations induce the illusion of ownership of virtual
- 28 body parts.
- 29 • Recent findings have demonstrated that seeing one's own body is analgesic, but
- 30 it is not known whether this effect is transferable to newly embodied body parts.
- 31 • The current study demonstrates that heat pain threshold significantly increases
- 32 following ownership of a digital body in virtual reality. Virtual reality itself or
- 33 just looking at a non-embodied digital body does not yield the same effect.

34

35

1 **Abstract**

2 **Background**

3 Appropriate sensorimotor correlations can result in the illusion of ownership of
4 exogenous body parts. Nevertheless, whether and how the illusion of owning a new
5 body part affects human perception, and in particular pain detection, is still poorly
6 investigated. Recent findings have shown that seeing one's own body is analgesic, but it
7 is not known whether this effect is transferable to newly embodied, but exogenous,
8 body parts. In recent years, results from our laboratory have demonstrated that a virtual
9 body can be felt as one's own, provided realistic multisensory correlations.

10 **Methods**

11 The current work aimed at investigating the impact of virtual body ownership on pain
12 threshold. An immersive virtual environment allowed a first-person perspective of a
13 virtual body that replaced the own. Passive movement of the index finger congruent
14 with the movement of the virtual index finger was used in the "synchronous" condition
15 to induce ownership of the virtual arm. The pain threshold was tested by thermal
16 stimulation under four conditions: 1) synchronous movements of the real and virtual
17 fingers, 2) asynchronous movements, 3) seeing a virtual object instead of an arm, and 4)
18 not seeing any limb in real world.

19 **Results**

20 Our results show that, independently of attentional and stimulus adaptation processes,
21 the ownership of a virtual arm *per se* can significantly increase the thermal pain
22 threshold.

23 **Conclusions**

24 This finding may be relevant for the development and improvement of digital solutions
25 for rehabilitation and pain treatment.

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Keywords: pain threshold, virtual reality, body ownership, pain modulation.

Introduction

Virtual reality (VR) technology represents a versatile tool for different areas of research since it allows the creation of sensory environments that can be replicated identically across experiments and that are under the full control of the experimenter (Sanchez-Vives and Slater, 2005). In particular, VR offers a novel and valuable resource for psychological and medical rehabilitation purposes. In pain management, immersive VR has been reported by Hoffman and colleagues as an adjunctive analgesic treatment of pain for burn-injured adolescent (Hoffman et al., 2000a) and adult patients (Hoffman et al., 2000b). Other studies refer to the employment of VR as a method for tackling phantom limb pain (Cole et al., 2009; Murray et al., 2007) and for the diagnosis and treatment of complex regional pain syndromes (Llobera et al., 2013a; Sato et al., 2010). The analgesic effect derived from the utilization of VR often stems from its power to draw attentional resources away from the hurting body part (Malloy and Milling, 2010). It has been shown that VR is highly effective since it can provide an alternative reality, fully immersive and interactive. Indeed, distraction *per se* has been recognized as a powerful factor in lowering pain ratings outside VR (Bantick et al., 2002). Nonetheless, not all the analgesic effects due to psychological factors rely on sheer attentional modulation. So, Studies conducted in healthy subjects have shown a modulatory effect of the vision of the body on experimentally-induced pain. For instance, Longo and colleagues have reported a decrease in the pain ratings when the participants looked at their own body but not when they looked either at a non-corporeal object or at someone else's body, suggesting that the vision of one's own body may have a local analgesic

1 effect (Longo et al., 2009, 2012). Another study has shown that the manipulation of
2 one's hand or limb size affects pain, such that seeing the hand smaller decreases pain
3 while seeing the hand larger increases it (Mancini et al., 2011).

4 Despite substantial evidence showing that a fake or a virtual body part can be
5 incorporated in one's body image (i.e. embodied), (Botvinick and Cohen, 1998;
6 Sanchez-Vives et al., 2010; Slater et al., 2008) and that looking at one's body can
7 modulate pain perception (Longo et al., 2009), to our knowledge only two studies have
8 investigated so far the relationship between pain and embodiment, with contradictory
9 results (Hansel et al., 2011; Mohan et al., 2012). In one of these studies (Hansel et al.,
10 2011), the authors assessed pressure pain threshold on the index finger using an out-of-
11 body experience paradigm (third-person perspective approach). They reported that just
12 the vision of the mannequin standing in front of the participants led to higher pain
13 thresholds, independently of the identification with it (Hansel et al., 2011). In the other
14 study, no effect of the rubber hand illusion was found on pain perception (Mohan et al.,
15 2012).

