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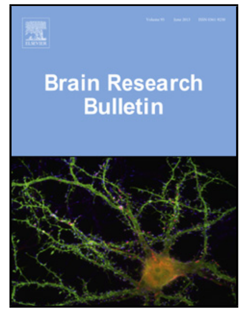

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Removing own-limb visual input using mixed reality (MR) produces a "telescoping" illusion in healthy individuals

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Abstract

The purpose of the present study was to assess changes in body perception when visual feedback was removed from the hand and arm with the purpose of resembling the visual deprivation arising from amputation. The illusion was created by removing the visual feedback from the participants' own left forearm using a mixed reality (MR) and green screen environment.

Thirty healthy persons (15 female) participated in the study. Each subject experienced two MR conditions, one with and one without visual feedback from the left hand, and a baseline condition with normal vision of the limb (no MR). Body perception was assessed using proprioceptive drift, questionnaires on body perception, and thermal sensitivity measures (cold, warm, heat pain and cold pain detection thresholds). The proprioceptive drift showed a significant shift of the tip of the index finger ($p < 0.001$) towards the elbow in the illusion condition (mean drift: -3.71 cm). Self-report showed a significant decrease in ownership ($p < 0.001$), shift in perceptual distortions, (e.g. "*It feels as if my lower arm has become shorter*") ($p = 0.025$), and changes in sensations of the hand (tingling, tickling) ($p = 0.025$). A significant decrease was also observed in cold detection threshold ($p < 0.001$), i.e. the detection threshold was cooler than for the control conditions.

The proprioceptive drift together with the self-reported questionnaire showed that the participants felt a proximal retraction of their limb, resembling the telescoping experienced by phantom limb patients. The study highlights the influence of missing visual feedback and its possible contribution to phantom limb phenomena.

Keywords: Visual feedback, Telescoping, Illusion, Phantom Limb Phenomena, Proprioceptive Drift, Mixed Reality

1. Introduction

Phantom limb phenomena have puzzled researchers for decades. The perception of amputees is a vivid feeling that the amputated limb is still present, along with accompanying sensations which can be manifested as itching, cramping, clenching and pain. In addition, some amputees experience the phantom limb as distorted or assuming different spatial positions, e.g. they may feel that the distal part of the amputated limb gradually moves closer to the site of the amputation; a phenomenon originally described by Guéniot [1] and later referred to as *telescoping* by Katz [2].

Merzenich et al. [3] discovered that substantial cortical reorganization occurred in the somatosensory areas of owl monkeys following amputation of the third digit as the cortical maps of the two adjacent fingers seemed to “invade” the now vacant area. These findings led Yang et al. [4] and Elbert et al. [5] to discover similar reorganization in human amputees. Later this reorganization was related to the phantom pain and telescoping perceived by the amputee [6–9]. Although the causal relationship between telescoping and phantom pain is unclear, they both correlate with each other and are hypothesized to be expressions of the cortical reorganization [10,11].

Ramachandran & Rogers-Ramachandran [12] introduced a treatment based on mirror-visual feedback to restore the perception of having an intact arm. This was achieved by mirroring the visual appearance of the contralateral intact limb across the midsagittal plane using a simple mirror. By performing simultaneous mirrored movements with both the phantom limb and the intact limb, the patients achieved congruent visual feedback. In some cases this led to reductions in phantom limb pain, unclenching of previously tightly clenched fists and a general perceptual congruence to the visualized intact limb. A recent study demonstrated that the magnitude of telescoping was a negative predictor for the amount of pain relief and cortical reorganization resulting from mirror therapy treatment [7], i.e. persons with telescoped phantoms benefited less from this type of therapy. This implies that an important connection exists between the three phenomena of telescoping, pain and cortical reorganization.

In recent years, there has been an increasing interest in experimental research investigating the role of visual perception and perceptual illusions in the modulation of body awareness in healthy volunteers (see [13] for a review of body illusions). Body position arises from mixed sensory modalities, where vision and the set of mechanoreceptors that contribute to proprioception are dominant (i.e. Ruffini endings are important to signal limb position). Additionally, recent studies have shown that “efference copy” and a forward model of the limb and its environment are significant actors in determining the sense of body position [14,15]. Muscle spindle afferents are important proprioceptors because they provide a mixed encoding of muscle length and rate of length change, and thus convey limb position and movement [16]. The most influential evidence in support of muscle spindles as the principal kinesthetic receptors is the illusion of limb movement and displaced position produced by vibration over the tendon or muscle. However, the vision of the arm can reduce or eliminate this illusory effect [17]. Hence, vision has a strong effect on our sense of the body in space, and evidence has supported a dominance of vision over proprioception [18–20].

Visual input alone is able to produce dynamic changes in both self-report and on the cortical level in relation to body perception. By altering the visual input alone, Schaefer and colleagues [21,22] created perceptual illusions of an elongated

