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Illusory finger stretching and somatosensory responses

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ABSTRACT

Resizing illusions, delivered using augmented reality, resize a body part through stretching or shrinking manipulations. These resizing illusions have been investigated in visuotactile, visual-only, and visuo-auditory presentations. However, the neural underpinnings of these resizing illusions remain undefined. This study sought to understand the neural mechanisms behind these illusions by using somatosensory steady state evoked potentials (SSEPs) in addition to subjective self-report questionnaires, to enhance knowledge of what drives the subjective embodiment during resizing illusions. Since these Illusions have been shown to provide analgesic effects for individuals with chronic pain conditions, this study also aimed to provide an empirical basis for future investigations in chronic pain samples. Confirmatory analyses (N = 46) demonstrated significant differences in subjective experience between non-illusion and multisensory illusion conditions, while electroencephalography (EEG) data measuring SSEP response across electrodes of interest (F1 & FC1) to 26Hz stimulation of the resized digit showed no significant effects of condition. However, further exploratory non-parametric SSEP analyses revealed a significant effect of condition, with reduced amplitudes in illusion conditions compared to non-illusion conditions, but no significant differences in exploratory post hoc tests. While confirmatory findings demonstrated no clear effect of resizing illusions on SSEP amplitudes for participants without chronic pain, exploratory findings could be interpreted as a potential “sharpening” of neural representations resulting from illusory stretching. These findings therefore provide a basis for investigations of comparable subjective and steady state illusion responses in a chronic pain population, who are thought to have more diffuse neural representations of their affected body parts.

1. Introduction

Illusory finger stretching is a form of multisensory illusion, specifically a resizing illusion, which alters the subjective perceptual experience of the size of one’s finger. Resizing illusions, through changing the way in which a body part is perceived, exploit principles of multisensory integration to elicit modulations in the perceived size and shape of the body (Preston and Newport, 2011; Preston et al., 2020; Stanton et al., 2018). Such resizing illusions are related to the rubber hand illusion, in which touch is delivered to a visible fake hand at the same time and in the same place that touch is delivered to the hidden real hand. This manipulation elicits feelings of ownership over the fake hand through the integration of multisensory (tactile and visual) inputs highlighting the apparent malleability of bodily self (Botvinick and Cohen, 1998). Multisensory resizing illusions typically involve both tactile and visual inputs and can be delivered via an augmented reality system or through magnifying optics. Recent studies have also shown resizing illusions to be effectively administered through visual only, and visuo-auditory manipulations (Schaefer et al., 2007; Tajadura-Jiménez et al., 2017). However, multisensory visuotactile manipulations are reported as the most effective at inducing a strong experience of the illusion within an augmented reality system (Hansford et al., 2023).

The augmented reality system used to deliver these resizing illusions presents real-time video capture of the hand, from the same position and perspective as if the hand were being viewed directly (Preston and Newport, 2011). Having real-time presentation of the hand is important to create an experience as close to real life as possible, since previous work has highlighted that the strength of embodiment can be decreased when presented in less human-like set ups (D’Alonzo et al., 2019). This augmented reality set up allows the experimenter to deliver tactile manipulations, such as gently pulling or pushing the hand/finger, whilst the participant views their hand/finger either stretching or shrinking in

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the augmented image. Newport et al. (2010) found strong embodiment using a synchronous multisensory visuotactile illusion, which was replicated in our pilot data using the same experimental set up as the current study. The pilot data showed, although not statistically significant, a stronger illusory experience during synchronous visuotactile manipulations compared to asynchronous (mismatching visuotactile manipulation) control conditions (Appendix A) for illusory finger resizing. When comparing multisensory visuotactile resizing illusions to unimodal visual resizing illusions, our recent work (Hansford et al., 2023) showed that multisensory illusions elicit significantly greater illusory experience compared to non-illusion and unimodal visual illusion conditions in healthy participants. We also showed, in exploratory analysis, that a subset of participants who experienced an illusion in the unimodal visual condition reported a stronger illusory experience in this condition than in an incongruent (mismatching visual and tactile inputs) control condition. Furthermore, we have demonstrated that a visuo-auditory presentation of the finger resizing illusion, using non-naturalistic auditory input, provides a stronger illusory experience than a visual only presentation, but this does not surpass the illusion strength given by a visuo-tactile illusion (Hansford et al., 2024).

Neuroimaging has previously been used in healthy populations experiencing resizing illusions, whereby modulation of the primary somatosensory cortex has been found using neuromagnetic source imaging during visual only resizing illusions of the arm (Schaefer et al., 2007). Briefly, the more that participants felt the subjective experience of an elongated arm, the more the cortical distance between the first and fifth digit decreased, showing the topographical representation of the somatosensory cortex being modulated by perceived location of a stimulus. Specifically looking at stretching multisensory visuotactile illusions, which as mentioned are those that elicit the greatest illusion strength in the majority of participants, recent research suggests that these illusions impact the neural representations of the body and reflect early-stage multimodal stimulus integration through modulation of gamma band activity (Kanayama et al., 2021). We have recently also investigated this illusion in healthy participants using electroencephalography (EEG) and found support for this previous research; observing significant increases in gamma band power, likely reflecting multimodal stimulus integration, in multisensory visuotactile compared to unimodal visual conditions during illusory resizing of a finger (Hansford et al., 2023). Previous research using rubber hand illusions reported this multisensory integration effect in early-stage gamma band increases (Kanayama et al., 2021), whilst our recent findings showed a later stage of multimodal stimulus integration when using illusory finger resizing manipulations that potentially relates to habituation of the enlarged finger given that the finger grows in length during the resizing illusion opposed to simply inducing an illusion of a larger finger size (Hansford et al., 2023).