16 Hence, it remains unclear whether the effect of seeing one's own body on pain
17 perception holds true when embodying new dummy or virtual bodies. In the current
18 study, we investigate the effects of virtual body ownership on the heat pain threshold. In
19 order to create the illusion of ownership of the virtual body we use multisensory
20 correlations and first-person perspective with respect to a virtual body.

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1 **Methods**

2 **Participants**

3 32 right-handed healthy participants (19 females, mean±SD age: 23.9±5.7) were
4 recruited for the experiment. They had normal or corrected-to-normal vision and no
5 history of neurological or psychological disorders. Also, any condition potentially
6 interfering with pain sensitivity (e.g. drug intake) was considered as a further exclusion
7 criterion. Upon arrival at the laboratory they were asked to read and sign a consent form
8 and the experiment was carried out in accordance with the regulations of our ethics
9 committee (Comité Ético de Investigación Clínica de la Corporación Sanitaria Hospital
10 Clínic de Barcelona). All participants received a monetary reimbursement for their
11 participation (10 €).

12 Since the purpose of the study was to examine the effects of virtual body ownership on
13 pain threshold, a pre-requisite was that participants were able to experience that body
14 illusion (Ehrsson et al., 2005). Therefore, only those participants that experienced the
15 illusion, i.e. those scoring between 5 and 7 in the question referring to virtual body
16 ownership (see Questionnaire section), were considered for this study. Thus, data from
17 24 healthy right-handed participants (14 females, mean±SD age: 25.5±5.8) were finally
18 taken into consideration. This represents 75% of the initial sample, which is comparable
19 to the percentage obtained previously in experiments with rubber (Ehrsson et al., 2005)
20 and virtual hand illusions (Perez-Marcos et al., 2012).

21

22 **Virtual reality system**

23 The stereoscopic head-mounted display (HMD) was a NVIS SX111 with a resolution of
24 1280x1024 pixels per eye and a total field of view of 111° x 64°, displayed at 60Hz. The
25 head-tracking was realized with a 6-DOF Intersense IS-900 device (InterSense,

1 Billerica, USA). Finger's tracking was permitted by attaching two markers to the
2 participant's finger. These markers were constantly tracked by 12 infrared Optitrack
3 cameras and their coordinates in the space were computed with the Arena software
4 (NaturalPoint, Corvallis, USA). Hence, when the participant's finger was moved, the
5 avatar's finger could move accordingly, mimicking exactly the same movements at the
6 same time. The virtual environment was programmed using the XVR system (Tecchia
7 et al., 2010) and the virtual body using the HALCA library (Gillies and Spanlang,
8 2010). Figures 1 and 2 show how the real and the virtual environments looked like.
9 Noise isolation was ensured by the administration of pink noise through a surround
10 audio system (Creative technology Ltd., Singapore), with a constant volume set at 65
11 dB. Figures 2A and 2B show the virtual environments for the different VR conditions
12 from a top view.

13

14 **Thermal stimulation and temperature**

15 Thermal heat stimuli were delivered by means of a Somedic-Thermotest machine
16 (Somedic, Stockholm, Sweden) with a 2.5 cm x 5.0 cm thermode tied with a Velcro
17 strap on the forearm, close to the radius bone (see Fig. 2D). Pain thresholds were
18 assessed with the method of limits (Yarnitsky et al., 1995). The probe temperature was
19 increased from normal skin temperature (constant baseline temperature = 31 °C) at 2
20 °C/s. Participants pressed a button with their left hand as soon as they perceived the
21 stimulation as being painful. Immediately after pushing the kill-switch button, the probe
22 temperature rapidly decreased to the baseline temperature. For safety reasons, maximal
23 temperature was set at 50 °C.

24 Skin temperatures on both the forearm (next to the thermode) and the hand (on the first
25 dorsal interosseous) were measured with two Type K (TF-500) thermocouple probes

1 linked to a PCE-T 390 digital thermometer (PCE Inst., Meschede, Germany), with a
2 resolution of 0.1°C and a sampling rate of 0.5 Hz. All temperatures were continuously
3 monitored. The analogue data from the sensors of the thermometer were acquired with a
4 NI-6008 card (National Instruments Corporation, Austin, USA) and the values saved in
5 MatLab Simulink (The MathWorks Inc., Natick, USA).

