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Lower Pain Threshold While Seeing a Virtual Limb – Boundary Conditions for Visual Analgesia Effect

Abstract
Background: *Observing one's own body has been shown to influence pain perception—a phenomenon called visual analgesia. The effect was originally obtained using a mirror reflection of one's own hand and later replicated with prosthetic and virtual hands. Most studies show increased pain thresholds during visual analgesia, but the opposite effect can be obtained by inducing ownership illusion over a limb that looks wounded. We tested the hypothesis that a resilient-looking virtual limb would lead to an increased pain threshold.*
Methods: *Eighty-eight students (*M_{age} = 21.4, SD_{age} = 2.98*) participated in a within-group experimental design study (natural hand virtual reality [VR], marble hand VR, and non-VR control). In both VR conditions, a visuo-tactile synchronous stimulation was used to elicit the illusion of embodiment. Pressure pain stimulus was applied to the forearm. Dependent variables were: pressure pain threshold, pain intensity and self-reported embodiment.*
Results: *There were significant differences between the control condition and the Natural Hand VR (*$V = 647$, $p < .0001$*), and between the control condition and the Marble Hand VR (*$V = 947.5$, $p < .005$*), but not between the Natural Hand and Marble Hand conditions (*$V = 1428.5$, $p = .62$*). Contrary to our predictions, pain threshold was higher in the control condition. Pain intensity differences were not significant.*
Conclusions: *We obtained a significant effect in the opposite direction than predicted. Such results may mean that the visual analgesia effect is more context-dependent than previously thought. We discuss methodological differences between the paradigm used in this study and paradigms reported in the literature as a possible explanation.*

Keywords: *visual analgesia, virtual reality, pain threshold*

Rubber hand illusion (RHI) is a widely studied method of altering body representations. It was first described by Botvinick & Cohen (1998) and, in the most common variant, participants watch a prosthetic hand being stroked in synchrony with their own unseen hand. As a result, the rubber hand is attributed to one's own body —a phenomenon called body ownership illusion (BOI; Maselli & Slater, 2013)—and touch location is experienced to be on the prosthetic hand, rather than on the real one. BOI can be evoked using either a physical object (e.g., a prosthetic hand) or a simulated, virtual body part.

In recent years, several studies explored the influence of BOI on pain. Modulatory effects of BOI on pain were reviewed by Martini (2016) in the context of analgesic effects of vision of the body. Lower pain intensity or higher pain threshold observed under RHI and BOI are often interpreted in relation to visual analgesia effect. A phenomenon was first described by Longo et al. (2009) where observing one's own hand without visual information about a pain stimulus led to lower pain intensity and unpleasantness, relative to looking at a non-hand object. In the above-mentioned study, participants were looking at a mirror reflection of their non-stimulated hand (mirror-box paradigm), but visual analgesia was later replicated several times with both classic RHI and virtual versions of BOI (Hänsel et al., 2011; Mancini et al., 2011; Martini et al., 2014).

However, other studies provide evidence that it is possible to obtain the opposite effect on pain (i.e., pain increase or lower pain thresholds) by inducing BOI over a limb that looks wounded (Giummarra et al., 2015; Osumi et al., 2014).

Research also suggests that other visual information related to virtual body parts may influence pain perception

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in various ways. A study by Martini et al. (2013) showed that looking at a red-coloured virtual hand led to lower heat pain thresholds compared to looking at a blue hand. In another study, looking at a semi-transparent virtual hand was related to lower pain thresholds, but only when feeling of ownership was considered (Martini et al., 2015).

Considering possible neurophysiological mechanisms of visual analgesia, Haggard et al. (2013) postulated that vision of the body produces analgesia by increasing intracortical inhibition in the somatosensory cortex, and thus produces more precise somatosensory representations. Vision of the body may lead to sharper somatotopic maps in the somatosensory cortex, and that in turn leads to analgesic effect. Chronic pain is related to somatosensory disorganization, and the magnitude of such disorganization predicts the severity of pain. In turn, tactile discrimination training is used to treat chronic pain – and such training should lead to greater precision of somatosensory representations. Haggard et al. (2013) postulate, that reduced organization (somatosensory blurring) plays a causal role in the experience of pain. In turn, an increase in somatosensory cortex organization (somatosensory sharpening) leads to diminished pain.