Looking specifically at research into somatosensory cortex modulation using steady-state evoked potentials (hereafter referred to as SSEPs), low-level somatosensory responses have been induced directly using vibrations of a known frequency applied to a body part. These generate a frequency-locked SSEP detectable at the scalp using EEG (Snyder, 1992; Tobimatsu et al., 1999) and are an index of the cortical response to a stimulus. This paradigm has been used with other sensory modalities to better understand the neural mechanisms underlying multisensory integration, with results showing that presentation of temporally congruent auditory and visual stimuli significantly enhances the magnitude and inter-trial phase coherence of auditory and visual steady-state responses (Nozaradan et al., 2012). Research has also found evidence of enhanced steady-state responses for within-modality stimulation of auditory and visual stimuli in isolation (Giani et al., 2012), complementing Nozaradan et al.'s findings regarding visuo-auditory combination. Studies using vibrotactile stimulation have found increases in steady-state response magnitude corresponding with the amplitude modulation rate of stimulation (Colon et al., 2012; Rees et al., 1986) suggesting an entrainment of oscillatory activity to temporal features of sensory stimulation (Timora and Budd, 2018). Given these findings, we postulate that SSEPs might change during finger resizing illusions, due to the multisensory manipulations present, to give a potential index of changes in neural representations during the illusion.

Several studies have investigated the analgesic effect of these resizing illusions, as they have been shown to reduce chronic pain in conditions such as osteoarthritis (Preston and Newport, 2011; Preston et al., 2020; Stanton et al., 2018), chronic back pain (Diers et al., 2013), and complex regional pain syndrome (Moseley et al., 2008). However, the precise mechanisms by which these illusions reduce pain is still undetermined. It has been suggested chronic pain involves cortical misrepresentations of the size of the affected body part (Boesch et al., 2016), however, it is unknown if resizing illusions affect this cortical misrepresentation, and if this is therefore what causes the reduction in pain. At the time of experimental testing, no study had yet used neuroimaging with a chronic pain population to determine the cortical activity correlated with this illusory analgesia. However, importantly, there has also been no research conducted using SSEPs in participants without chronic pain, to understand what the cortical representations of these resizing illusions are like without the impact of a chronic pain condition. Therefore, the aim of this study was to examine potential changes in the somatosensory cortex during illusory finger resizing in participants without chronic pain, using vibrotactile SSEPs, to use as a basis for later investigations in a sample of chronic pain participants. If we can identify a link between illusory resizing and somatosensory cortex changes, this will enhance our understanding of what is happening in the brain during these illusions and will act as a reference for comparison with neural representations in individuals with chronic pain conditions.

Using different sensory manipulations of finger resizing illusions, in addition to using an electromagnetic solenoid stimulator, this study aimed to investigate subjective illusory experience and SSEP responses in participants without chronic pain, to better understand the subjective experience of body ownership illusions and any resulting alterations cortical representation. To test this, different finger resizing illusions consisting of multisensory (visuotactile) stretching (MS), unimodal-visual stretching (UV), a non-illusion control condition without tactile input (NI), and a non-illusion control condition with tactile input (NIT) were used to assess alternate aspects of illusory resizing manipulations and their related effects on SSEP response. The inclusion of two control conditions (NI, NIT) was to assess whether localisation of cortical representations arise from resizing manipulations to the finger, or from tactile input given to the finger. The first hypothesis, acting as a positive control (1), was that there would be a greater illusory experience, measured via a subjective illusory experience questionnaire, in the (1a) MS condition compared to the NI condition and in the (1b) MS condition compared to the NIT condition. The main experimental hypothesis for this study was that (2) there would be a significant difference in SSEP response at the electrodes of interest (F1 & FC1, see Appendix A Pilot Data) when comparing across all conditions. Subsequent hypotheses were that there would be significant differences in SSEP response when comparing (2a) the MS condition to the NI condition, when comparing (2b) the UV condition to the NI condition, but (2c) that there would be no significant difference when comparing the NIT condition to the NI condition. A visual schematic of these hypotheses can be seen in Appendix B.

2. Methods

2.1. Preregistration

This study was preregistered as a stage 1 registered report which was given in-principal acceptance (IPA) by PCI-RR as be seen at the following OSF page: https://osf.io/pfksu/. Due to the exploratory nature of this study and thereby the need for some slight methodological deviations from those initially stated during registration (please see below), this study was withdrawn as a registered report during stage 2 revisions. All data and code to reproduce the analyses and manuscript for this study can be found at the following OSF page: https://osf.io/yhz6j/.

2.2. Deviations from preregistration

1. After IPA there was an artefact from a previous round of revisions stating that if a participant needed *either* of the electrodes of interest removed due to noise, that the participant's whole dataset would be removed. This should have stated that a participant's dataset would only be removed if *both electrodes* of interest needed removal, otherwise analyses would be run using the remaining electrode of interest. The latter was the approach taken with SSEP data and analyses.
2. It was preregistered that parametric analyses would be run to assess all hypotheses; however, the data did not meet all assumptions for parametric tests and therefore non-parametric tests were run instead, following standard statistical practice.

2.3. Sample size

Overall, based on the power analyses in section 2.7 "Power Analysis", a total sample size of 46 participants was tested. This sample size adheres to the higher end of sample size estimates (Hypothesis 2 (2.7.2) showing 46 participants were needed for post hoc tests 2a – 2c).

2.4. Participants

Ethical approval for this research was obtained from the Department of Psychology, University of York (ethics application code 950), in line with the Declaration of Helsinki. All participants gave informed written consent prior to the start of any experimental set up, and participants were instructed that they could withdraw their participation at any time during or after completion of the experiment. 46 participants were tested, with the participants' manipulated finger being randomly split between use of either the index or middle finger. However, 2 participants' data needed removal due to over 50 % of their electrodes requiring removal after noise checks (see section 2.6 "Preprocessing Steps" for more details), and therefore 2 additional participants were tested to account for this missing data, both using the index finger as the manipulated digit, resulting in a final sample size of 46 participants (37 Female, 8 Male, 1 Prefer not say; Mean age = 20.3 years, age range = 18.3–32.7 years; 32 White, 11 Asian or Asian British, 3 Mixed or Multiple Ethnic Groups; Sample population = students at the University of York). 23 participants were tested using their index finger, the other half using their middle finger.

2.4.1. Sample inclusion/exclusion criteria

Inclusion and exclusion criteria were determined using self-report responses relating to each item listed below.