6

7 **Procedure**

8 Participants sat comfortably on a chair with both arms resting on a table covered with a
9 black cloth as shown in Figures 1 and 2. The arms were in a straight but rested posture
10 and were 60 cm apart. Before entering the VR, participants were given three heat
11 stimuli to familiarize them with the heat ramps.

12 As the subject donned the HMD, the room's lights were turned off and the pink noise
13 played. The HMD allowed participants to experience an immersive virtual environment
14 around them and to see a virtual body collocated with their own from a first-person
15 perspective (Fig. 2A). When they looked down towards their own body, they could see
16 the virtual body in place of their real own body. Before the start of each VR condition,
17 participants were given approximately one minute to familiarize with the virtual room
18 and with the virtual body. The experiment consisted of four different conditions:

19 a) A control condition run outside VR ("control outside", or "CO") served as a baseline.
20 Participants were asked to look at a fixation mark placed on top of a foam cover, which
21 prevented them from seeing their limbs (Fig. 2D).

22 b) A control condition run within VR ("control inside" or "CI"), where no virtual body
23 was present. Instead, a non-corporeal object (an oblique cylinder) appeared on the table
24 (Fig. 2B). Participants were asked to look at the tip of the cylinder, which corresponded
25 to the place where the avatar's fingers were in the other conditions.

1 c) A condition within VR, where the avatar's index finger moved independently from
2 the real finger ("asynchronous", or "A" condition).

3 d) A condition within VR, where the avatar's index finger moved in accordance with
4 the real finger ("synchronous", or "S" condition).

5 Both in the A and S conditions, participants were asked to focus on the finger
6 movements. The virtual right arm appeared bent at about 41 degrees away from the real
7 arm and towards the body midline (Fig. 2A). This procedure was meant to hamper the
8 illusion of ownership in the A condition, which may have occurred by simply matching
9 the collocation of one's limb with the avatar's limb (Slater et al., 2010). Importantly,
10 both the virtual hand and forearm were always kept in the field of view of the
11 participants. In all conditions, an experimenter constantly moved the participant's right
12 index finger in a flexion-extension fashion. This passive movement was meant to
13 provide the proprioceptive feedback without calling into play the role of agency induced
14 by active movement (Kalckert and Ehrsson, 2012). Characteristic of the S condition was
15 that correspondence between the visual, motor and the proprioceptive inputs provided
16 the experience of "embodying" the avatar's limb, a phenomenon already documented as
17 effective for inducing the virtual hand illusion (Sanchez-Vives et al., 2010). All
18 participants completed the four conditions, with the order of the conditions balanced
19 across participants. Each condition started with the participant looking at the indicated
20 point for 20 s. Then, the finger movement started, the first heat stimulus provided 20 s
21 later. The inter-stimulus interval was set at 60 s and three heat ramps were provided for
22 each condition.

23

24 **Questionnaire**

1 After each condition, the HMD was removed and participants were given a
2 questionnaire in Spanish (Table 1), which included different questions to evaluate
3 anxiety, attention, presence in the virtual environment and body ownership for all given
4 conditions. Each item was measured along a seven-points Likert-scale. The order of the
5 items in the questionnaire was randomized among subjects.

6

7 **Data handling**

8 Skin temperatures and pain thresholds were all recorded in degrees Celsius. For each
9 condition hand/arm skin temperatures and pain thresholds were recorded. Despite the
10 proximity of the arm sensor to the thermode, the recorded arm skin temperature was not
11 influenced by the increasing heat ramps. The temperature at which participants pressed
12 the button to stop the thermal stimulation was considered as the pain threshold (see
13 above).

14 All variables were normally distributed according to both the Kolmogorov-Smirnov and
15 the Lilliefors tests (all $p_s > 0.05$). One-way repeated-measures ANOVA (factor:
16 “Condition” with 4 levels) was conducted on mean pain thresholds, as well as on the
17 arm and hand skin temperature separately. Post-hoc analysis after one-way ANOVAs
18 was conducted with Newman-Keuls tests.

19 Being obtained from an ordinal scale, the scores reported for the same variable (item) of
20 the questionnaire in each condition were subjected to nonparametric Friedman
21 ANOVAs. Post-hoc analysis with Wilcoxon Matched Pairs Tests was conducted with a
22 Bonferroni correction applied for the number of possible comparisons. This resulted in a
23 significance level set at $p < 0.008$ for anxiety and attention scores, $p < 0.016$ for
24 cylinder/arm, cylinder/hand ownership and the level of presence.