We hypothesized that visual information suggesting resilience of a virtual limb would lead to an increase in the pressure pain threshold. In this repeated measure experiment, we manipulated virtual hand type on three levels (natural skin texture virtual reality [VR], marble texture VR, and no-VR control). Dependent variables were pressure pain threshold, self-reported embodiment, and pain intensity. We predicted that the marble hand condition would lead to a higher pain threshold compared to natural hand, and that both VR conditions would lead to higher pain thresholds compared to the control condition. However, we also formulated an alternative hypothesis. Research on visual analgesia suggests that higher embodiment leads to stronger analgesic effects. Realistic skin textures may be linked to stronger embodiment effect (Maselli & Slater, 2013). Therefore, higher pain thresholds could be observed in realistic skin in comparison with marble skin, depending on the degree to which participants would be able to embody the marble hand.

Understanding how visual cues signalling body resilience can influence pain perception is important for both theoretical and practical reasons. It is known that visual information related to body vulnerability is integrated and influences pain perception. There is a gap in knowledge regarding how visual information about a virtual or artificial limb affects pain experience. Previously published literature focuses on the effect of body parts looking weak or injured, but there is a lack of research on the possible modulatory effect of body parts looking resilient and strong. Knowing whether an opposite effect of resilience cues also exists would help to create a more complete explanation of how body-related visual information shapes pain. If found, such effect could also have an applied value, possibly increasing the effectiveness of visual analgesia interventions.

METHODS

Study Design

Within-participants experimental design was used in this study. Each subject participated in in two experimental conditions and in a non-VR control condition. The order of conditions was counterbalanced. In both VR conditions, a visuo-tactile synchronous stimulation was used to elicit the illusion of embodiment. In VR conditions the forearm and hand had either a natural skin texture (Natural Hand condition) or marble skin texture (Marble Hand condition). In the control conditions, there was a blank screen on the head-mounted displays. After stimulation was complete, measurements of pressure pain threshold were taken on each participant's left hand. The pressure was synchronized with the movement of the object falling on the forearm. For each condition we measured pain intensity and embodiment.

Participants

Power analysis was conducted using G*Power, and a sample size of 80 was determined necessary to detect medium effect size with the power of 0.8. We recruited 88 participants (convenience sampling) in order to compensate for possible missing data. Participants (M_{age} = 21.4, SD_{age} = 2.98) were mostly students of Wrocław Universities.

APPARATUS AND EQUIPMENT

Pressure Pain Threshold

Pressure stimulus was applied to the forearm (Wagner Instruments, FPX 50 Algometer) with the pressure increasing at a rate of approximately 0.5 kgf (one kilogram-force is by definition equal to 9.80665 N) per second. Measurement was performed by two trained research assistants. The apparatus was not automated, and the pressure was applied manually—thus, potential variations relate to experimenter variability. The range of pressure rate variations was between 0.48 and 0.53 kgf per second.

Virtual Reality

VR conditions were displayed via Oculus DK2 head-mounted displays (HMDs; 960 × 1080 pixels per eye, 75 Hz refresh rate, 100 deg FOV). Virtual environments were programmed in Unity3D, C#, and were showing a simple virtual room and a seated virtual avatar with left forearm and hand placed on the table. The forearm and hand had either a natural skin texture (Natural Hand condition) or marble skin texture (Marble Hand condition; see Figure 1).

Marble skin texture choice was dictated by previous research showing that auditory cues signalling marble material influenced participants' body perception, and that processes of multisensory integration can influence perceived material of one's own body (Senna et al., 2014).