- Inclusion Criteria: Right-handed, 18 years of age or over, no older than 75 years of age (include those aged 75 years).
- Exclusion Criteria: Prior theoretical knowledge, experience or informed expectations about the research (other than given within the participant information sheet), a history of developmental, neurological or psychiatric disorders, history of drug or alcohol abuse, history of sleep disorders, history of epilepsy, having visual abnormalities that cannot be corrected optically (i.e., with glasses), or being under 18 years of age, or over 75 years of age. A history of chronic pain conditions, operations or procedures that could damage peripheral nerve pathways in the hands, current experiences of pain or more than 4 h of consistent pain experienced in the preceding week.

Raw data exclusion criteria.

- Less than 100 % of the experiment completed by a participant, more than 50 % of electrodes for a single participant requiring removal from EEG data, or if both electrodes F1 and FC1 (electrodes of interest) required removal. More information about data removal can be found in section 2.6 Preprocessing Steps.

2.5. Experimental procedure

All participants completed a demographic survey, asking their age, ethnicity, and sex, and were asked to complete the revised Waterloo Handedness Questionnaire (WHQr; Elias et al., 1998). The WHQr consists of 36 self-report items answered on a 5-level Likert scale to determine the degree of preferred hand use, with right always being +2, right usually being +1, equal use being 0, left usually being −1, and left always being −2. The sum of the total WHQr score was then used to categorise respondents as left-handed (score of −24 or lower), mixed handed (score of −23 to +23), or right-handed (score of +24 or higher). Only participants who were categorised as right-handed continued participation. Mean handedness score across participants was +57.91 (range = +29 to +71).

Participants were then set up with an appropriately sized 64-channel EEG cap with electrodes arranged according to the 10/20 system. The experimenter used saline gel to make a conductive bridge between the electrodes and the scalp to attempt to obtain impedance levels of <10 kΩ per electrode. Data were collected using an ANT Neuroscan system, sampling at 1 kHz. The whole head average was used as a reference.

Participants were then seated behind the augmented reality system (Fig. 1) and instructed to place their hand onto the black felt fabric within the lower part of the system. Within the self-built system there was a 1920 x 1080-pixel Spedal Webcam Wide Angle Camera at the edge of the black felt on the side the participant sat, away from the participant's view. 26cms above the felt base, there was a mirror, which was placed 26cms below a screen with a resolution of 1920 x 1200 pixels, with a width of 52cms and a height of 32cms. The thickness of the section on which the mirror sat was 2cms. This screen was 54cms from the base of the system, and the base of the system was 82cms from the ground. Participants were instructed to place either their right index or middle finger outstretched onto the felt, with finger selection pseudo randomised (to give equal representation of each finger) via MATLAB prior to any participants taking part. There were two white dots for each hand on the felt and participants were instructed to place their hand between these two dots. Participants were instructed to view their hand's image in the mirror (whilst the real hand was hidden from view) throughout the experiment. Participants were asked to remain still during each trial to avoid muscle artefacts impacting the SSEP data. Participants were free to move as they wished during the breaks between trials as EEG data from these time periods were not analysed. The camera placed underneath the mirror on the felt base was used to deliver a live feed video of the participant's hands to the computer screen at the

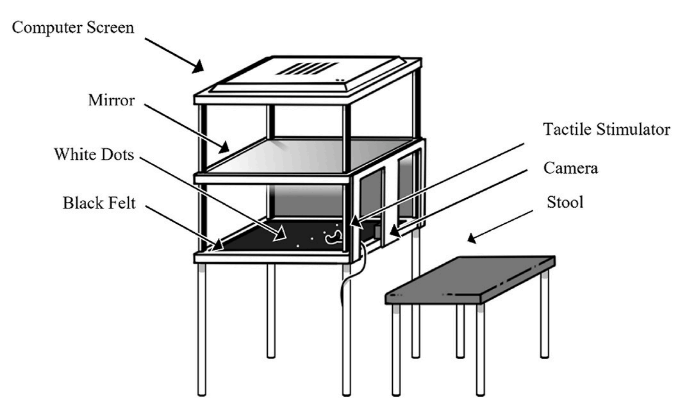

Fig. 1. Schematic of augmented reality system with tactile stimulator.

top of the augmented reality system, which showed in the mirror reflection to the participants. There was a delay of 170ms in the video processing pipeline from the camera image to the presentation of the augmented video image.

Participants underwent 4 conditions: multisensory stretching (MS), unimodal-visual stretching (UV), a non-illusion control condition without tactile input (NI), and a non-illusion control condition with tactile input (NIT). All conditions included vibrotactile stimulation to the finger, but only tactile input from the researcher touching the participant's finger in the MS and NIT conditions. The MS condition consisted of the researcher touching and pulling the participant's finger (at the distal interphalangeal joint) as the participant viewed the augmented live footage of their finger stretching in a congruent manner. The UV condition consisted of participants viewing augmented live footage of their finger stretching, but without any tactile experimenter manipulation. The NI condition provided no visual or touch-based tactile manipulations to the finger, the live video feed of their unmanipulated finger was visible and unchanged throughout the trials. The NIT control condition involved no visual input of the finger stretching (the video feed of their finger was visible but unchanged just like in the NI condition) but did include tactile input from the experimenter's hand touching the participant's finger at the distal interphalangeal joint (the same as in the MS condition), but without pulling the finger. Each trial lasted 2.4 s for the manipulation phase, where the augmented image of the finger was stretched by 60 pixels (2.1 cm) in UV and MS conditions, followed by a further 2.4 s habituation phase in which participants could view and move their (augmented) finger, whilst they keep the rest of their hand still, before the screen went dark, indicating that the next trial could start. Visualisation of all conditions can be seen in Fig. 2.

