The Effect of Non-Naturalistic Auditory Input on Conscious and Unconscious Experiences of Resizing Illusions

Kirralise J. Hansford[1], Kirsten J. McKenzie[2], Daniel H. Baker[1], and Catherine Preston[1]

[1] Department of Psychology, University of York

[2] School of Psychology, University of Lincoln

Abstract

Background: Bodily resizing illusions typically use visual and/or tactile inputs to produce a vivid experience of one's body changing size. Naturalistic auditory input (input that reflects the natural sounds of a stimulus) has been used to increase illusory experience during the rubber hand illusion, whilst non-naturalistic auditory input can influence estimations of finger length. Aims: To use non-naturalistic auditory input during a hand-based resizing illusion using augmented reality, to assess whether the addition of auditory input would increase both subjective experience of the illusion and measures of performance-based tasks. Methods: 44 Participants completed three conditions: no stretching, stretching without tactile feedback, and stretching with tactile feedback. Half of the participants had auditory input throughout all conditions, the other half did not. After each condition, participants were given one of three tasks: stimulated (right) hand dot touch task, non-stimulated (left) hand dot touch task and a ruler judgement task. Dot tasks involved participants touching a virtual dot, whereas the ruler task concerned estimates of the position of the tip of their finger on a ruler, whilst the hand was hidden from view. Finally, participants completed a subjective questionnaire capturing illusion strength. Results: The addition of auditory input increased subjective experience of the stretching illusion for manipulations without tactile feedback but not for those with tactile feedback. No facilitatory effects of audio were found for any performance task. Conclusions: Adding auditory input to illusory finger stretching increased subjective illusory experience in the absence of tactile feedback, but did not affect performance-based measures of illusory experience.

Keywords: Multisensory Integration, Resizing Illusions, Non-Naturalistic Auditory Input, Consciousness

1. Introduction

Resizing illusions can be delivered through either augmented reality or magnifying optics and typically use visual and tactile inputs to manipulate the size of a body part, making it appear either larger or smaller. These illusions, through changing the way a body part is perceived, exploit principles of multisensory integration to elicit modulations in the perceived size and shape of the body part (Preston et al., 2020; Preston and Newport, 2011; Stanton et al., 2018). In addition to visual and tactile illusions, the combination of visual and proprioceptive, or, visual and motor inputs, has also been found to elicit resizing illusions, with research finding that proprioceptively aligning a child avatar body with the participants adult body elicited a strong illusion of having a smaller child-sized body (Banakou et al., 2013) and further research showing similarly that synchronous movements of an avatar with an elongated arm was able to influence judgements of arm length (Kilteni et al., 2012). Furthermore, visuotactile inputs have been compared to unimodal visual inputs for finger stretching illusions, with findings showing greater subjective embodiment during visuotactile compared to the unimodal visual illusions (Hansford et al., 2023). Thus, highlighting the importance of multisensory integration for subjective embodiment during illusory changes in finger length.