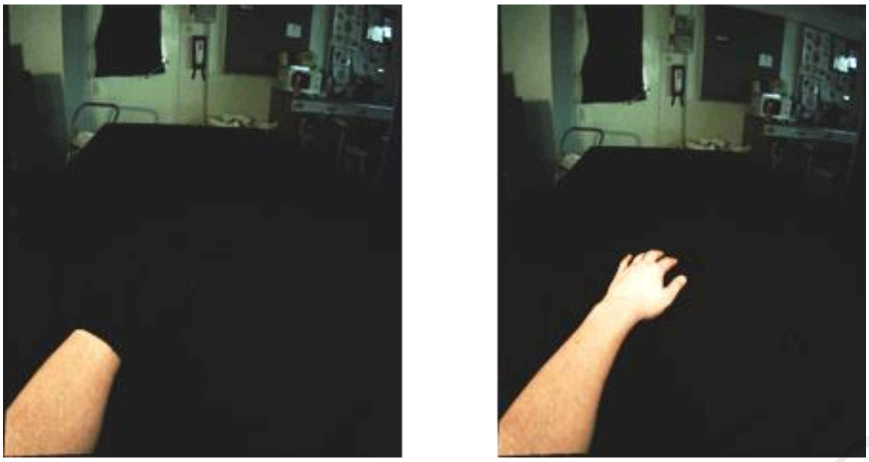

Fig. 1 *Inside view of the illusion. On the left, the illusion is active and on the right, the MR helmet is see-through and the visual feedback is normal*

or a third arm which correlated with altered cortical responses in the primary somatosensory cortex. Similar observations were found in an experimental setting using mirror visual feedback [23]. Modifications of body perceptions are also reached by the combination of visual and tactile feedback in the rubber hand illusion, in which a rubber hand is embodied in the corporeal image [24]. Additionally, the perception of a telescoping limb was induced in healthy volunteers using a full body illusion by integrating visuo-tactile stimulations [25]. The idea that visual feedback and perception are crucial is also supported by the observation that amputees using an active prosthesis and thereby receiving a visual and functional feedback seem to experience an embodiment of their prosthesis and less occurrence of phantom limb pain and telescoping [26]. Taken together, these findings suggest a key role of perception in which visual feedback is paramount. Furthermore, vision and somatic senses seem to interact strongly as simply viewing one's own body increases tactile acuity, modulates somatosensory evoked potentials, creates analgesic effects, and modulates pain responses by enlarging/decreasing the vision of the body size [27–31].

The aim of the present study was to determine the effects of visual adaptation on body perception in healthy volunteers by removing own-limb visual input. We hypothesized that if own-limb visual feedback was removed in healthy volunteers in a realistic way by means of mixed reality technology, the arising visual loss would produce perceptual correlates similar to the ones observed in amputees.

2. Materials and Methods

2.1 Participants

A total of 30 participants (15 male and 15 female, mean age 23.77 and ± 4.19 SD, age range 19-35) were enrolled in this experiment. Participants were recruited through personal inquiry at Aalborg University. All participants were paid according to the amount approved by regulations, 10.75 € an hour, and informed consent was obtained from all participants. Exclusion criteria were: pregnancy; drug addiction defined as the use of cannabis, opioids or other drugs; previous neurologic, musculoskeletal or mental illnesses; claustrophobia; migraines and any form of chronic/neuropathic pain; tendency to headaches, nausea and/or blurred vision; body dysmorphic disorders and individuals taller than 187 cm (due to constraints of the mixed reality (MR) system). The experiment was performed solely on the left hand as the proprioceptive drift measure was not set up for the right hand. Four participants were left-handed. All procedures performed were in accordance with the approval from the Local Ethics Committee (reg. no.: N-20160039) and in accordance with the Helsinki Declaration.

2.2 Mixed Reality (MR) system description

In order to remove visual feedback from the subject's hand (see fig. 1), a novel system was designed based on green-screen technology together with a mixed reality (MR) system (see fig. 2).

The MR system consisted of an Oculus Rift® (Developer kit 2, Oculus VR, LLC, USA) with two 60 fps SXGA (1024 x 1280) cameras (uEye® UI-3241LE-C-HQ, Imaging Development Systems GmbH, Germany). The cameras were attached in front of the eyes on a set of rails allowing for adjustment of separation of the cameras to match the inter-pupillary distance of the wearer. In normal operation, the cameras streamed directly into the screens of the oculus rift enabling a see-through of the helmet. The benefit of the system was that the video streams could be modified in real-time to manipulate the visual feedback.

The camera lenses had a 4mm focal length and were for a 1/1.8" sensor size with a field of view of 101° horizontal x 76° vertical (Lensagon® BM4018S118C, Lensation GmbH, Germany). The Oculus DK2 specifications were 110° vertical x 85° horizontal and a resolution of 960 x 1080. The specification differences between cameras, lenses and screen were compensated by undistorting the images (lens correction) and matching camera image and the oculus' angle of views.

2.3 Removing own-limb visual input using MR

The participant was seated in a chair in front of a large table with a black cloth covering it. Above the chair, a head fixation array was arranged to ensure that the head was held in a steady position during the experiment. The array allowed for minimal motion of the head without applying pressure. The MR system was mounted on the array in order to ensure that it was fixated on the head of the participant (See fig. 2).

Before starting the illusion, a "background photo" was captured using the two front cameras. Then, the illusion was activated by replacing everything with a green color in the camera view with the pre-captured background image rendering everything that was green as invisible. Hence, in order to remove the visual input from the participant's arm and thus making the arm disappear, a green glove and a green sleeve were placed on the hand and on the arm of the participant (See fig. 2b).

The MR system was based on a stereoscopic setup which worked simultaneously for both eyes and therefore retained a depth perception (i.e. the 3D-effect) during the illusion. This setup created a highly realistic view for the participant. In order for the device to work optimally, any motion of the MR system was kept limited. To ensure that accidental movements went unnoticed, the experiment was performed in a controlled dimmed light environment. An inside view of the illusion is shown in fig. 1.