The experimenter was seated opposite the participant, the other side of the augmented reality machine and touched the digit during MS and NIT conditions by holding onto the distal interphalangeal joint and gently touching (NIT) or pulling (MS) the finger whilst the participant kept their hand in place. Conditions were delivered across 4 blocks, with each block consisting of 24 trials of the same experimental condition, totalling 96 trials over all 4 blocks. The ordering of the blocks was randomised for each participant to prevent ordering effects. The experiment was programmed in, and the conditions randomised using MATLAB R2017a and the experimenter was informed of whether to pull the finger or to touch the finger via an indicative box displayed on the screen out of the participant's view. If the box was blue, this indicated a need to pull the finger, if it was white this indicated a need to touch the finger, if there was no box displayed then this indicated no tactile manipulation from the experimenter. The researcher used a button press to trigger the start of the manipulation, and started pulling the finger, when needed, synchronously within the 2.4 s manipulation phase. If the experimenter were to forget to pull the finger during a multisensory condition, or mistakenly pulled the finger in a control trial, then this would be noted during the experiment, and that trial would be removed from analysis. No trials needed removal due to experimenter error. Vibrations were delivered to the participant's finger in all conditions using a miniature electromagnetic solenoid stimulator (Dancer Design Tactor; diameter 1.8 mm) emitting vibrations produced by sending amplified 26Hz sine wave sound files, with stimulus intensity controlled by an amplifier (Dancer Design TactAmp). The tactor was driven at 50 % of the maximum (i.e. a peak input voltage of 3V) using a 26Hz sine-wave, and delivered a peak force of 0.18N. The electromagnetic solenoid stimulator was attached to the participant's outstretched finger using clear medical tape, between the knuckle and the first finger joint, and gave continuous stimulation for the duration of each trial. Participants were encouraged to take a break between each of the blocks to stretch their hand. EEG was recorded throughout as a continuous recording with conditions recorded on the EEG trace using an 8-bit digital signal at the start of each trial (USB-TTL Module, Black Box Toolkit Ltd.).

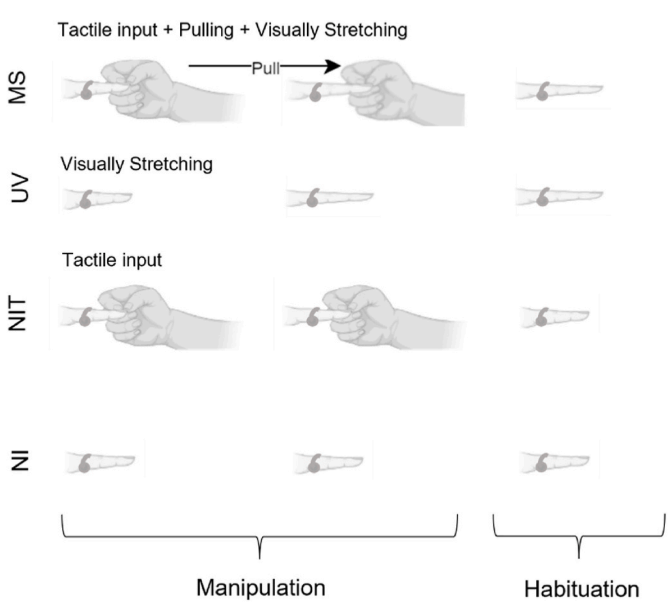

Fig. 2. Infographic of Experimental Conditions. MS = Multisensory Stretching, UV = Unimodal Visual Stretching, NIT = Non-Illusion Tactile, NI = Non-Illusion. During the manipulation phase (2.4 s) the visual image of the finger is stretched in the MS and UV conditions, and/or the experimenter provides tactile input (touch) in the MS and NIT conditions. The tactile input in the MS condition is accompanied by pulling. During the habituation phase (2.4 s) participants are free to move their finger. The arrow denotes the direction of the experimenter's action. The vibrotactile stimulator is depicted on the finger in each phase of the experiment as vibrations are presented throughout.

Finally, at the end of each block, the participant was asked to complete the subjective illusory experience questionnaire for that condition using a Samsung Galaxy Table A6 that presented the questions via Qualtrics (Qualtrics, Provo, UT). This questionnaire consisted of six questions relating to the trials the participant had just experienced. Two statements related to illusory experience: "It felt like my finger was really stretching"/"It felt like the finger I saw was part of my body", two related to disownership: "It felt like the finger I saw no longer belonged to me"/"It felt like the finger I saw was no longer part of my body", and two were control questions: "It felt as if my finger had disappeared"/"It felt as if I might have had an extra finger" (all questions were directed towards the participant's manipulated finger*)*. A visual analogue scale from 0 to 100 was used for each statement, with 0 being strongly disagree, 50 being neutral and 100 being strongly agree. Control questions were included to create an index for the illusion and disownership questions (more detail can be found in section 2.6 Preprocessing steps), whilst disownership questions were included to assess if the potential experience from the illusions resulted from a disownership of the body part, or from subjective embodiment of the body part (McCabe, 2011). Our previous work (Hansford et al., 2024) has found that this questionnaire can produce results in line with more objective measures of proprioceptive drift and ruler judgement tasks and therefore can confidently be used to assess illusory experience.

Data collection was terminated when the full sample of participants had been tested. If a participant completed <100 % of the experiment or if over 50 % of electrodes needed removal, or if both electrodes F1 and FC1 needed removal, then their data was not included, and additional participants were recruited to replace any lost data.

2.6. Preprocessing steps

EEG data were first converted using MATLAB and EEGlab from the ANT EEprobe.cnt format to EEGlab.set format. All subsequent analysis was then conducted using the MNE-Python toolbox (Gramfort et al., 2013). A 50Hz notch filter was first applied to the raw EEG data for all electrodes, followed by calculation of the standard error across time for each electrode for each participant (Luck et al., 2021). Across the standard errors for all participants, the 5 % of electrodes which showed the largest standard errors were used to create a standard error threshold. Any electrode with a standard error above this threshold, or with a value of 0, was defined as noisy and was removed from analysis. Where a participant had over 50 % of their electrodes over the standard error threshold or with a value of 0, or if the electrodes requiring removal included both electrodes F1 and FC1 (electrodes of interest), then their data were removed, which was the case with 2 participants. Two additional participants were then recruited to replace this lost data. Primary analysis of the remaining EEG data then involved averaging the signal across the electrodes of interest (or using just electrode F1 or FC1 in case of electrode removal), and calculating the Fourier transform for each trial per participant. These amplitudes were then averaged across trials for each condition to give overall results for each participant per condition. Statistical comparisons were then performed on the Fourier amplitudes at the stimulation frequency (26Hz), across conditions and participants. No additional filtering or denoising steps were applied to the EEG data, in line with Figueira et al.'s (2022) report that only a Fourier transform is typically needed for this type of EEG data.