Multisensory processing helps us to perceive a stimulus as a single coherent experience despite being a combination of several different sensory inputs. This process is thought to be important for experiencing our body as our own, as has been demonstrated in the rubber hand illusion, where the integration of visual and tactile inputs to a rubber hand at the same time and location as inputs given to a real hand occluded from view, can manipulate our understanding of what we experience to be part of our own body (Botvinick and Cohen, 1998). Because tactile and proprioceptive inputs are thought to be unique to the bodily experience, unlike senses such as vision and audition which are experienced not only in relation to our body but also relating to objects in the external world, many of the theories explaining body ownership and multisensory body illusions focus primarily on these senses (Botvinick and Cohen, 1998; Tsakiris, 2010). However, more recent Bayesian accounts of body ownership suggest that the addition of other senses may facilitate feelings of embodiment and vividness of body illusions (Kilteni et al., 2015). Studies have claimed that additive effects of additional senses in multisensory integration concerning non-body events, though investigating the addition of auditory inputs to visual detection tasks, finding that the addition of auditory stimuli enhanced overall efficiency in difficult detection tasks (Frassinetti et al., 2002). It has also been found as an inverse effect, wherein the addition of visual cues to an auditory task can improve the detection of a low-intensity sound (Lovelace et al., 2003). Additionally, above threshold, there is evidence supporting audio cues modulating tactile perception, which comes from a study by Zampini and Spence (2004), which found that increasing the overall volume and / or the amplitude of high frequency sounds, combined with the tactile input of biting a potato chip, increased the reported crispness of the chip. Research examining multisensory integration regarding the body and body illusions has also begun to explore the importance of other senses, notably the role of auditory input in multisensory interactions has been found to influence body representations regarding perceptions of body size and length (Tajadura-Jiménez et al., 2012), along with altering perceived material properties (Senna et al., 2014) and weight (Tajadura-Jiménez et al., 2015) of the body. Looking specifically at visual, tactile, and auditory inputs in the rubber hand illusion, which is used as a theoretical basis for the embodiment experienced in resizing illusions, O'Mera (2014) found using proprioceptive drift tasks, that the addition of auditory inputs consistent with the visual and tactile inputs of stroking the hand (here they used the sound of sandpaper scratching the skin) heightened the illusory experience more than when white noise was added to the illusion. This is supported by Radziun and Ehrsson (2018), who also looked at the addition of ecologically relevant auditory inputs to the rubber hand illusion. This study used the sound of a surface being stroked with a paintbrush, subjective questionnaires, and proprioceptive drift tasks. They found that synchronous auditory cues made the illusion stronger compared to when using asynchronous auditory cues, in line with O'Mera (2014) findings.

The addition of auditory input in the studies mentioned above involve naturalistic auditory input, i.e., experimental auditory input that is consistent with realistic auditory stimuli that we are used to encountering in everyday life. However, Tajadura-Jiménez et al. (2017), looked at the influence of non-naturalistic auditory inputs, to see if this still resulted in changes to body perception. Here, they used changes in pitch, due to their associations with a change in height or size (Hubbard, 2018). Such sounds are not typically associated with bodily movement. They found that when participants pulled their right index finger with their left hand with an accompanying rising pitch sound (700 – 1200Hz), they estimated the length of their index finger to be longer than when this pulling was accompanied with either a descending (700 – 200Hz) or constant (700Hz) tone and coined this the "Auditory Pinocchio" effect (though they did not attempt to stretch participants' noses).

Given previous findings involving naturalistic auditory input in the rubber hand illusion (O'Mera, 2014) and non-naturalistic auditory input in auditory-tactile resizing manipulations (Tajadura-Jiménez et al., 2017), it is plausible that the addition of non-naturalistic auditory input when using augmented reality to induce visual and visual-tactile resizing illusions, could heighten the experience of the illusory effects, referring again to the notion that the inclusion of more senses provides a more holistic and vivid experience of an event. Measuring the experience of illusory effects often consists of questionnaires given to participants after they have experienced an illusory condition to gain a subjective measure of their experience. However, more performance-based evidence can also be taken from behavioural measures of proprioceptive drift, which is defined as the change in proprioceptively perceived position of the participant's hidden body part (Davies et al., 2013). Previous studies assessing proprioceptive drift during the rubber hand illusion have found differences regarding the influence on body schema. Body schema are representations of the body based on bottom-up sensory inputs that are needed for action, whereas body image refers to a top-down representation that is needed for perception (Paillard, 1999). Kammers et al. (2009) investigated body schema and body image using the rubber hand illusion with a reaching proprioceptive drift task (action movement), where participants were asked to reach with one hand to point to the tip of the index finger of the other hand in a single movement to assess body schema, and were asked to verbally report when the experimenter's moving finger represented the felt location of their own finger (perceptual task), to assess body image. They found that only the perceptual judgements regarding limb ownership were sensitive to distortion in the rubber hand illusion, finding that action movements, therefore body schema, were not affected. Newport et al. (2010) used augmented reality and a dot touch proprioceptive drift task with supernumerary limbs to assess body schema using the rubber hand illusion and found that distortions in body schema were apparent, evidenced through pointing errors in the dot touch task that were consistent with the remapped limb position.

The terms "subjective" and "performance task" in relation to data regarding bodily experience can be used to refer to several concepts. For the purpose of the current study, the term "subjective" is in reference to data collected from self-report questionnaire, whereas the term "performance task" is taken to refer to data collected from proprioceptive drift and ruler judgement tasks, such as those used by Davies et al. (2013), Kammers et al. (2009) and Newport et al. (2010). This is due to self-report tasks indexing personal, subjective, experience of resizing illusions, whereas proprioceptive drift and ruler judgement tasks index more impartial, performance based, data regarding the effects of resizing illusions on one's percept of their bodily experience.