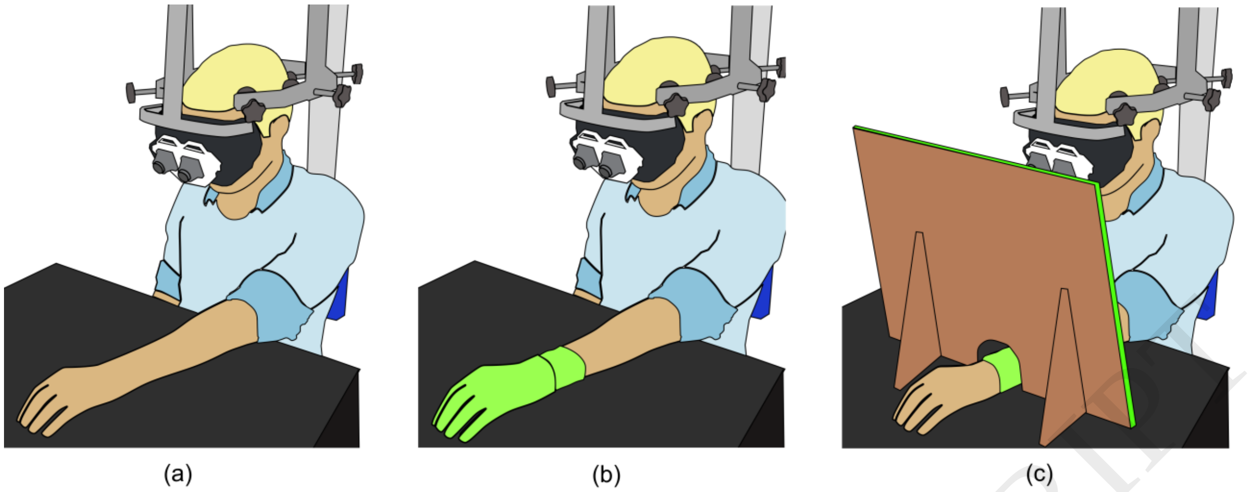

Fig. 2 *From left to right: a) Depiction of setup: a participant was seated with the fixture around the head and the AR helmet in front of the view. The fixture was attached to a chair such that the participant's weight stabilized the whole rig and ensured that it did not move. b) During the illusion induction, the participant wore a green glove and sleeve. c) When measuring in the illusion condition, the glove was removed allowing for direct skin contact*

After the hand "disappeared" from the view of the participant, a green cardboard screen with a hole at the base was placed on top of the wrist (but without touching the wrist). The use of this green screen occluded the vision of the hand hidden behind the screen allowing for projection of the previously recorded background image onto the green screen; hence, rendering the hand invisible to the participant. The green screen is shown in fig. 2c. Following, the green glove was removed from the participant's hand to take measurements on the hand surface and to reduce the tactile sensations of wearing a glove (see fig. 2c). During the illusion, physical interaction and handling of the invisible hand were kept at a minimum to avoid distorting the illusory effect.

2.4 Measurements

2.4.1 Proprioceptive drift

The proprioceptive drift is a measure used in several studies on the rubber hand illusion (RHI) [24,25,32,33]. It is used as a proprioceptive marker for the perception of the spatial layout of the body. Usually, in an RHI experiment the participant is asked to indicate the position of the actual hand on a ruler using the opposing hand. This measure is usually conducted on a transverse or horizontal axis in front of the participant to detect a proprioceptive drift towards an embodied object, such as a rubber hand. In the present study, the measurement was conducted on a distal proximal axis in front of the participant, i.e. away from the body, on the axis of the resting arm on the table. It was measured using a slider underneath the table which the participant was asked to move to the positions described by the experimenter. This procedure was comparable to the original assessments [24]. Here, three points were used as references: the tip of the index finger, the knuckle at the index finger root, and finally the wrist joint. These points were chosen because they were relatively easy to locate on the actual hand and because of their approximately equidistant distribution, which combined would give a good indication of the individual's proprioception of the hand. A subsequent reference measurement was conducted from a certain fix line on the surface of the table to the tip of the index finger. See fig. 3 for a depiction of the proprioceptive drift measure.

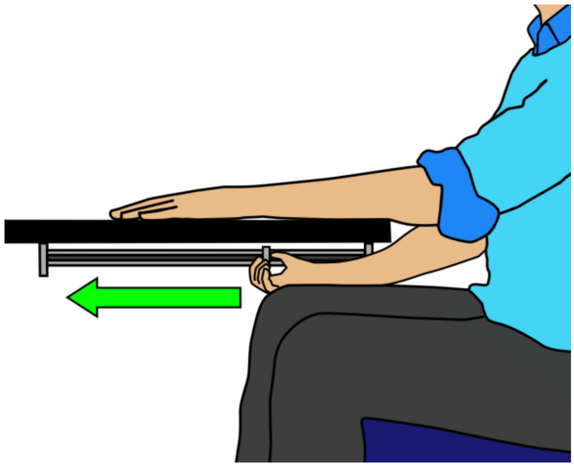

Fig. 3 *Depiction of the proprioceptive drift measure. Participants were asked to move the slider underneath the table to the perceived position of the finger, knuckle and wrist*

2.4.2 Thermal thresholds

According to several studies, somatosensation may be modulated by illusions and visual feedback [34–37]. Thermal sensitivity was assessed by thermal detection thresholds for warm and cold stimuli and for heat and cold pain stimuli. The test was performed according to the recommendations of the German Research Network on Neuropathic Pain [38]. All thermal thresholds were assessed by using the methods of limits protocol and measured four times for each stimulus. Stimuli were delivered by a Peltier-based thermode with a surface of 30x30 mm of the thermo-sensory stimulator (Medoc Pathway®; Medoc Ltd., Ramat Yishai, Israel). The probe was applied to the skin of the left index finger with the minimum pressure necessary to ensure that the entire surface had contact to the participant's skin and to ensure minimum perturbation in relation to the illusion. For warm detection and pain stimuli, the temperature of the thermode was continuously increased from 32°C to a maximum of 52.5°C at a rate of 1°C/s. For cold detection and pain stimuli, the temperature of the thermode was continuously decreased from 32°C to a minimum of 0°C at a rate of 1°C/s. The subjects were instructed to click on a computer mouse with their right hand as soon as they reached their threshold.