Regarding questionnaire data, scores for both illusion experience questions were combined to give median scores, along with both disownership questions and both control questions, resulting in 3 median scores per condition per participant. The median control scores were used to create an index of the illusion and disownership scores by subtracting the median control score from the median illusion and median disownership scores, in line with previous research (Matsumiya, 2021; Kilteni and Ehrsson, 2017; Kalckert and Ehrsson, 2012). The normalised (control indexed) data were used for analyses, with a new scale from −100 to +100, with 100 indicating strongly agree, 50 indicating a neutral opinion, and scores below 0 indicating strongly disagree with the statements on the questionnaire. 50 was maintained as a neutral opinion so that the normalised data still adhered to the thresholds that the participants were presented with during the experiment.

All planned analyses can be seen within the stage 1 IPA report at the following OSF page: https://osf.io/pfksu/.

2.7. Power analysis

2.7.1. Hypothesis 1 (positive control)

Effect sizes were determined by research from Hansford et al. (2023) using the subjective illusory experience questionnaire and comparing MS, UV, and incongruent finger-based resizing illusions to control conditions with no illusory resizing, using the same finger stretching illusions and the same equipment (n = 48), which show an effect size of $\eta^2 = 0.33$ (converted to Cohen's $f = 0.70$ and Cohen's $d = 1.4$). Additional effect size information comes from a visual capture study (n = 80) using a subjective embodiment questionnaire and visual and tactile manipulations to a mannequin body (Carey et al., 2019), showing an effect size of r = 0.64 (converted to Cohen's $f = 0.83$) when comparing embodiment scores from the questionnaire against control scores. An effect size of f = 0.70 was used for hypothesis 1 to adhere to the lower end of previous effect sizes.

Hypothesis 1. A priori power analysis using G*Power for the smallest effect size of interest (f = 0.70) showed that for a repeated measures, within factors one way ANOVA, with an effect size (f) of 0.70, alpha level of 0.05, power at 80 % and 1 group with four measurements, 5 participants were needed.

Hypotheses 1a and 1b: A priori power analysis using G*Power shows that for a one-tailed difference between 2 means (pairwise) *t*-test, with an effect size of $dz = 1.4$, alpha of 0.025, power at 80 %, a total sample size of 7 participants was required.

2.7.2. Hypothesis 2

This was the first study to investigate illusory finger stretching using SSEPs, so appropriate effect size estimates were not available. We therefore conducted power calculations based on a smallest effect size of interest, in line with the recommendation of Lakens (2014). Here, we have chosen an effect size of d = 0.5 (a medium effect, see Cohen, 1988), since this is the smallest effect size we were interested in detecting, which we converted to a Cohen's f of 0.25 for Hypothesis 2's power analysis, and have maintained at 0.5 for the subsequent post hoc power analyses.

Hypothesis 2. A priori power analysis using G*Power showed that for a repeated measures, within factors one way ANOVA, with an effect size (f) of 0.25, alpha of 0.05, power at 80 %, and 1 group with four measurements, a total sample size of 24 participants was needed.

Hypotheses 2a – 2c: A priori power analysis using G*Power shows that for a two-tailed difference between 2 means (pairwise) *t*-test, with an effect size of $dz = 0.5$, alpha of 0.016 (corrected for multiple comparisons), power at 80 %, a total sample size of 46 participants was needed.

3. Results

Positive control analyses of the subjective illusion data can be seen in Fig. 3. A one-way ANOVA found a significant overall effect of condition with a large effect size (F(3,135), p = <0.001, $\eta_p^2 = 0.229$). Post hoc t tests with Bonferroni corrections indicated significantly greater combined illusion scores in the MS condition (Mean = 61.79, SD = 28.31) compared to the Non-Illusion (NI; Mean = 31.2, SD = 26.08, t = −5.67, *p.adj* = < 0.001, Cohen's d = −1.18) and Non Illusion Tactile (NIT; Mean = 37.41, SD = 20.59, t = −5.61, *p.adj* = < 0.001, Cohen's d = −1.17) conditions, thereby supporting hypotheses 1, 1a, and 1b and fulfilling the positive control checks.

Analyses of SSEP data can be seen in Fig. 4. The left panel confirms the presence of a clear steady-state signal at 26Hz, which was strongest over the fronto-central electrodes. A one-way ANOVA found no significant effect of condition and a small effect size (F(3,135), p = 0.209, $\eta_p^2 = 0.033$), opposing Hypothesis 2. Post hoc t tests with Bonferroni corrections found no significant differences between SSEP amplitudes when comparing the NI condition (Mean = 0.49, SD = 0.76) to the MS condition (Mean = 0.31, SD = 0.57, t = 1.7, *p.adj* = 0.571, Cohen's d = 0.35), or UV condition (Mean = 0.36, SD = 0.83, t = 1.15, *p.adj* = 1.000, Cohen's d = 0.24), meaning Hypotheses 2a and 2b were unsupported. There was no significant difference found when comparing the NI condition to the NIT condition (Mean = 0.29, SD = 0.35, t = 2.02, *p.adj* = 0.298, Cohen's d = 0.42), supporting Hypothesis 2c.

3.1. Exploratory analyses

Since illusion data violated assumptions for parametric tests, an exploratory Friedman test was run and found a significant overall effect of condition with a moderate effect size ($\chi^2(3) = 42.05$, $p < 0.001$, Kendall's W = 0.305) and post hoc Wilcoxon tests with Holm corrections found a significantly greater combined illusion score in the Multisensory Stretching (MS) condition (Median = 68, SD = 28.31) compared to the Non-Illusion (NI; Median = 41.75, SD = 26.08, z = 103, *p.adj* < 0.001, r = 0.70), Non Illusion Tactile (NIT; Median = 46.5, SD = 20.59, z = 118, *p.adj* < 0.001, *r* = 0.68) and UV conditions (Median = 37.25, SD = 34.37, z = 903.5, *p.adj* < 0.001, r = 0.64).

In addition to illusion data, disownership and control data were collected and therefore analyses on these datasets have also been run. Exploratory analysis of subjective disownership and control data can be seen in Figures C1 and C2 in Appendix C. A significant increase in disownership scores were found in the UV condition compared to all other conditions, and there were no significant comparisons found for control data. All statistical reporting can be seen in Appendix C.