Given previous research showing the additive effects of including several different sensory inputs for overall experience, and the recent evidence of the addition that auditory inputs can have on illusory experience, compared to unimodal stimulation alone, we hypothesise that adding a non-naturalistic auditory input to augmented reality resizing illusions that is consistent with the visual and tactile manipulations of stretching a finger, will (1) heighten conscious subjective illusory experience, measured via a subjective illusory experience questionnaire, for (1a) visuo-tactile and (1b) unimodal-visual manipulations. In addition, we hypothesise (2) that the addition of auditory input will heighten ability on performance tasks, measured using a dot touch proprioceptive drift task that indexes body schema for (2a) visuo-tactile and (2b) unimodal-visual manipulations. We also hypothesise that the addition of auditory input will heighten ability on performance tasks measured using a ruler judgement task that indexes body image for (3a) visuo-tactile and (3b) unimodal-visual manipulations. The inclusion of two different proprioceptive drift tasks, a dot touch task and a ruler judgement task, is to address the previous discordance of findings from Kammers et al. (2009) and Newport et al. (2010), relating to body image and body schema.

2. Method

2.1 Pre-registration

Pre-registration of this study can be found at the following OSF link: https://osf.io/6x4ce

2.2 Participant Sample

2.2.1 Power Analysis and Sample Size

A priori power analysis using subjective illusion data and performance task dot touch data from a pilot study showed a minimum sample size of 26 participants is required for hypothesis 1a regarding visuo-auditory / visuotactile-auditory manipulations ($d = 1.02$, power = 0.8, alpha = 0.05), and a sample of 22 participants is required for hypothesis 2 regarding the dot touch task ($f = 0.64$, power = 0.8, alpha = 0.05). Due to the inherent ambiguity of power analysis, and to account for the additional ruler judgment task, the upper sample size of 26 participants will be doubled to a sample size of 52 participants.

2.2.2 Participants

52 participants (84.6% Female. 11.5% Male, 3.8% Non-Binary; Mean age = 19.3 years, age range = 18 − 24 years) completed the experiment. Exclusion criteria were: prior knowledge or expectations about the research, a history of neurological or psychiatric disorders, operations or procedures that could damage peripheral nerve pathways in the hands, a history of chronic pain conditions, 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. From these 52 participants, 8 scored above 50 (indicating experience of the illusion) on the subjective experience questionnaire item regarding feeling stretching of the finger within the baseline condition where no stretching took place, therefore these 8 participants were removed from the analysis, resulting in 44 participants, 23 in the No-Audio group, and 21 in the Audio group.

2.3 Materials

The resizing illusions were delivered using an augmented-reality system (see Figure 1) that consisted of an area for the hand to be placed which contained a black felt base, LED lights mounted on either side and a 1920 x 1080 camera situated in the middle of the area, away from the participant's view. Above this area, there was a mirror placed below a 1920 x 1200 resolution screen, so that the footage from the camera was reflected by the mirror such that the participant could view live footage of their occluded hand. The manipulation of the live feed from the camera was implemented using MATLAB r2017a, wherein the participant's finger would stretch by 60 pixels (2.1 cm) during illusions lasting 2.4 seconds. This stretching would be accompanied during the visuotactile / visuotactile-auditory conditions by the experimenter gently pulling on the participant's right index finger to induce immersive multisensory illusions. In the audio group, the stretching manipulations in the visuotactile-auditory and the visual-auditory conditions was accompanied by a pure tone that increased in linearly frequency from 308Hz – 629Hz, where no stretching took place, were accompanied by a 440Hz tone. After each condition, the participants hands were occluded from view and the dot touch or ruler judgement tasks were presented (detailed in section 2.3), until the experimenter pressed a button to indicate the start of the next trial. A blue rectangle was superimposed on the screen so that participants knew where to reposition their hands to after each task. Subjective illusion experience data were collected via Qualtrics (Qualtrics, Provo, UT) on a Samsung Galaxy Tab A6 tablet. This was given to participants towards end of the experiment, wherein each manipulation was presented again, without the subsequent tasks, and participants were asked to recall the trial they had just experienced and previous trials that were similar, and then give a response on a visual analogue scale of 0 to 100, with 0 being strongly disagree, 50 being neutral, and 100 being strongly agree with statements made. The questionnaire consisted of six statements, two relating to illusory experience: "It felt like my finger was really stretching" / "It felt like the hand I saw was part of my body", two relating to disownership: "It felt like the hand I saw no longer belonged to me" / "It felt like the hand I saw was no longer part of my body", and two were control statements: "It felt as if my hand had disappeared" / "It felt as if I might have had more than one right hand". The questionnaire was delivered 3 times, once after baseline manipulations, once after visuotactile / visuotactile-auditory manipulations, and finally once after unimodal visual / visual-auditory manipulations.