2.4.3 Questionnaire about the magnitude of the illusion

To quantify the perceptual experiences associated with the illusion, the subjects replied to a questionnaire at the end of each condition. The questionnaire was inspired by previous studies investigating body illusions and phantom limbs [24,33,34,39,40] and was modified to probe different aspects of body perception: ownership, dis-ownership and perceptual distortions. The complete set of questions is given in table 1. Answers were based on a 7-point Likert-scale from -3 to +3, in which -3 corresponded to "I strongly disagree", and +3 to "I strongly agree".

2.5 Experimental design

A within-subject design was used for the experiment with a baseline (without the MR system) and two conditions (with the MR system) in a counterbalanced order: visible hand (control) and invisible hand (illusion). The two conditions were similar in structure with the only difference in the visual feedback.

2.5.1 Baseline

As an initial step, a set of demographic data was obtained from the participant including gender, age, length of fingers and hands, handedness and height. Upon completion of the data collection, the participant was asked to sit in the chair in front of the table with the head in the fixed array. The participant was then instructed to rest his or her left arm on the table and keep it still and to grab the slider underneath the table with the right hand to perform the proprioceptive measures. The participant was asked to drive the slider to three different positions in relation to his/her left hand: (i) tip of the index finger; (ii) the knuckle; and (iii) the wrist. Between each measure the experimenter read off the slider and reset it to a random position at the beginning of the slider range, i.e. close to the edge of the table. Next, the thermal thresholds were obtained. The participant was instructed to detect four different thermal thresholds: cold, warm, cold pain and heat pain. The thermal probe was applied on the left index finger while the participant pressed the trigger button using the right hand.

2.5.2 Illusion condition

The participant was asked to sit as comfortably as possible in the chair with the MR system fixated in front of the head and mounted on the array to ensure a steady head position. Before the start of the experiment the experimenter ensured that the participant had a clear view through the screens and the cameras. A background photo was taken with the participant's arm outside the view. Meanwhile, the green glove and sleeve were mounted on the left hand. Then the participant was asked to place the left hand on the table (in full view) in a relaxed, comfortable, and steady position. A small manuscript was read to the participant, wherein he or she was asked to relax, to keep the visual focus on the hand and listen to the experimenter's instructions. The instructions were added as a consequence of our pilot experiments, which showed that additional instructions were needed to focus the attention of the participants on the hand. They were designed as a verbalization of what the participant was seeing through the MR device. Sample lines from the manuscript are: "I would like you to focus on your left hand. You start to notice how your hand slowly begins to disappear… disappears and becomes nothing…". The talk was timed with the MR system such that the hand slowly faded away until it completely disappeared. Two minutes of silence followed to let the illusion settle. Following the talk, the green screen was placed on top of the wrist and the first measure, proprioceptive drift, was carried out followed by the questionnaire. Prior to assessing the thermal thresholds, the glove was removed to allow for direct skin contact. The condition was ended by re-measuring the proprioceptive drift to check if any changes occurred from a temporal perspective.

2.5.3 Control condition

The control condition progressed similarly to the illusion condition, except for the visual feedback. In this condition, the participant was able to see the arm and hand through an unaltered camera feed. The participants were verbally instructed to focus on their left arm for a time period comparable to the time it took for the talk given during the illusion condition. All further measurements and procedures were identical to the illusion condition.

2.6 Data Analysis

From each condition, the following variables were measured: Thermal thresholds, detection and pain thresholds, proprioceptive drifts (twice for both conditions) and questionnaire data for both conditions. Prior to analysis, the thermal