1 Statistical comparisons between conditions were conducted with STATISTICA
2 (StatSoft, Inc., Tulsa, OK, USA).

3

4 **Results**

5 **Pain thresholds and skin temperature**

6 The heat pain thresholds and skin temperature were measured for the four experimental
7 conditions (CO, CI, A, S). Group mean pain thresholds for each condition and skin
8 temperatures are reported in Table 2. The one-way ANOVA on the mean pain
9 thresholds revealed a significant effect of the factor “Condition” ($F_{3, 69}=4.36$, $p=0.007$)
10 indicating that participants’ pain threshold was differently affected under our
11 experimental conditions. Newman-Keuls post-hoc test revealed that the only condition
12 reporting significant difference with the others was the S condition, namely when the
13 ownership of the avatar’s arm occurred. Indeed, only in this condition the mean
14 threshold was significantly higher with respect to either the CO condition ($p=0.006$) and
15 also the CI condition ($p=0.038$). No other comparison was found to be significant (S vs.
16 A: $p=0.22$; A vs. CO: $p=0.092$; A vs. CI: $p=0.21$; CI vs. CO: $p=0.39$);. These results
17 suggest that only when participants had the illusion to own the virtual body their pain
18 threshold was effectively higher, while just the vision of an avatar’s body or of an
19 object replacing the body did not yield any statistically relevant difference.

20 With respect to skin temperature, the one-way repeated-measures ANOVA showed no
21 significant effect of the factors for the arm ($F_{3,69}=0.73$, $p=0.53$) or for the hand
22 (“Condition”: $F_{3,60} = 0.63$, $p=0.60$) revealing a lack of modulatory effect on skin
23 temperatures by the ownership of the virtual arm and hand under the present
24 experimental design.

25

1 **Questionnaire results**

2 The scores obtained from the questionnaires after each condition are reported in Table
3 3. The analysis with Friedman ANOVAs reported that the arm/cylinder was embodied
4 differently by the participants while experiencing the different conditions ($\chi^2=39.29$,
5 $p<0.00001$). In particular the illusion of ownership of the avatar's arm in the S condition
6 was stronger than the sense of ownership of a cylinder ($p=0.000004$) and also of the
7 same virtual arm in the A condition ($p=0.00002$). Irrespective of the synchronous or
8 asynchronous movement, the virtual arm was more embodied than the cylinder, as the
9 significant difference between A and CI shows ($p<0.0005$). Also the Friedman ANOVA
10 conducted on the hand/cylinder embodiment showed significant differences for the
11 reported level of ownership among conditions ($\chi^2=38.50$, $p<0.00001$). In particular the
12 sense of ownership of the virtual hand was found to be significantly stronger in the S
13 condition compared both to A ($p=0.000008$) and CI conditions ($p=0.000003$) and also
14 higher in the A condition compared to the cylinder ($p=0.0074$). Importantly, the
15 synchronous movement of the finger not only led to the ownership of the hand but it
16 extended to the entire arm.

17 A significant effect was found between Condition and the attention scores ($\chi^2=7.93$,
18 $p=0.047$), but not for anxiety scores ($\chi^2=6.30$, $p=0.097$). However, post-hoc tests failed
19 to report any significant difference between conditions in terms of attention paid to the
20 painful stimulus (all $ps>0.0083$: CO vs. CI, $p=0.76$; CO vs. A, $p=0.029$; CO vs. S,
21 $p=0.012$; CI vs. A, $p=0.11$; CI vs. S, $p=0.027$; A vs. S, $p=0.50$). This would rule out a
22 differential role of attention on the modulation of pain thresholds.

23 The analysis of the "presence" score (the illusion of being in the virtual space)
24 highlighted a significant effect of Condition ($\chi^2=27.35$, $p<0.00001$). Post-hoc tests
25 revealed that the sense of presence reached in the S condition was significantly higher

1 than both in CI ($p=0.00029$) and in A ($p=0.00030$); also the presence in A was higher
2 than in CI ($p=0.0161$).