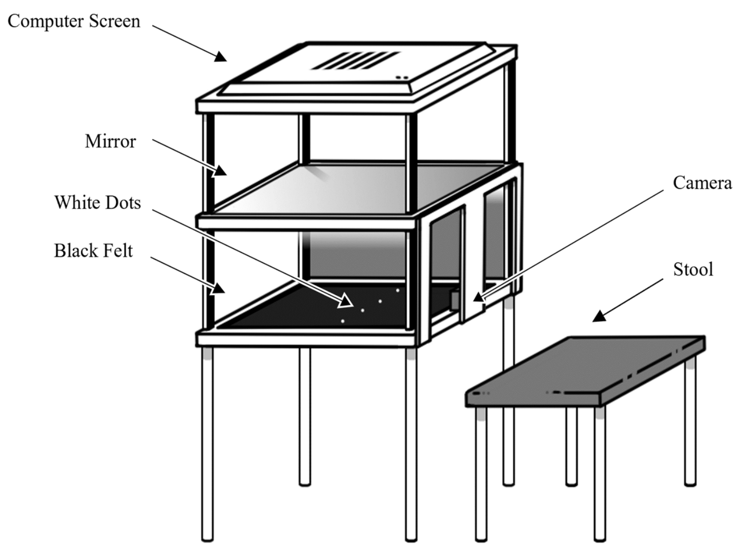

Figure 1: Schematic of Augmented Reality System.

2.4 Procedure

Participants were randomly assigned to either the auditory group or the non-auditory group. Participants were then seated at the augmented-reality system and were instructed to place both of their hands, with their index fingers outstretched, onto the felt. There were two white dots on the felt to guide where their hands should be placed, and arm rests were provided for comfort. Participants were instructed to view the image of their hands in the mirror (whilst their real hands were hidden from view) throughout the experiment. They viewed their hands whilst receiving baseline conditions where no manipulations were given (a 440Hz sound was played in the auditory condition), stretching conditions where they saw the index finger on their right-hand stretch (unimodal visual / visual-auditory conditions with accompanying 308Hz – 629Hz sound), and stretching conditions where as they saw their index finger on their right hand stretch as a researcher gently pulled on the end of their finger (visuotactile / visuotactile-auditory conditions with accompanying 308Hz – 629Hz sound).

After viewing the manipulation of their right hand, participants completed either a left-hand dot touch task, a right-hand dot touch task, or a ruler judgement task. The dot touch tasks consisted of a magenta dot appearing in front of either their right or left hand, and participants being asked to move their index finger in one smooth motion to touch the dot. When the participant had made this movement, the experimenter pressed a button to record an image of the hand position through the camera. The participant then returned their finger to the indicated pre-trial position. The ruler judgement task consisted of a 14 cm ruler, with 8 marks spaced 1.75cm apart, which appeared to the right of the participants right hand, which changed in position and scale to avoid trial order bias, and participants were asked where they believed the tip of their right index finger was on that ruler.