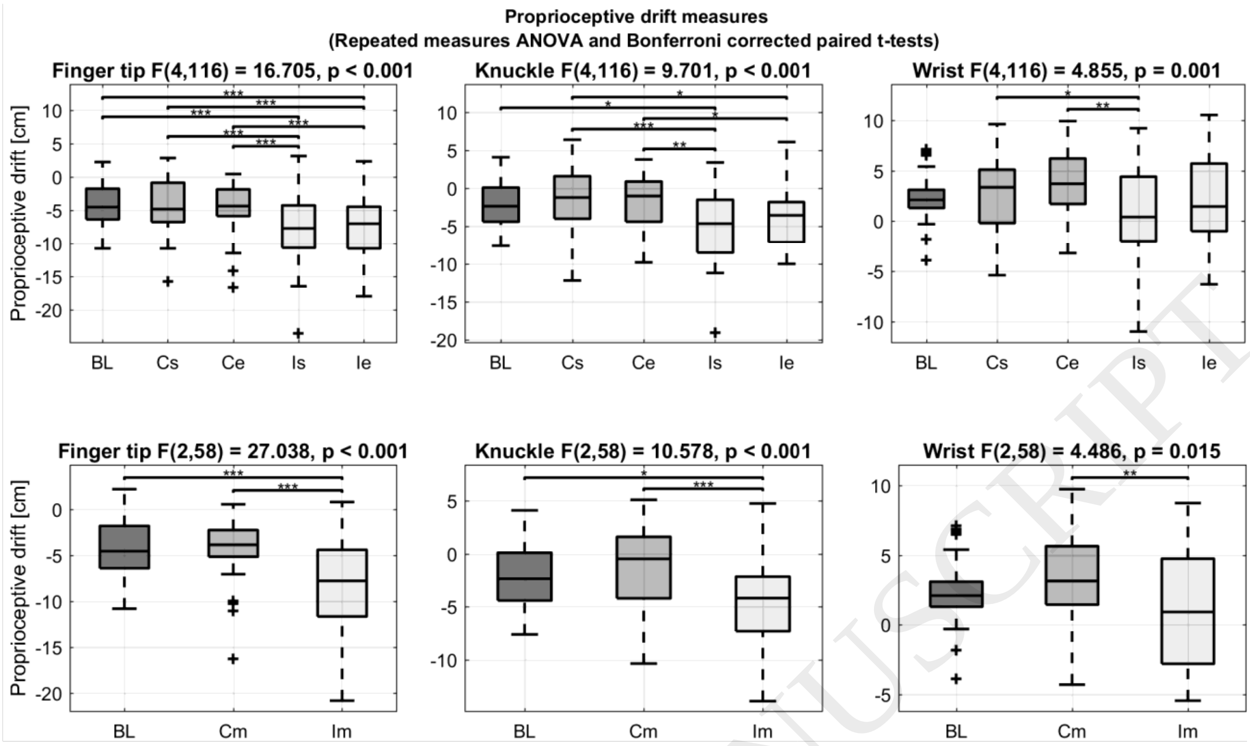

Fig. 4 *The proprioceptive drift measure, i.e. the difference in actual position and proprioception determined position. The upper row of plots shows all five measures; at baseline (BL), control start and end (Cs and Ce), and illusion start and end (Is and Ie). The lower row of plots shows the averaged values for each condition; baseline (BL), control mean (Cm) and illusion (Im). Outliers are plotted as the values outside of +/- 2.73σ interval. However, in the ANOVA and paired t-tests all values were considered*

and proprioceptive data were tested for normality using Shapiro-Wilks tests. Before processing the thermal data, cold and heat detection thresholds were log transformed as recommended in the QST protocols developed by the DNFS [38]. A repeated measures ANOVA with condition as factor was initially used, and if significant differences were found, post hoc Bonferroni-corrected paired t-tests were performed to observe the statistical differences between conditions. To correct for possible violations of sphericity, only the Greenhouse-Geisser corrected significance values are reported here. The questionnaire data were tested using Wilcoxon signed ranks tests between the two conditions. All reported results are with $\alpha = 0.05$ significance level.

3. Results

3.1 Proprioceptive drift

The proprioceptive measure, shown in fig. 3, was measured once at baseline and twice per condition to investigate if the illusion had any temporal effect. This effect showed no significant differences within the condition, i.e. between the measures at the beginning and end of the illusion and control conditions. Therefore, we report both the results for each measurement point *and* the average for each condition. Sphericity was not violated in any of the proprioceptive drift measures. Bonferroni-corrected paired t-tests between the mean control and illusion conditions (second row of plots in

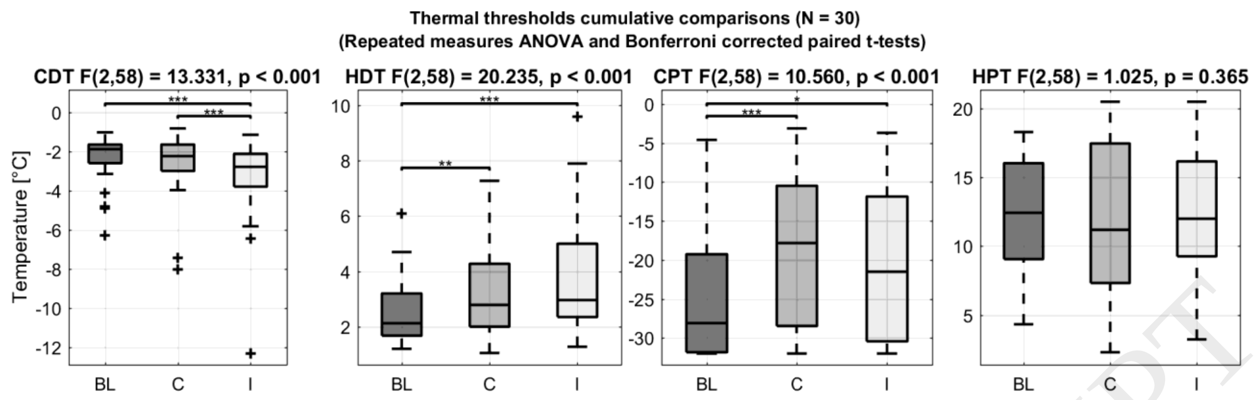

Fig. 5 *Thermal threshold results. From left: Cold detection threshold, heat detection threshold, cold pain threshold and finally heat pain threshold. Each graph in the plots corresponds to: the baseline (BL), the control condition (C) and the illusion condition (I). The outcome of one-way repeated measures ANOVAs are presented at the top*

fig. 4) are reported here: Index finger tip control and illusion $p < 0.001,\ t(29) = 6.59$; Knuckle control and illusion $p < 0.001,\ t(29) = 4.97$; Wrist control and illusion $p = 0.004,\ t(29) = 3.28$. The proprioceptive drift data show a consistent picture in line with our hypothesis that there would be a proximal drift towards the elbow when comparing the illusion and control conditions ($\mu_{\Delta\text{Drift}} = -3.65$ cm and $\sigma_{\Delta\text{Drift}} = 3.03$ cm for the fingertip; $\mu_{\Delta\text{Drift}} = -2.85$ cm and $\sigma_{\Delta\text{Drift}} = 3.14$ cm for the knuckle; and $\mu_{\Delta\text{Drift}} = -2.06$ cm and $\sigma_{\Delta\text{Drift}} = 3.28$ cm for the position of the wrist). A table of the mean and standard deviations is provided in Online Resource 1.