3

4 **Discussion**

5 The aim of the present study was to investigate whether the analgesic effects of seeing
6 one's own limb are transferable also to the ownership of a fake limb. Specifically, we
7 explored heat pain threshold under different experimental conditions involving
8 ownership of a virtual arm. We found a significant increase in the pain threshold with
9 respect to the baseline conditions only in the case where the virtual and the real hand
10 moved synchronously, where synchronous stimulation meant that the passive
11 displacement of the participant's finger and the proprioceptive information that it
12 evokes was congruent with the movement of the virtual finger that was visually
13 perceived. Indeed, synchronous multisensory stimulation is known to induce an illusion
14 of ownership of the virtual arm and thus of ownership of the virtual body part (Sanchez-
15 Vives et al., 2010). No significant alteration of pain threshold occurred just by being
16 immersed in the virtual environment. Furthermore, simply watching a virtual arm *per*
17 *se*, i.e. the A condition, does not significantly affect the pain threshold compared to the
18 baselines. Previous evidence outside VR has demonstrated that there is an analgesic
19 effect of seeing a body, an effect that is restricted to the vision of one's own body
20 (Longo et al., 2009). Here we extend these findings by demonstrating that looking at a
21 fake body may also be analgesic, as long as it is perceived as one's own. Since
22 synchronous multisensory stimulation along with first-person perspective (Sanchez-
23 Vives et al., 2010; Slater et al., 2008) are powerful inducers of ownership of a virtual
24 body, that would be the virtual counterpart to seeing one's own body. Recently it has
25 been reported that the illusion of owning a rubber hand does not induce any significant

1 change in the perception of pain (Mohan et al., 2012). Likewise, we found no difference
2 in pain threshold between the S and A conditions. However, contrary to the S condition,
3 the pain threshold recorded during the A condition did not significantly differ from
4 those of the other conditions (i.e. CO and CI). Importantly, our design allowed the
5 disclosure of significant differences between the S condition and the two main control
6 conditions, namely the vision of virtual non-corporeal objects and the absence of VR.

7 It is well known that attention is an important modulator of pain perception (Johnson,
8 2005; McCaul and Malott, 1984; Ossipov et al., 2010; Villemure and Bushnell 2002).
9 VR experiences can be highly immersive and interactive and they work well to decrease
10 pain sensation through a decreased attention to the own body (Hoffman et al., 2001;
11 Malloy and Milling, 2010). Although our participants spontaneously reported that both
12 asynchronous and synchronous conditions were the most distractive ones with respect to
13 the pain stimulation, no significant differences in self-reported levels of attention paid to
14 the painful stimulus were found among conditions (Table 3). As aforementioned, the
15 asynchronous condition did not result in a significant modulation of pain thresholds
16 compared to any other condition, in spite of the subjective reports of a decreased
17 attention to the pain stimulation. These observations suggest that the difference in the
18 pain threshold reported by the synchronous condition was probably not due to mere
19 attentional processes. Nevertheless, it has to be acknowledged that self-reported
20 measures of attention, although widely used in cognitive science, lack objectivity. The
21 introduction of a concurrent cognitive task, e.g. a temporal order judgment (see for e.g.
22 Spence and Parise 2010), could eventually provide further and more objective insights
23 to this extent. A caveat to the introduction of a parallel task though, is that this may
24 interfere with the establishment of the illusion.

1 As well as for attention, our findings support that the feeling of “presence” in VR, i.e.
2 the illusory sensation of being in the virtual room and not in the laboratory, is not a
3 major modulatory factor of the pain threshold. Participants reported a significantly
4 higher sense of presence in S condition compared to either A and CI, and of A
5 compared to CI. This is of interest in itself, because it evidences the relevance of
6 owning a body in VR in order to increase the experience of being in the virtual world.
7 The sense of presence in VR has been decomposed into the illusions of being in the
8 virtual place and the plausibility of the situation (Slater et al., 2009). Having a body that
9 is seen from a first-person perspective and with appropriate sensorimotor correlations
10 seems to add to the plausibility. In our study, the differences in presence were not
11 accompanied by differences in pain thresholds across conditions. Other authors have
12 found a positive correlation between the feeling of presence and the decrease of pain
13 threshold (Hoffman et al., 2004), given that higher presence can result in less attention
14 to the actual body. However, in the study of Hoffman and colleagues no virtual body
15 was present, therefore participants could not experience the virtual body ownership of
16 an avatar’s body in the virtual world. Moreover, their task was clearly distractive.