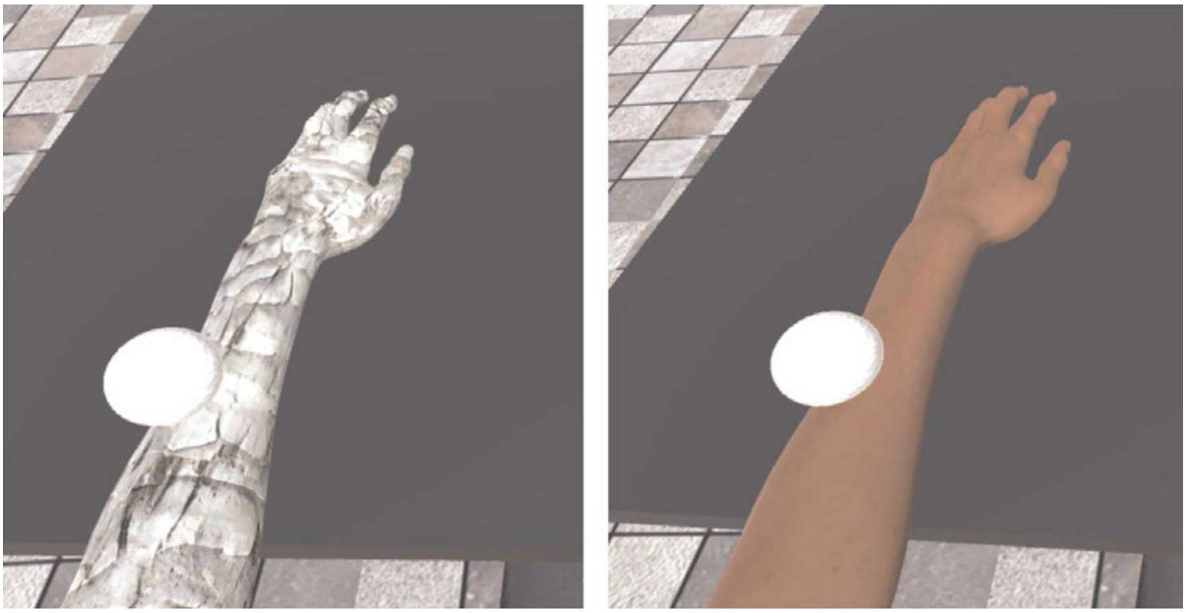

Figure 1. View on a virtual body in the Marble and Natural Hand conditions.

MEASURES

Pain Intensity

A numerical scale was used: “How intensive was your pain, on a scale from 1 meaning no pain to 10 meaning extreme pain?” Participants assessed pain intensity immediately after pressure stimulus was removed, and while they were still wearing HMDs and seeing the virtual body.

Embodiment Question

A single-item self-report measure was used in both VR conditions. The question was asked while participants were still wearing HMDs and seeing the virtual body. “On a scale from one to five assess how much you felt as if the virtual hand is your hand.”

PROCEDURE

Our experiment took place in a lab room of the Institute of Psychology, University of Wrocław. Upon arriving, the participants were told that the purpose of the study was to investigate body perception in VR, and that a pressure stimulus would be applied several times to their forearms. They gave a written informed consent and were told that they could refrain from participation at any moment without giving justification. The study was approved by the local ethics committee at the University of Wrocław.

Two test measurements of pressure pain threshold were taken on each participant’s right hand—for participants to familiarize themselves with the stimulus, and with the task of noticing and reporting the onset of pain. The instruction was: “Say ‘stop’ when you begin to feel pain. Do not endure pain, just signal its onset.” The experimenter stopped applying pressure immediately after verbal response from the participant.

After completing the test trials, participants put on the HMDs and entered three experimental conditions in a counterbalanced order. Each participant was seated and kept their left forearm and hand on the table (see Figure 2).

In both VR conditions, a visuo-tactile synchronous stimulation was used to elicit the illusion of embodiment, with an oval-shaped object moving slowly on the virtual forearm, while the experimenter touched each participant’s physical forearm with a similar physical object. Participants aligned their hands to match the seen virtual hand position. Physical hand position was not tracked. Participants were instructed to keep looking at the virtual hand throughout the entire timespan of the experimental condition. After 30 seconds of the synchronous visuo-tactile stimulation, participants looked at the virtual hand for a further 5 seconds, and then a soft-textured virtual ball slowly descended and touched the virtual hand near the wrist while the experimenter applied pressure on the corresponding place on the physical hand.

After participants signalled the onset of pain, and while still wearing HMDs, pain intensity was assessed, followed by the embodiment question. Participants then removed the HMDs and, after a 1-minute break, the next experimental condition started.

In the control conditions, there was a blank screen on the HMDs and participants only assessed the pain threshold and pain intensity.

Statistical analysis

Data from five participants was excluded. Four participants were excluded because of the software failure in at least one experimental condition, and one person did not signal the onset of pain.

Statistical analysis was performed using R statistical programming language. Effect sizes and 95% confidence intervals were computed with the bootES package for R (Kirby & Gerlanc, 2013).