3.2 Thermal thresholds

Thermal thresholds are shown in fig. 5. Normality of the data was tested and all passed, except cold pain threshold measures. One-way repeated measures ANOVAs are given above each graph in fig. 5. The means and confidence intervals for the cold and heat detection thresholds were transformed back and are reported here: Cold detection threshold ($\mu_{\text{BL}} = -2.06°$, 95% CI, $-1.74°$ to $-2.43°$; $\mu_{\text{C}} = -2.28°$, 95% CI, $-1.88°$ to $-2.77°$; $\mu_{\text{I}} = -2.83°$, 95% CI, $-2.36°$ to $-3.38°$) and heat detection threshold ($\mu_{\text{BL}} = 2.28°$, 95% CI, $1.95°$ to $2.67°$; $\mu_{\text{C}} = 2.90°$, 95% CI, $2.42°$ to $3.48°$; $\mu_{\text{I}} = 3.35°$, 95% CI, $2.77°$ to $4.05°$). Bonferroni-corrected paired t-tests showed a significant difference from baseline and control to the illusion condition in cold detection threshold ($p < 0.001$ and $p < 0.001$, respectively), indicating a possible effect of the illusion condition. Contrary to the results of the cold detection thresholds, the heat detection thresholds were significantly different from baseline to control ($p < 0.004$) and illusion ($p < 0.001$). The same significant shift in differences was observed for cold pain threshold ($p < 0.001,\ t(29) = 4.39$ and $p < 0.001,\ t(29) = 2.64$, control and illusion conditions respectively). No significant differences were detected in the ANOVA on the heat pain thresholds.

3.3 Questionnaire data

The results of the 7-point Likert-scale questionnaire are plotted as a bar graph in fig 6 with the Wilcoxon signed ranks test provided on the vertical axis of the plot. The questions found to be significant were: Q2 “I feel like my hand has disappeared” ($p < 0.001$), Q3 “It feels as if I cannot move my hand” ($p < 0.001$), Q4 “It feels like my hand belongs to me” ($p < 0.001$), Q5 “I have a hard time localizing my hand” ($p < 0.001$), Q8 “It feels as if my lower arm has become

Q#	Questions
	Control question
1	It feels as if I have more than one hand or arm.
	Dis-ownership
2***	I feel like my hand has disappeared.
3***	It feels as if I cannot move my hand.
4***	It feels like my hand belongs to me.
5***	I have a hard time localizing my hand.
	Ownership
6	It feels as if my arm belongs to me.
	Perceptual
7	I feel as if my hand has moved closer towards my elbow.
8*	It feels as if my lower arm has become shorter.
9*	It feels as if my lower arm has disappeared.
10	My hand feels heavier.
11*	My hand feels lighter.
12	It feels as if my fingers have shrunk.
13	It feels as if my fingers are enlarged.
14	It feels as if my hand has shrunk.
15	It feels as if my hand is enlarged.
16*	I can feel a tickling or a tingling sensation in my hand.

Table I *Questions with according category.*

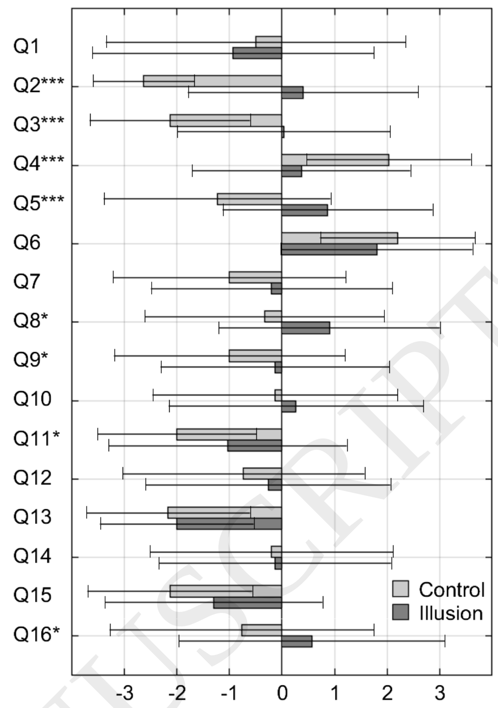

Fig. 6 *Questionnaire results. The average response is shown here as a bar graph with standard deviation. Control is the red bar and illusion is the blue bar. A Wilcoxon signed ranks test was used for evaluating the difference across conditions. The number of stars indicate the significance level (* $p < 0.05$, *** $p < 0.001$)*

shorter" ($p = 0.025$) and Q16 "I can feel a tickling or a tingling sensation in my hand" ($p = 0.025$). All of the questions are presented in table 1.