17 It is also notable that although anxiety has been notoriously linked to pain perception
18 (Jones and Zachariae, 2002; Colloca and Benedetti, 2007), we observed no differences
19 in the level of anxiety among conditions. Furthermore, the adaptation to painful stimuli
20 was cancelled out by balancing the order of the conditions across participants. Hence we
21 believe that, in the current experiment, other mechanisms intervened in the modulation
22 of pain, in particular related to the ownership of artificial body parts.

23 To our knowledge, this is the first study with objective evidence on the relationship
24 between body ownership and pain threshold. In a previous work we demonstrated that
25 the variation of the colour of the embodied arm affects pain threshold. However, body

1 ownership was not differentially manipulated, as all the experimental conditions implied
2 the ownership of the avatar's limb (Martini et al., 2013). In a recent study, Hansel and
3 co-workers (Hansel et al., 2011) investigated whether the pressure pain threshold varied
4 during states of illusory dislocation of one's body, which implied an autoscopic
5 phenomenon, i.e. seeing the fake body in a different location (out-of-body experience).
6 In order to induce (or not) the illusion, tactile stimulation on the back of the participants
7 was synchronously (or asynchronously) provided with respect to the touch that they saw
8 either on a mannequin's back, or on a non-corporeal object, visualized in front of the
9 participant. The authors found that the pain threshold increased in the conditions where
10 the mannequin was visualized but could not find a specific effect of the out-of-body
11 illusion, i.e. identification with the mannequin, on the pain thresholds. Our results
12 instead, show that the heat pain threshold increases only when there is ownership of the
13 avatar's limb. This said, due to important differences in the experimental paradigm,
14 caution should be taken when comparing our results with the ones from Blanke's group
15 (Hansel et al., 2011). Indeed, while these authors explored pain threshold on relation to
16 self-location and self-identification with a dummy body placed in front of the subject,
17 we explored the ownership of a collocated virtual body seen from a first-person
18 perspective, a feature that has been shown to be a key factor in inducing virtual body
19 ownership (Slater et al., 2010). Also, their smaller participants' sample may have not
20 provided them enough statistical power. Another crucial difference may rely on the
21 distance between the body area where the multisensory stimulation was applied (i.e. on
22 the participant's back) and the location where the pressure pain was induced (index
23 finger). Actually, the strength of the ownership illusion decreases when moving away
24 from the stimulation area (Tsakiris et al., 2006) and psychologically induced cooling of
25 the body is strictly limited to the limb interested by the illusion (Moseley et al., 2008).

1 These findings suggest that the effect on pain threshold may be spatially limited to an
2 area proximal to the stimulated area.

3 Even if the rubber and virtual hand illusions take only a few seconds to work after
4 stimulation onset (Ehrsson et al., 2005; Lloyd, 2007; Perez-Marcos et al., 2012), our
5 results suggest that physiological changes may require longer duration under the
6 illusion. This is in line with a previous rubber hand illusion study where changes in the
7 limb skin temperature were observed after at least five minutes of stroking (Moseley et
8 al., 2008). In our case, the shorter overall stimulation time may have prevented from any
9 change on skin temperature. Therefore, inducing significant variations in skin
10 temperature or pain threshold may need some tens of seconds to occur after the illusion
11 starts to be experienced. It could also be that, the recording of the temperature of the left
12 limb (control limb), compared with the temperature recorded in the right (experimental)
13 limb, might have disclosed significant differences in the temperatures of the two limbs.

14 Although sensory mismatches reduce the strength of the virtual body ownership
15 illusion (Perez-Marcos et al., 2012), the mere vision of a collocated virtual body seen
16 from a first-person perspective is enough to induce the illusion to some extent (Slater et
17 al., 2010). In the experiment described here, the subjective illusion of ownership was
18 greater in the synchronous than in the asynchronous condition. However, the difference
19 in the pain thresholds observed between the synchronous and asynchronous conditions
20 did not reach the statistical significance. The strong perceptive cue that the first-person
21 perspective provides could be the cause. Moreover, a few works on body ownership
22 with healthy subjects have recently suggested that the ownership of a fake limb could
23 involve the disownership of the corresponding real body part (for ex. Moseley et al.,
24 2008; Guterstam et al., 2011) However, the actual occurrence of this disownership
25 process has been lately questioned (de Vignemont, 2011). We think that the pain

1 threshold effect found in the current study should be attributable to ownership of the
2 virtual limb and not to the disownership of the real limb based on different facts. On the
3 one hand, this would be in agreement with studies where the vision of one's own limb, -
4 no disownership is thus implied-, is analgesic (Longo et al., 2009, 2012). On the other
5 hand, recent findings show that somatosensory alterations following body ownership
6 would not involve disownership (Folegatti et al., 2009; Llobera et al., 2013b).
7 Moreover, we did not observe any change in either hand's or arm's skin temperature,
8 while disownership has been associated to a temperature drop (Moseley et al., 2008).