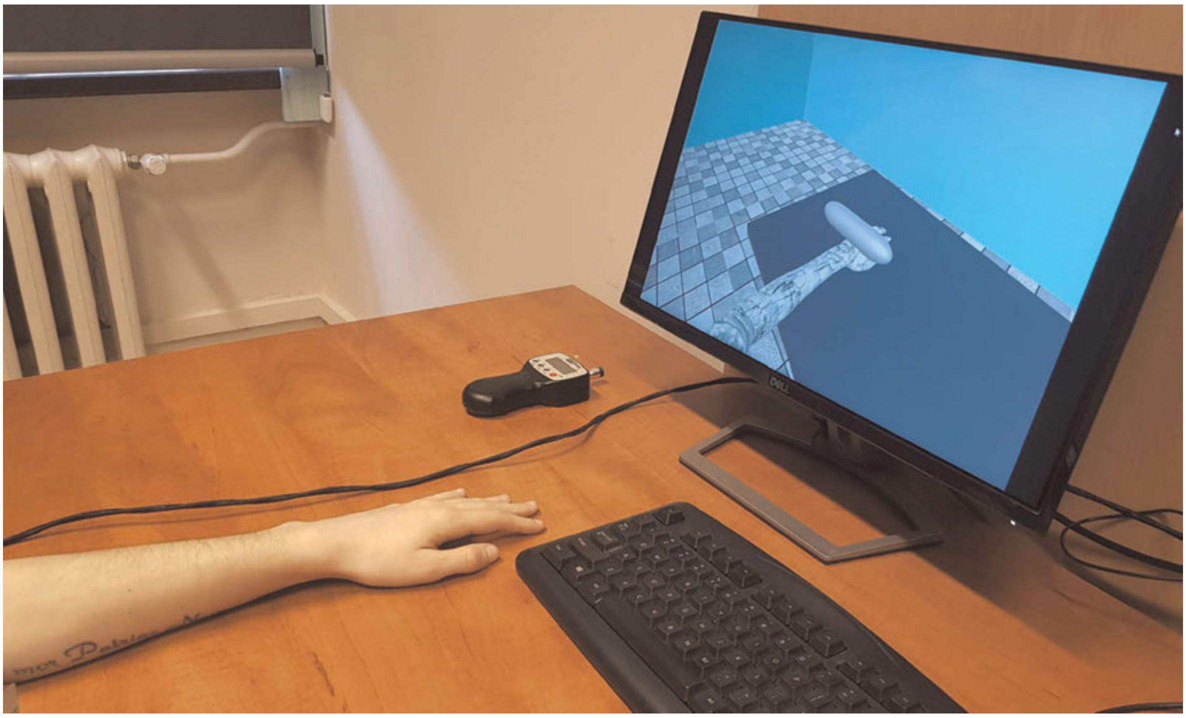

Figure 2. Experimental setup – positioning of the participant's arm

Distribution of both pain threshold and pain intensity data deviated significantly from normal; therefore, we used non-parametric statistics for the hypothesis testing (Friedman tests, followed by the Wilcoxon signed-rank tests for pairwise comparisons), *p* values were adjusted for multiple comparisons using Bonferroni correction. Distributions of pain thresholds across experimental conditions are shown in the Figure 3.

RESULTS

Pain threshold was considered as a primary outcome variable. The Friedman rank sum test was significant: χ^2 = 30.05, *df* = 2, $p < .0001$. Pairwise comparisons yielded significant differences between the control condition and the Natural Hand VR ($V = 647$, $p < .0001$), and between the control condition and the Marble Hand VR ($V = 947.5$, $p < .005$), but not between the Natural Hand and Marble Hand conditions ($V = 1428.5$, $p = .62$). All p-values are reported after Bonferroni corrections. Effect size for the difference between the control condition and Natural Hand was Hedges $g = 0.58$, 95% CI [0.35, 0.79]. Between the control condition and Marble Hand it was $g = 0.27$, 95% CI [0.01, 0.51].

The Friedman rank sum test for pain intensity results was not significant: χ^2 = 1.77, *df* = 2, $p = .41$. The difference in self-reported embodiment was also not significant between the Natural Hand and Marble Hand conditions ($V = 812.5$, $p = .25$). Descriptive statistics for pain threshold, pain intensity, and self-reported embodiment data are shown in Table 1.

The correlation between self-reported embodiment and pain threshold in the Marble Hand condition was significant, $r = -.23$, $t = -2.1(81)$, $p < .05$. However, the correlation between embodiment and Natural Hand was not. Both correlations were negative, meaning that higher self-reported embodiment was related to lower pain threshold. Correlations between embodiment and pain intensity were not significant, nor were correlations between pain thresholds and pain intensity in any of the experimental conditions.