4. Discussion

The purpose of this study was to assess the impact of the removal of concurrent own-limb visual input on body perception. The findings show that it was possible provoke significant body perceptual distortions in our participants. Our illusion caused a proprioceptive drift, changes in the cold detection thresholds and in own-body perception. The perceived shortening is reminiscent of the frequent reports from amputees experiencing a shortening of their phantom limb (49% to 63% of amputees, [8–10,41]). The phantom limb experience, however, includes an array of sensory deprivations and changes, and visual feedback may not account for telescoping alone. However, it seems that healthy participants can experience aspects of the phantom limb phenomenon by manipulating their own-limb visual feedback. A decreased cold detection threshold was also observed in the present study; a result that could be related to ownership. In the rubber hand illusion, a decreased sense of ownership over the real hand has been associated with a decrease in temperature of the hand [42]. If the same is true for the present experiment, a centrally mediated regulation of the homeostatic control may result in a drop in temperature and conversely lower the detection threshold for cold sensation [42]. Recently, a progressive degradation in cold sensation together with dynamic changes in the size and perceived posture of the hand were reported in an experimental phantom hand study [43]. Although the authors used a different method based on ischemic block, the results showed that cold sensation was affected more than heat sensation; thus showing more sensibility of cold sensations to experimental manipulation. The thermal cold thresholds also showed that the pain threshold was reached at lower temperatures during the baseline condition compared to control and illusion conditions. This may seem paradoxical, but as noxious and innocuous cold sensations are mediated by different fibers that are modulated differentially (possibly in the periaqueductal gray) [44], the earlier onset of cold pain response seen in the control and illusion conditions could be an effect of a top-down modulation. Perhaps, psychological factors could be implicated in this process (i.e. related with the experience of wearing the AR device). However, since no literature investigating both innocuous and noxious cold pain thresholds under similar experimental manipulations has previously been done this remains to be further clarified.

As in previous studies [19,20,45,46], the proprioceptive drift observed in the present study suggests that our body schema is not only updated by proprioceptive information. Instead vision plays a significant role in the perception of physical layout of the body. In Longo and Haggard’s study from 2010 [45], the hand of healthy subjects was covered using a board on which the participants were asked to locate fingertips and knuckles of their occluded hand. The results showed a remarkably skewed representation of the hand; with shorter estimated fingers and an overall wider hand. The authors associated this skewness to the relative representation size of these groups on the somatosensory homunculus. By doing this, they related the body schema directly to the somatosensory layout suggesting that the cortical representations provide a mental map of the body itself. This result is intriguing in relation to the present study as we observed a similar shortening of the fingers but also a shortening of the hand. In addition, this shortening was strongly perceived distally and gradually decreasing proximally. It would seem that the body schema is somewhat distorted and the visual information “normalizes” it towards the actual physical layout; an idea supported by the results of Inui and Masumoto [19]. Evidence for the same idea is indirectly supported by the findings of Schaefer and colleagues [21], who induced an illusion of an elongated arm while measuring the cortical responses to a tactile stimulation on the affected limb using magnetoencephalography. They showed that the corresponding peak of activation moved according to the perceived elongation of the arm, indicating that their illusion modulated the layout of the somatosensory homunculus in the short-term. The same result led Flor and Nikolajsen [10] to propose that telescoping in phantom limb patients is indeed a manifestation of permanent cortical reorganizations and noting that the somatosensory system responds to the perceived rather than the actual sensory input. Therefore, the proprioceptive drift seen in the present study could be a reflection of a short-term modulation of the somatosensory homunculus induced by a shift in body perception; a shift arising from the missing visual feedback. Our study did not focus on this aspect and it remains a speculation. A future study should investigate cortical responses to the illusion.

4.1 Bodily illusions and previous approaches

Numerous studies have shown the malleability of the human body perception by developing experimental paradigms that embodied extracorporeal objects such as rubber hands, mannequins, and even empty volumes of space [25,33,47–51] (see [13] for a review of some illusions). To induce embodiment, a combination of tactile and visual coherent cues is often used. The approach in the present study relied on visual feedback from the body part and circumvented the idea that a coherent multi-modal manipulation is necessary to obtain illusory phenomena. The multi-modal integration processes can be viewed as a statistical optimization problem in which the mind tries to integrate all sensory information to give one optimal perception of the current state of our experience [30]. If the previous research is viewed in this light, it makes sense that in order to trick the mind to embody an extracorporeal object, a coherent multi-sensory induction must occur to create the link between the own-body and the object (e.g. stroking a rubber hand in front of a participant will not induce any ownership over the rubber hand, but adding a coherent tactile stimulus on the real hand will create a plausible sensory link between what is seen and felt). In the case of our system, no intermediate embodiment of an extracorporeal object was present, but rather a direct manipulation of the visual feedback of the real body. Hence, the body ownership did not need to be moved from the actual hand to an extracorporeal object because we manipulated the already embodied real hand.

Schmalzl and Ehrsson [25] created an illusion of having a phantom limb using a full-body illusion [52]. They achieved this by means of an amputated mannequin with two cameras attached to the head such that the cameras pointed downwards to capture the view of the mannequin body. Through a stereoscopic head-mounted display, the video feeds from the cameras were shown to the participant, who stood in a similar posture to the mannequin. Through simultaneous stroking, they attempted to induce a telescoping effect by touching the stump of the amputated mannequin and the fingertips of the participant. The findings suggested a similar proprioceptive drift using a different method. Although the results are similar in measurement, we propose that these are different results based on different principles. In the case of the full-body illusion, an embodiment of the stump is the crucial factor for observing a proprioceptive drift. The present experiment visually manipulated the real body of the participant with no embodiment procedures and may therefore be a more valid way to measure the impact of missing own-limb visual feedback.