9 At last, neither in the present experiment nor in previous similar experiments (Longo
10 et al., 2009; 2012; Hansel et al., 2011; Mohan et al., 2012), the role of emotional arousal
11 has been taken into account. What is known, is that if the owned body part is threatened,
12 one tends to react as if the threat was directed to the real body (Slater et al., 2010;
13 Kiltner et al., 2012). The investigation of affective response during the ownership of a
14 new body could help understanding the relationship between body and emotions not
15 only within a single individual but also in a social context. For instance, given the
16 proven ability that people have to share the emotional components of pain (Singer et al.,
17 2004), future studies might investigate the affective reactions and the
18 neurophysiological responses to an avatar in pain or under threat conditions, having
19 previously manipulated the level of relationship (good or bad, strong or weak, etc.) of
20 the real subject with the avatar.

21 **Conclusions**

22 In summary, we investigated the effects of the ownership of a digital body on thermal
23 pain threshold. Our results show that the ownership of an avatar's limb can significantly
24 increase the thermal pain threshold in that limb. Given the modulatory effect that the
25 vision and the visual alteration of the affected real body part has on acute (Hoffman et

1 al., 2011; Longo et al., 2009; 2012; Mancini et al., 2011) and chronic pain
2 (Ramachandran et al., 2009; Ramachandran and Seckel, 2010), our findings may be
3 relevant for the development and improvement of digitalized solutions for the treatment
4 and rehabilitation from both acute and chronic pain states, by the application of
5 customized visual feedback over the owned virtual body.

6

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12

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4

1 **Figure legends**

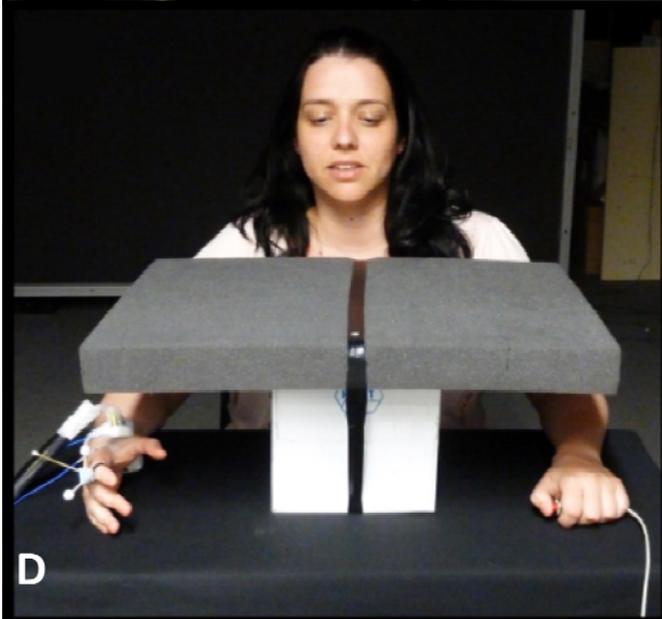
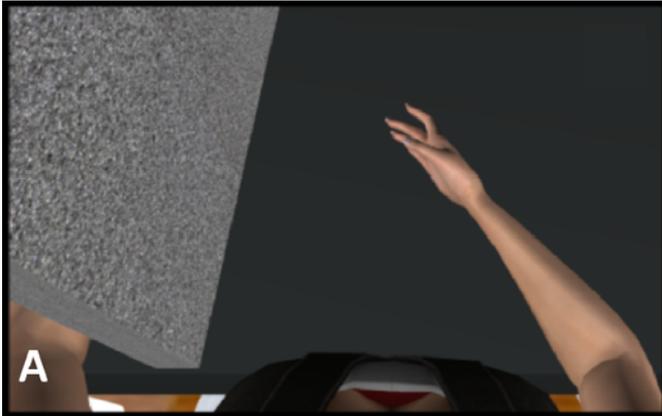
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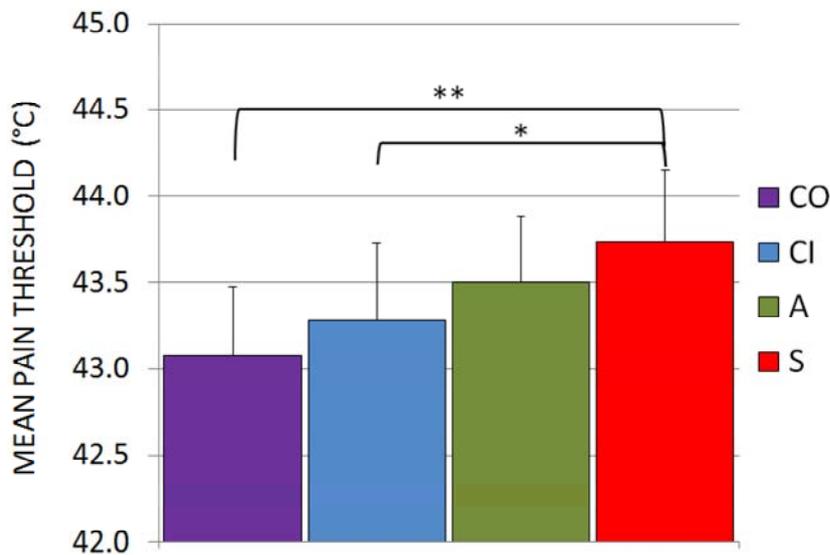
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4 **Figure 1.** Illustrative picture of the real environment (left panel) and of the virtual
5 environment with the female avatar (right panel).