DISCUSSION

Contrary to our predictions, and to most of the previous studies on visual analgesia, we observed a significant increase in pain threshold in the control condition compared to any of the VR conditions. We will focus our

Table 1. Descriptive Statistics for Pain Threshold, Pain Intensity, and Self-Reported Embodiment

Condition	Pain threshold		Pain intensity		Self-reported embodiment	
	M	*SD*	*M*	*SD*	*M*	*SD*
Marble Hand	1.97	1.37	3.18	1.79	3.54	1.24
Natural Hand	1.83	1.09	3.17	1.65	3.68	1.11
Control	2.87	1.20	2.99	1.73	—	—

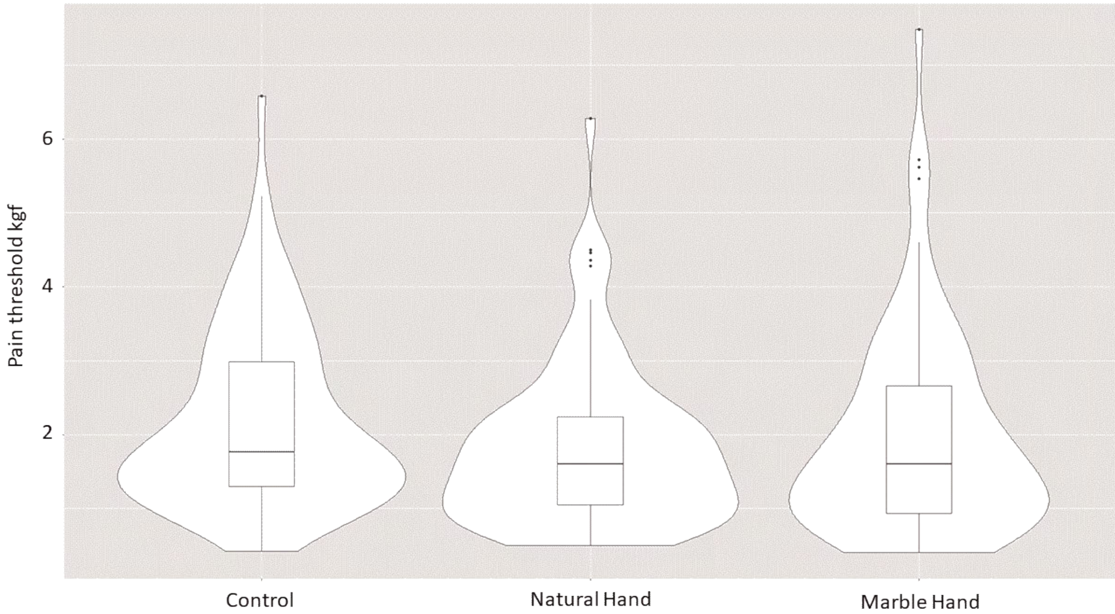

Figure 3. Distributions of pain threshold results (kgf) across three experimental conditions

discussion primarily on the difference between the control condition and the Natural Hand condition, since it is most relevant to previously published studies on visual analgesia.

The difference in pain threshold was highly significant, with a medium effect size. Observed effect size of g = 0.58 means that 72% of the participants reported higher pain threshold in the control condition than the mean of the Natural Hand condition. Also, 95% confidence intervals around this effect size are quite narrow, showing that true effect is at least g = 0.35.

It is unlikely that the observed effect can be explained by an experimenter bias (e.g., applying faster or stronger pressure in the control condition compared to the VR conditions). Data collection was done by two research assistants who knew the hypothesis of the study; therefore, any experimenter behaviour in support of the hypothesis would be aimed at evoking higher pain thresholds in VR conditions, and specifically in the Marble Hand VR condition. Similarly, it is unlikely that demand characteristics from the participants contributed to the effect. Our previous experimental work was related to VR analgesia, and many participants could know that; thus, they rather expect that VR conditions should lead to diminished pain.