EEG data also violated assumptions for parametric tests and therefore a Friedman test was also run and found a significant overall effect of

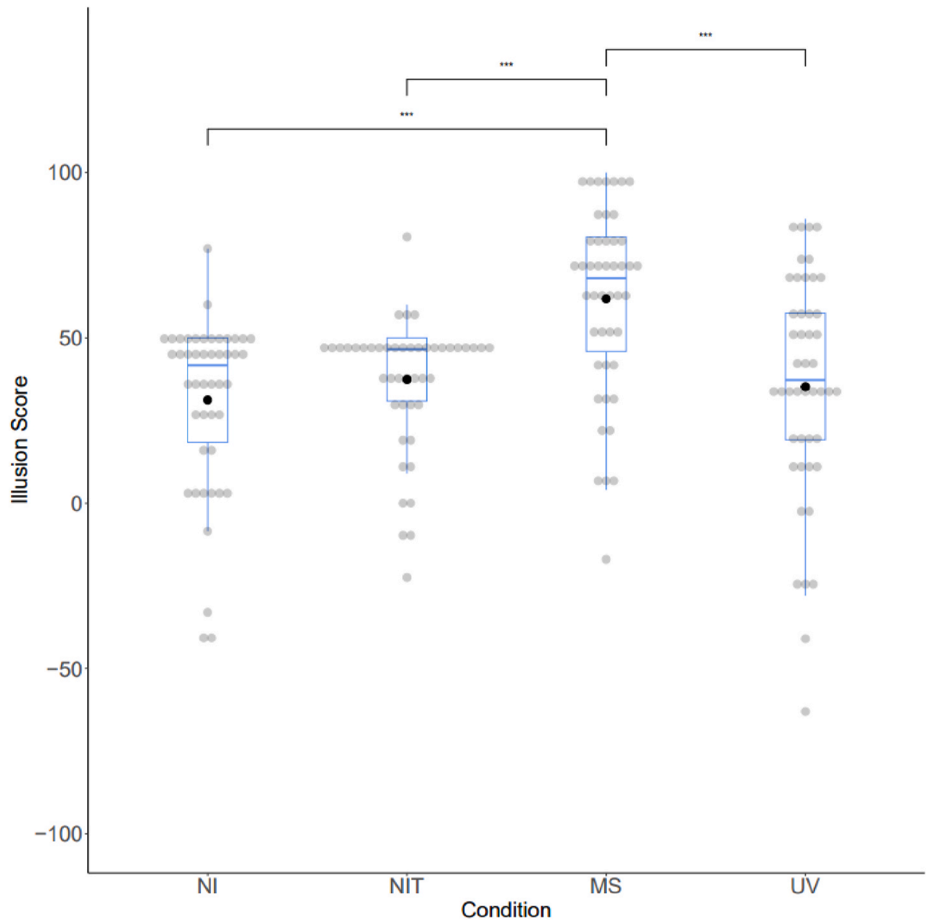

Fig. 3. Combined Illusion Score Index Across Conditions (NI: Non-Illusion; NIT: Non-Illusion Tactile; MS: Multisensory; UV: Unimodal Visual). Scores below 50 indicate disagreement with experience of illusion statements, whilst scores above 50 indicate agreement. A continuous visual analogue scale was used in data collection, with agreement and disagreement statements located at each end of the scale. Box plots show means, medians and inter-quartile ranges of data. Medians are indicated with a horizontal line whilst means are indicated by a black dot. Box and whiskers show inter-quartile ranges. Data points are shown in grey jitter binned along the y-axis, grouped by condition.

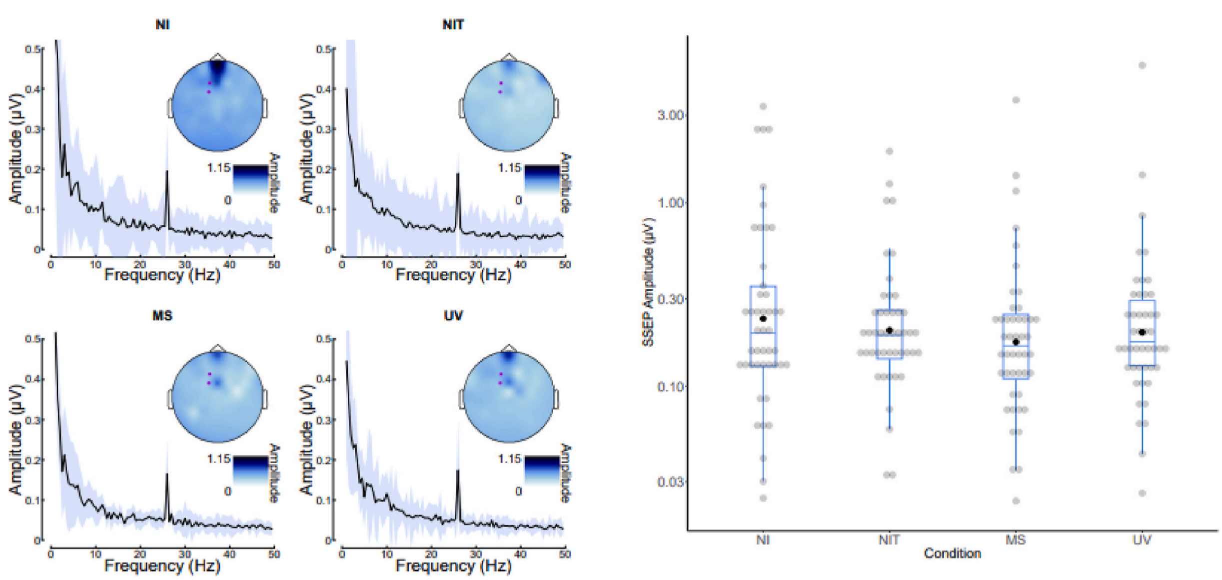

Fig. 4. Left Panel: SSEP Amplitude Spectra Across Conditions (NI: Non-Illusion; NIT: Non-Illusion Tactile; MS: Multisensory; UV: Unimodal Visual) for electrodes of interest (F1 & FC1). Black line shows data average, shading shows ±1 standard error across participants (n = 46). Right Panel: SSEP Amplitudes Across Conditions. Box plots show means, medians and inter-quartile ranges of data. Medians are indicated with a horizontal line whilst means are indicated by a black dot. Box and whiskers show inter-quartile ranges. Data points are shown in grey jitter binned along the y-axis, grouped by condition. A logarithmic scale is used for visual representation of data.