Participants completed 6 repetitions of 9 distinct conditions: 1, Baseline with left dot touch; 2, Unimodal visual / visual-auditory stretching with left dot touch; 3,Visuotactile / visuotactile-auditory stretching with left dot touch; 4, Baseline with right dot touch; 5, Unimodal visual / visual-auditory stretching with right dot touch; 6,Visuotactile / visuotactile-auditory stretching with right dot touch; 7, Baseline with ruler judgement task; 8, Unimodal visual / visual-auditory stretching with ruler judgement task; 9,Visuotactile / visuotactile-auditory stretching with ruler judgement task. (Video of a participant undergoing visuotactile stretching can be seen in supplementary material). Conditions were randomised via MATLAB r2017a, and the experimenter was unaware which condition would be presented on a given trial. The experimenter was informed of whether to gently pull the index finger or to apply no manipulation via the presentation of a small blue rectangle on the screen out of the participants view. 6 repetitions of the 9 conditions were presented, followed by a break for the participant to remove their hands from the box and rest, and then the baseline, visuotactile / visuotactile-auditory and the unimodal visual / visual-auditory conditions were presented once in a random order, without any dot touch or ruler judgement tasks, after which the participant completed the subjective illusory experience questionnaire.

2.5 Analysis

During each trial a still image was taken of the participants hands within the augmented reality system, to be used for analysis of the dot touch and ruler judgement data. Preprocessing was done algorithmically through a pipeline using image intensity data, which can be seen in the code available on OSF at the following link: https://osf.io/b9s48/. All data and code for analysis are available on the OSF page, which also contains resources to computationally reproduce this manuscript, all analyses, all figures, and statistical outputs from the raw data. For the dot touch data, the image was used to determine how far away the participant's finger was from the magenta dot, which was stored as an error rating for each trial and then averaged across the same trial types for each participant. This was completed for both left and right dot touch tasks. The ruler judgement data analysis consisted of using the still image with the superimposed ruler and the ruler rating given verbally by the participant during the experiment to check that the rating given was within the range of the ruler, if this was not true, as was the case with 4 participants, then their data for those trials were removed before statistical analysis. Then, the difference between the given ruler rating and the actual tip of the finger on the still image were used to generate error data, which was then used for statistical analysis.

For statistical analysis of the data, linear mixed effects models were used for all hypotheses as these are more robust to missing data and unequal groups.

3. Results

Hypothesis 1 predicted that adding a non-naturalistic auditory input to augmented reality resizing illusions that is consistent with the visual and tactile manipulations of stretching a finger, would heighten conscious subjective illusory experience. We measured this via a subjective illusory experience questionnaire, for (1a) visuo-tactile and (1b) unimodal-visual manipulations, with results shown in figure 2. A random intercepts linear mixed effects model with fixed effects of group and condition, and a random effect of participant, was used to assess if there was an effect of group (Audio vs Non-Audio) on subjective illusory experience score in the V/VA and VT/VTA conditions. Analysis showed a statistically significant interaction between condition and group $F(2, 84) = 3.62$, $p = 0.031$. Simple main effects analysis showed that both condition

(p = <0.001) and group (p = 0.040) had a significant effect on subjective illusory experience score. The random effects term did not make a significant contribution to the fit of the model (p = 0.293), and the marginal R^2 value was 74.26% with the conditional R^2 value being 76.74%. Post hoc pairwise t tests with Holm correction for multiple comparisons found that participants experienced a significantly stronger illusion in the VA condition (M=61, SD=29) compared to the V condition (M=41, SD=27) (p = 0.021) and found no difference in illusion strength when comparing the VT/VTA conditions (p = 0.818), indicating that the effect of non-naturalistic auditory input significantly effected subjective illusory experience in the traditional unimodal visual condition. Participants reported mean scores of above 50 in all conditions for the second item on the subjective questionnaire, indicating experience of ownership of the hand in all conditions, whilst reporting mean scores for disownership and control statements below 50, indicating no average disownership of the hand and no average violations of the control statements (results can be seen in supplementary materials S1 – S3).