In the work of Newport and Gilpin [53], they applied a trick in which visual feedback of the right hand was maintained in a static position, whereas in reality the hand was slowly moved to the side. Due to the slow movement, the displacement went unnoticed by the participant who only received the static image of the hand (i.e. a hand not moving). Subsequently, the participants were asked to touch the right hand using their left hand, only to find that the hand was not there. Thus, Newport and Gilpin found a disembodiment of the hand similar to the present study. Their study showed another way of inducing disownership by manipulating the senses. They used the dominant dependence on vision to trick the sensory integration processes to disregard the proprioceptive input from the moving hand. In our study we relied on vision only and showed that mere removal of collocated visual feedback was enough to provoke a change in body perception. The two studies complement each other and both underline the importance of visual feedback. New interesting results have emerged from studies using ischemic anesthesia of the arm/leg to study the effects of visual information on experimental phantom limbs[19,43]. Surprisingly, the authors found that if the limb was flexed before and during the anesthesia, the phantom arising from the sensory deprivation was an extended limb and vice versa. The authors explained the phenomenon in the following way: when the limb is bent and the flexors on the front of the limb are signaling that they are in stretched state, the ischemic block kicks in, gradually diminishing the signaling, which leads the cortex to assume that the flexion has ceased. However, if the participants were able to see their contralateral limb (which was in the same pose as the leg with the ischemic block), the perception was normalized towards the current physical pose of the anaesthetized leg, demonstrating once again a dominance of vision.

4.2 Proprioceptive drift: an overlooked measure?

In this and previous studies, the proprioceptive drift has been used to measure the perceptual spatial layout of the body. A similar method and measurement could be applied to phantom limb patients to assess telescoping effects. Existing descriptions of telescoping are based on verbal explanations from patients [11] and visual analogue scale ratings on intensity of the telescoping [7]. To our knowledge, no published work has used the proprioceptive drift to evaluate the effects of treatments that rely on restoring sensory feedback (e.g. visual feedback treatment such as mirror therapy). However, it would be a valuable measure to assess the correlation between phantom limb pain and telescoping effects. Even if patients do not consciously feel a telescope, a proprioceptive distortion of their phantom limb may exist, and by measuring the proprioceptive drift over treatment sessions, these distortions could be captured and compared to the effects of the treatment.

In relation to the rubber hand illusion experiments, in which the measure was first conceived, the proprioceptive drift is also thought to indicate the embodiment or strength of the illusion. However, recent studies have questioned the relationship between limb ownership and proprioceptive drift [50,54]. Though the present experiment is not entirely comparable to the RHI, our results would also imply that a distinction should be made between these two facets of body illusions as we report a strong proprioceptive drift together with a disownership of the actual hand and vice versa.

4.3 Implications for research on phantom limbs

The observed changes resemble the accounts of amputees experiencing phantom limbs. Often, amputees report a feeling of the amputated part retracting proximally to the point of amputation or even inside the neuroma [9–11,55]; an effect that could be compared with the proprioceptive drift and is supported by the perceptual questionnaire data. Though the similarities between these two phenomena have to be studied in closer detail, the ability to recreate the perceptual correlates of amputees in healthy participants using experimental illusions is intriguing. The question “I can feel a tickling or a tingling sensation in my hand” also gave a significant response which is interestingly also a common phantom limb sensation [56]. If a visual distortion such as the one presented in this paper is able to disrupt the own-body perception of a healthy participant, it seems likely that the opposite, i.e. regaining visual feedback, can have normalizing effects on own-body perception in amputees and in turn reverse cortical reorganization.

Inui and Masumoto used ischemic block anesthesia as an experimental model of a phantom limb [43]. A combination of their approach and the method employed in the present study could provide an accurate perceptual phantom limb model with loss of visual, proprioceptive, tactile, and to some extent thermal sensation. Having an accurate experimental model of phantom limbs is valuable in research to study the many characteristics of the phenomenon.

4.4 Limitations

This work relies on the MR system to relay an accurate reproduction of the visual feedback of the hand. With this, certain limitations should be mentioned: (i) reproduction of a vision is limited by the relative quality and resolution of the retina, the screens in the goggles and the cameras used. In the employed system, the screens are the limiting factor with a resolution of 960 x 1080 relatively close to the eyes; inferior to what the eye can see; (ii) furthermore, the screen-door effect (that every pixel in itself is discernable) is still an inherit problem of these types of goggles, and this may break the immersion; (iii) finally, a main assumption in this study is that embodiment is preserved through this MR system. We argue that spatially coincident and coherent visual feedback in combination with low latency video maintains the embodiment of the hand. This aspect is supported by the results of the questionnaire data on ownership in which the embodiment is clear from the control condition.

The illusion condition of this experiment was also combined with a verbalization of the fading hand to ensure the attention of the participant. However, it must be considered that this alone could have provoked some suggestions or expectations in the induction of the illusion. The effect of this verbalization on the results has not been accounted for since similar proprioceptive, thermal and subjective results were obtained during a pilot test conducted without this verbalization. Consequently, the impact of verbalization is deemed to be of less importance.

The perceptual and proprioceptive data advocates a resemblance to phantom limb experiences. A subset of phantom limb patients experience phantoms that are twisted or turned into anatomically implausible configurations and none of the participants during the present experiment reported such perceptions. However, it should be noted that it is far more common to experience a telescope rather than an extension or deformation [8].

5. Conclusion

Using a novel MR system, it was possible to manipulate visual feedback from a limb in a realistic way. By removing the own-limb visual feedback in healthy volunteers, a proprioceptive drift could be generated along with perceptual changes (limb shortening, disownership and tickling or tingling sensations). The effects of the manipulation may resemble the phenomenon of telescoping phantom limbs seen in amputees. Furthermore, the MR system used to induce the illusion may be a valuable tool to assess several aspects of visual feedback ranging from motor integration tasks to importance of visual feedback during prolonged pain.

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Conflict of interests

The authors declare no conflict of interest.

Ethical approval

All procedures were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki Declaration and its later amendments or comparable ethical standards.

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