condition with a small effect size ($\chi^2(3) = 8.17$, $p = 0.043$, Kendall's W = 0.059), however, post hoc Wilcoxon tests with Holm corrections found no significant differences between SSEP amplitude when comparing the NI condition (Median = 0.19, SD = 0.76) to the MS condition (Median = 0.17, SD = 0.57, z = 725, *p.adj* = 0.131, r = 0.3), or UV condition (Median = 0.17, SD = 0.83, z = 719, *p.adj* = 0.131, r = 0.29). There was no significant difference found when comparing the NI condition to the NIT condition (Median = 0.19, SD = 0.35, z = 686, *p.adj* = 0.131, r = 0.23). As the topographical maps in Fig. 4 show, the electrodes of interest were not located in the areas where peak amplitudes were identified. Therefore, exploratory analysis was conducted to assess which electrodes gave the greatest overall response, which resulted in electrodes FPZ and FCZ being used for further exploratory analysis. A Friedman test found no overall effect of condition with a small effect size ($\chi 2(3) = 4.41$, p = 0.221, Kendall's W = 0.032). Post hoc Wilcoxon tests with holm corrections found no significant differences between SSEP amplitude when comparing the NI condition (M = 0.25, SD = 1.38) to the NIT condition (M = 0.17, SD 466 2 = 0.72, p = 0.266), MS condition (M = 0.18, SD = 1.24, p = 0.102), or UV condition (M = 0.21, SD = 1.4, 467 p = 0.266). A figure showing this can be seen in Appendix C, Figure C3.

Exploratory correlational analyses were conducted to assess the correlation between participant's subjective illusion score and their SSEP amplitude across electrodes of interest (F1 & FC1) for each condition to see if those who experienced a stronger feeling of the illusion had more reduced SSEP amplitudes, results showed no significant correlations and can be seen in Figure D1 in Appendix D.

4. Discussion

This study sought to understand both subjective and neural responses to resizing illusions in participants without chronic pain. Our aim was to provide not only a greater understanding of how bodily illusions affect cortical representations, but also a basis for investigating differences in cortical representations between participants with and without chronic pain conditions when using resizing illusions for analgesic treatment. Subjective (behavioural) data replicated previous findings of greater subjective illusory experience in multisensory compared to non-illusion conditions, showing that the addition of vibrotactile stimulation does not appear to impact the subjective experience of resizing illusions using augmented reality, since these effects replicate previous findings without vibrotactile stimulation. Confirmatory EEG analyses showed no significant effect of condition when assessing SSEP amplitudes across the electrodes of interest (F1 & FC1) at 26Hz. Exploratory non-parametric analyses of SSEP amplitudes, however, showed a significant effect of condition with a decreased median amplitude in the multisensory and unimodal visual conditions compared to the non-illusion condition. However, these differences did not reach statistical significance with exploratory post hoc tests. These findings, therefore, suggest that illusory resizing may lead to small reductions in SSEP amplitude, but replication within confirmatory analyses is needed.

Whilst the subjective illusory experience data supported the positive control hypothesis of the multisensory condition providing greater illusory experience than either of the non-illusion conditions, exploratory analyses found that the unimodal-visual condition demonstrated a significantly reduced experience of the illusion compared to the multisensory condition. This reduction in illusory experience for the unimodal visual condition compared to the multisensory condition was also found in our previous work (Hansford et al., 2023), and similarly shows a more diverse range of responses compared to the multisensory condition. These findings reinforce the idea that not everyone experiences resizing illusions with only visual stimuli, and this should be considered when assessing the application of resizing illusions to chronic pain samples, as if subjective experience of the illusion is required for analgesic effects, then it is possible that not everyone will experience this from a unimodal visual presentation. Exploratory analyses looking at disownership of the digit during illusory resizing found significantly greater experiences of disownership during the unimodal visual condition compared to the multisensory, non-illusion, and non-illusion tactile conditions. This heightened disownership might explain the reduced illusory experience in the unimodal visual condition, as it may be that the presence of tactile input is needed during illusory resizing to ground the digit within the augmented reality system, otherwise feelings of disownership can arise. It is important to note that the subjective illusory experience questionnaire used in the present study is not a validated measure of illusory experience, as an applicable validated test does not yet exist. However, several previous studies have used the same or similar questionnaires (depending on the specific tests and body parts being manipulated) to assess illusory experience (e.g. Preston and Ehrsson, 2014; Newport et al., 2010; Van der Hoort and Ehrsson, 2016; Hansford et al., 2023; Hansford et al., 2024).

The topographical maps presented in Fig. 4 show peak SSEP amplitudes across frontocentral electrodes in all conditions, which is in line with previous research using vibrotactile input to the fingers in the 20–30Hz frequency range (Timora and Budd, 2018; Porcu et al., 2014) and with the pilot data for the present study (Appendix A). Peak amplitudes, however, were not found across the electrodes of interest (F1 and FC1), but were instead found to be located across electrodes FCz and FPz. Since no differences were found when comparing the conditions at these electrodes, it is possible that the increased amplitudes identified here could be due to noise artefacts consistent across the small sample of EEG caps used for all participants. When assessing the differences in amplitudes seen in the exploratory analysis of the electrodes of interest (F1 and FC1), the reduced SSEP amplitudes found in the multisensory and unimodal visual conditions could be explained by the somatosensory blurring/sharpening hypothesis (Haggard et al., 2013). This theory proposes that the somatosensory representation of a body part can be sharpened through improved tactile discrimination and acuity training. This sharpening is thought to represent increased organisation of the somatosensory area responding to the stimuli (Haggard et al., 2013). Tactile acuity can be increased through simply viewing an enlarged body part (Kennett et al., 2001). Therefore, it is possible that the enlarged digits created through illusory resizing are sharpening the somatosensory representations of the digits. The reduced amplitudes found during exploratory analyses in the illusory conditions compared to the non-illusion conditions therefore could demonstrate a neural representation of this somatosensory sharpening. However, since these differences were not found to be significant via confirmatory (parametric) analyses or exploratory post hoc tests, it is possible that the magnification factor in the present study was not great enough to induce improved tactile acuity and therefore show effects within the somatosensory cortex. In Kennett et al., 's 2001 study, the arm was magnified by a factor of 2.5 which far exceeds the 60-pixel (2.1 cm) enlargement used in the present study. Furthermore, since the effect sizes were small for the SSEP analysis, whilst it is possible that somatosensory sharpening might contribute to our experiences of resizing illusions, multisensory integration might play more of an important role in illusory experience than somatosensory changes do. In the present study we replicated findings of an increased illusory experience in the MS condition compared to the UV condition, which is in line with our previous work finding greater illusory experience in conditions with tactile input compared to those with visual input (Hansford et al., 2024). These findings could suggest that tactile input is more of a predictor of illusory experience than somatosensory changes.