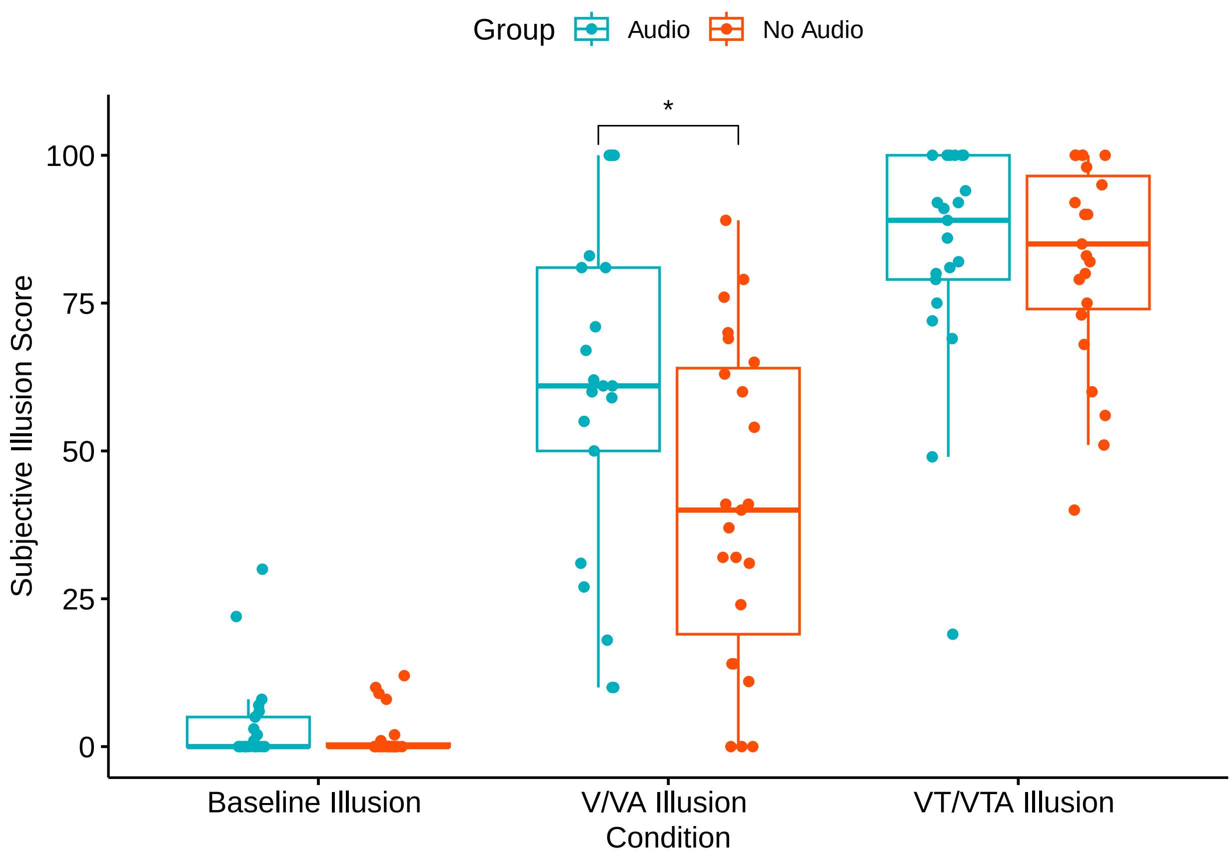

Figure 2: Subjective Illusory Experience Score for Baseline, V/VA and VT/VTA conditions. Group is indicated by colour, with red showing the no audio group and blue showing the audio group.

Positive control analyses were first run on the performance data to check that we were able to see an effect of the illusion with the dot touch and ruler judgement tasks. Positive control data plots can be seen in supplementary materials (S4-S6). A random intercepts linear mixed effects model with fixed effects being group and condition, and a random effect of participant, was used to assess if the V/VA and VT/VTA conditions showed a significant difference in performance on dot touch and ruler judgement data compared to the baseline condition. First regarding the right dot touch data, we found a significant effect of condition $F(2, 84) = 31.25$, p = <0.001, with the random effects term making a significant contribution to the fit of the model (p = <0.001), with the marginal R^2 value being 8.78% and the conditional R^2 value being 81.92%. Post hoc Tukey's Test for multiple pairwise comparisons found that participants placed their finger significantly lower than the dot in the V/VA condition (p = <0.001, 95% C.I. = [-1.25, -0.52], M = -0.88) and the VT/VTA condition (p = <0.001, 95% C.I. = [-1.45, -0.71], M = -1.08) compared to the baseline condition (95% C.I. = [-0.58, 0.16], M = -0.21), indicating an effect of the finger stretching manipulation being indexed by this performance measure. Secondly, regarding the left dot touch data, we found a significant effect of condition $F(2, 84) = 18.35$, p = <0.001, with the random effects term making a significant contribution to the fit of the model (p = <0.001), with the marginal R^2 value being 4.57% and the conditional R^2 value being 87.11%. Post hoc Tukey's Test for multiple pairwise comparisons found that participants placed their finger significantly lower than the dot in the V/VA condition (p = <0.001, 95% C.I. = [-1.66, -0.86], M = -1.26) and the VT/VTA condition ($p = 0.041$, 95% C.I. = [-1.29, -0.49], M = -0.89) compared to the baseline condition (95% C.I. = [-1.04, -0.24], M = -0.64). Finally, regarding the ruler judgement data, we found a significant effect of condition $F(2, 84) = 11.5$, p = <0.001, with the random effects term making a significant contribution to the fit of the model (p = <0.001), with the marginal R^2 value being 2.41% and the conditional R^2 value being 89.51%. Post hoc Tukey's Test for multiple pairwise comparisons found that participants judged their finger to be significantly longer in the V/VA condition ($p = 0.001$, 95% C.I. = [-1.32, -0.28], M = -0.8) and the VT/VTA condition ($p = 0.001$, 95% C.I. = [-1.42, -0.38], M = -0.9) compared to the baseline condition (95% C.I. = [-1.86, -0.82], M = -1.34), indicating the effectiveness of the experimental conditions to make the participants experience a longer finger.