In order to understand why we observed an effect in the opposite direction than those reported in the literature, we will discuss differences between our paradigm and those other studies. The main difference was the type of control condition, which was a blank screen on HMDs in our study. In Longo et al.'s (2009) study, it was looking at a mirror reflection of a neutral, non-hand object. In Hänsell et al.'s (2011) study, it was looking at a video stream of a non-human object via HMDs. Martini et al. (2014) used two control conditions, referred to as CI (control inside) and CO (control outside). In the CI, participants observed a virtual stick through HMDs; in the CO, they were looking at a grey foam cover without the HMDs. Especially regarding the CO condition, it is hard to conceive why looking at a grey foam without VR would lead to the opposite effect on pain compared to looking at a blank screen with HMDs (as in our study). In two studies with chronic low back pain patients (Diers et al., 2016; Löffler et al., 2017), participants observed their own back via video feedback. The authors used several control conditions and, apart from the analgesic effect of watching the video of one's own back, the eyes-closed condition led to pain reduction effects, although smaller in size. Results of our study interpreted in the context of other published research on visual analgesia may mean that details of the control condition may not only reduce the chances of observing this phenomenon, but actually create a strong effect in the opposite direction.

Another difference between our paradigm and most of the other published research on visual analgesia is the type of pain stimulus. Most studies used heat pain thresholds (Mancini et al., 2011; Martini et al., 2013; Martini et al., 2014; Martini et al., 2015; Nierula et al., 2017), but laser pain was also used (Longo et al., 2009). Pressure pain threshold paradigm was used in one study demonstrating visual analgesia effect (Hänsell et al., 2011). However, pressure was applied to each participant's index finger in that study, compared to the forearm in our paradigm.

Vision of the body was non-informative about pain stimulation in most of the studies. However, Nierula et al. (2017) programmed a virtual replica of the thermode used for pain stimulation, and that replica was placed on a virtual hand. A fake thermode was also touching the rubber hand in a study by Hegedüs et al. (2014), where the authors observed visual analgesia effect. Similarly, participants in our study saw the virtual representation of the stimulus (which was a soft-textured, non-threatening virtual ball).

Both the details of the control condition and visual information about the pain stimulus need to be tested in further studies in order to reveal their contribution to the magnitude and direction of the visual analgesia effect.

Significant negative correlation between embodiment and pain threshold during Marble Hand condition is somewhat surprising. Such result is contrary to most of the literature on visual analgesia – where we would rather expect a positive direction of the relationship between those two variables. One possible explanation could be that marble hand was perceived not as resilient but as somehow damaged or injured hand. Previously published research suggests, that inducing BOI over a limb that looks wounded may lead to an opposite effect on pain (Giummarra et al., 2015; Osumi et al., 2014).

Some aspects of our study can be seen as limitations, rather than just differences in the details of the experimental paradigm. One limitation was that we did not use an asynchronous VR condition, as many of the other studies did. This decision was made because we used a well-established paradigm to induce RHI (synchronous visuo-tactile stimulation on a co-located, realistic looking virtual limb). Multiple studies already demonstrated that such conditions are sufficient to reliably induce the illusion of embodiment. Moreover, in a recent study by Nierula et al. (2017) the authors did not observe any significant differences between the baseline (looking at one's own physical hand) and either synchronous or asynchronous VR hand conditions (when the virtual hand was co-located). Another limitation is that the embodiment was measured only with a single item. This was done because we wanted participants to give answers while they were still immersed in the VR. It is also possible that our resilience manipulation was not effective, and participants either did not interpret the texture as marble, or associated marble material not with resilience but with fragility (e.g., a marble tile can break when dropped). Lastly, pressure pain stimulus was applied immediately after visuo-tactile stimulation and not during the stimulation.

Despite those limitations, we believe the results of this study provide valuable information regarding boundary conditions under which visual analgesia can be observed. Our results suggest that visual analgesia is context--dependent, and relatively small departures from the commonly used paradigm may lead to the opposite of predicted effects. Future research should test if the results obtained by us can be replicated using other types of pain. Most importantly it would be valuable to see if heat pain thresholds are affected in a similar way as pressure pain used in this study. Future research should also focus on testing several control, non-VR conditions – in order to reveal how details of the control condition may influence results in studies on visual analgesia. This would be especially valuable, because apart from providing valuable methodological information such studies could also increase understanding of mechanisms behind the visual analgesia effect. Lastly future research should include more elaborate measures of embodiment. Longo et al. (2008) distinguished several components of the embodiment experience. Those components include affective aspects, feelings of loss of own hand, and experiences related to agency, and perceived body location. Preferably all major aspects of embodiment experience should be measured to better understand how phenomenology of embodiment relates to pain perception during visual analgesia experiments.

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