A possible explanation for the observed SSEP reductions could be through the direction of attention to the digits in illusory conditions. Previous research, however, has found that attending to a specific vibrotactile stimulus can result in an increase, rather than a reduction, in SSEP amplitude (Giabbiconi et al., 2004). Furthermore, brain computer interfaces (BCIs) are used to intentionally modify a brain signal that can be detected by a computer to manipulate one's environment, and these are often based on increasing SSEP response amplitudes through directing attention (Muller-Putz et al., 2006). Therefore, it is unlikely that the reduction in SSEP amplitudes seen here is due to increased attention during illusory manipulation conditions. It is possible that if somatosensory sharpening is occurring, the reduction in amplitude associated with this could be confounded by this attentional effect, with somatosensory sharpening reducing amplitudes whilst attention is increasing the amplitudes, resulting in the small effect sizes we see within this dataset. Due to these small effect sizes, replication of these effects in larger samples might be better able to assess somatosensory sharpening or attentional effects, as here the sample size was only powered to detect at least medium-sized effects. Additionally, a limitation of this study is that a resting-state baseline EEG measure was not included. If this had been included, it would have been possible to also assess whether attentional increases in SSEP amplitude were found, which could have then been used to compare experimental condition data to. Should this study be replicated, it would be beneficial to include such a true baseline measure to assess attentional effects and resting-state effects.

Further exploratory analyses assessed correlations between subjective illusory experience and SSEP amplitude across electrodes of interest and found no significant correlations for any condition. These findings could indicate that subjective experience of the illusion is not required for there to be changes in cortical responses, although without clear support for changes in SSEP amplitudes found within the confirmatory analyses, and without the use of a validated illusory experience test, this suggestion cannot be empirically justified. It is possible that SSEP amplitudes are too noisy to show such somatosensory changes, or that the sample needed to detect these effects would have to be larger than the one in the present study. However, when considering resizing illusions as a non-pharmaceutical method for pain reduction, a lack of correlation between SSEP amplitude and illusory experience could mean that patients do not need to subjectively experience resizing illusions per se for there to be the potential of illusory analgesia. Future research is needed to consolidate both this hypothesis and the exploratory correlational findings from the present study. It is also possible that there are alternate neural correlates of illusory experience that were not assessed within the present study which might correlate with subjective illusory experience, which would thereby change these ideas regarding correlations between SSEP amplitude, illusory experience, and analgesic effects.

One of the main aims of the present study was to provide a basis for investigating somatosensory representations of illusory resizing in samples with hand-based chronic pain. Illusory resizing has been found to provide analgesic effects for hand-based chronic pain (Preston and Newport, 2011), however, the neural underpinnings of this analgesia remain undefined. Since chronic pain is thought to create blurred somatosensory representations of the painful body part (Haggard et al., 2013), it is possible that when comparing the results seen here in participants without chronic pain to a sample of participants with chronic pain, the differences between amplitudes in the non-illusion and illusion conditions could be greater, due to more blurred initial representations of the painful digits. If somatosensory response changes are found in a sample with chronic pain, then these changes could underscore the analgesia experienced after illusory resizing, however, if these changes are either not seen or do not align with pain reduction, then alternate mechanisms are likely behind illusory resizing analgesia. It is, however, possible that since there were no SSEP effects found through confirmatory analyses in the present study, that the impact of illusory resizing on SSEP responses could be too small to meaningfully detect in both population groups, especially since a patient group could have more varied and/or noisy data.

5. Conclusions

The present study enhances our understanding of whether there are cortical changes associated with illusory resizing in people without chronic pain and provides an empirical basis for subsequent investigations of somatosensory response changes in a sample with chronic pain. The subjective data suggest that vibrotactile stimulation does not affect experience of resizing illusions, and therefore highlights the suitability of this method for eliciting somatosensory steady state evoked potentials in future investigations. Confirmatory analyses of SSEP data showed no clear effect of illusory resizing on SSEP amplitudes, however, trends toward supporting the somatosensory blurring/sharpening hypothesis were found within exploratory analyses whereby reduced amplitudes were seen in both illusory conditions compared to the non-illusion conditions. If similar reductions are observed in a sample with chronic hand-based pain, then it would be possible to assume that these neural response changes could be driving illusory analgesia.

CRediT authorship contribution statement

Kirralise J. Hansford: Writing – original draft, Visualization, Validation, Software, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Daniel H. Baker:** Writing – review & editing, Validation, Supervision, Software, Resources, Project administration, Methodology, Data curation, Conceptualization. **Kirsten J. McKenzie:** Writing – review & editing, Supervision, Resources. **Catherine E.J. Preston:** Writing – review & editing, Supervision, Resources, Project administration, Methodology, Funding acquisition, Conceptualization.

Data and code Availability

All data and code to reproduce the analyses and manuscript for this study can be found at the following OSF page: https://osf.io/yhz6j/.

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Declaration of competing interests

The authors declare no competing interests.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.neuropsychologia.2025.109243.

Data availability

All data and code used for the study can be found at a linked repository within the manuscript text.

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