We then addressed hypothesis 2, that the addition of auditory input would heighten ability on performance tasks, using a dot touch proprioceptive drift task as an index of body schema for (2a) visuo-tactile and (2b) unimodal-visual manipulations (see Figure 3). Again, a random intercepts linear mixed effects model with fixed effects being group and condition, and a random effect of participant, was used to assess if there was an effect of group (Audio Vs Non-Audio) on dot touch data in the V/VA and VT/VTA conditions. Analysis on right dot touch data showed no significant interaction between condition and group $F(1, 42) = 0.75$, $p = 0.391$ and simple main effects showed no effect of condition ($p = 0.154$) or group ($p = 0.971$). The random effects term did not make a significant contribution to the fit of the model ($p = 0.223$), and the marginal R^2 value was 2.51% with the conditional R^2 value being 20.7%. Analysis on left dot touch data showed no significant interaction between condition and group $F(1, 42) = 0.43$, $p = 0.516$ whilst simple main effects showed no effect of group ($p = 0.858$) but did show an effect of condition ($p = 0.002$), with participants placing their finger significantly lower in the V/VA condition (M =-0.63, SD =0.69) compared to the VT/VTA condition (M =-0.25, SD =0.62). The random effects term made a significant contribution to the fit of the model (p = 0.010), and the marginal R^2 value was 7.71% with the conditional R^2 value being 43.19%.

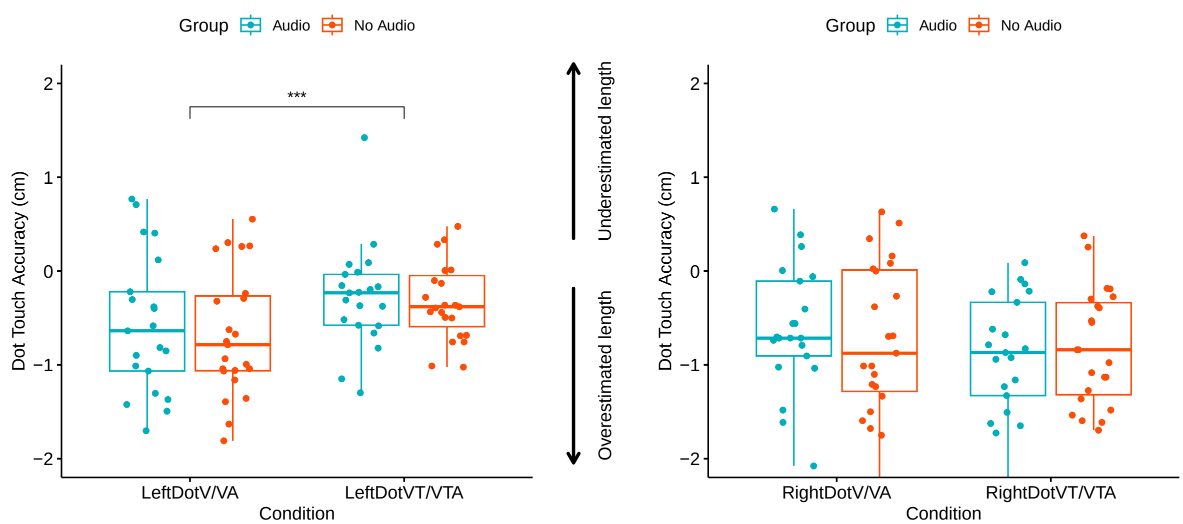

Figure 3: Dot Touch Data in relative centimetres for V/VA and VT/VTA conditions for both left and right hand data. Group is indicated by colour, with red showing the no audio group and blue showing the audio group. Arrows denote the direction of finger length estimation.