6



1 **Figure 2.** Experimental set-up: the avatar’s body used in the asynchronous and
 2 synchronous conditions (A), and the non-corporeal object in the “Control Inside”
 3 condition (B) are visualized through the HMD while one experimenter moves the
 4 participant’s finger (C). In the “Control Outside” condition, the sight of the limbs was
 5 prevented by using a foam cover (D).



8
 9 **Figure 3.** Mean and SE of the pain thresholds reported by the participants in each
 10 condition. Purple, light blue, green and red are associated to the “Control Outside”,
 11 “Control Inside”, “Asynchronous” and “Synchronous” conditions respectively (CO, CI,
 12 A and S). Stars indicate significant comparisons (* $p < 0.05$ and *** $p < 0.001$).

13
 14 **Table 1.**

Category	“During the current condition..”
Ownership	<p>1...I felt as if the virtual right arm was my own right arm.” (total disagreement = 1 / total agreement = 7). #</p> <p>2...I felt as if the virtual right hand was my own right hand.” (total disagreement = 1 / total agreement = 7).</p>
Presence	<p>3...I had a strong feeling of being in the lab (1) / in the virtual room (7).” #</p>

Anxiety	4... <i>I felt totally relaxed (1) / totally anxious (7).</i> " *#
Attention	5... <i>my attention was totally focussed on other things (for example on what I was watching) (1) / totally on the thermal stimulus (7).</i> " *#

1
2
3
4
5

Items 1 to 5 were used for both A and S conditions.

* used in CO condition

used CI condition. The term "virtual right arm" was replaced by the term "cylinder" (item 1).

6 **Table 1.** The questionnaire administered to the subjects, sorted by category.

7

8 **Table 2.**

Condition	Pain Threshold	Arm Temperature	Hand Temperature
CO	43.08 ± 0.40	30.72 ± 0.41	30.38 ± 0.51
CI	43.29 ± 0.44	30.92 ± 0.39	30.55 ± 0.54
A	43.50 ± 0.38	30.77 ± 0.36	30.35 ± 0.50
S	43.74 ± 0.40	30.77 ± 0.38	30.32 ± 0.52

10

11 **Table 2.** Pain thresholds and skin temperatures (mean ± SE) reported per each
12 condition. Temperatures are expressed in Celsius degrees.

13

14 **Table 3.**

Condition	Anxiety	Attention	Presence	Arm/Cylinder embodiment	Hand embodiment
CO	2.79 ± 1.32	3.88 ± 1.68	—	—	—
CI	2.50 ± 1.35	3.71 ± 1.76	4.46 ± 1.67	1.83 ± 1.40	—
A	2.75 ± 1.57	3.00 ± 1.44	5.17 ± 1.31	3.54 ± 1.61	3.04 ± 1.60
S	2.08 ± 1.21	2.83 ± 1.58	6.13 ± 1.03	6.21 ± 0.83	6.29 ± 0.81

16

17 **Table 3.** Questionnaire scores (mean ± SE) reported per each condition.

18