Finally, we assesed hypothesis 3, that the addition of auditory input would heighten ability on a performance task measured using a ruler judgement task that indexes body image for (3a) visuo-tactile and (3b) unimodal-visual manipulations (see Figure 4). Again, a random intercepts linear mixed effects model with fixed effects being group and condition, and a random effect of participant, was used to assess if there was an effect of group (Audio Vs Non-Audio) on ruler judgement data in the V/VA and VT/VTA conditions. Analysis showed no significant interaction between condition and group $F(1, 39.7) = 0.157$, $p = 0.694$ and simple main effects showed no effect of condition ($p = 0.440$) or group ($p = 0.580$). The random effects term did make a significant contribution to the fit of the model ($p = <0.001$), and the marginal R^2 value was 0.91% with the conditional R^2 value being 66.67%.

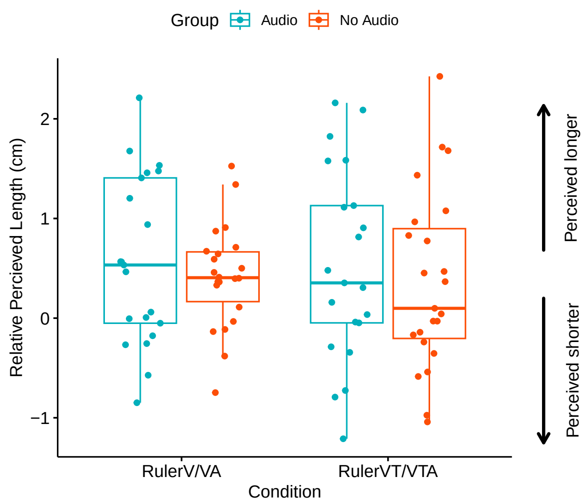

Figure 4: Ruler Judgement data in relative centimeters for V/VA and VT/VTA conditions. Group is indicated by colour, with red showing the no audio group and blue showing the audio group. Arrows denote direction of perceived finger length.

4. Discussion

This study sought to understand what impact the addition of non-naturalistic auditory input would have on traditional visuo-tactile and unimodal-visual hand-based resizing illusions. Findings showed that the addition of non-naturalistic auditory input that was consistent with the resizing illusion increased subjective experience of the illusion in the traditional unimodal-visual condition, with participants experiencing a significantly stronger illusion in the visual-auditory condition compared to the visual-only condition, supporting our first hypothesis. However, we found no facilitatory effects of auditory input for subjective experience of the visuo-tactile condition or for either of the performance tasks, opposing our remaining hypotheses, highlighting a potential discordance between conscious subjective experience of resizing illusions compared to more unconscious performance-based experiences.

The subjective findings showed that participants in the audio group rated the experience of their illusion to be greater in the visual condition compared to the non-audio group, showing the expected effect of multisensory integration heightening the experience of a stimulus. There was, however, no difference between the audio group and the non-audio group in the visuo-tactile condition, likely due to ceiling effects, wherein the addition of auditory input in addition to tactile input, did not increase subjective experience of the illusion. The combination of visual and tactile inputs in the VT condition resulted in a significantly higher mean subjective illusion score ($t(42) = -2.92$, $p = 0.006$) (M = 82, SD = 17.3) than in the visual-auditory conditions (M = 61.3, SD = 29), highlighting that the combination of two different senses produces differing levels of subjective experience of the illusion, with visuo-tactile surpassing that of visual-auditory manipulations. It is likely that the increased subjective experience in the visuotactile condition comes from the idea that tactile and proprioceptive inputs are thought to be unique to the bodily experience, whereas senses such as vision and audition are thought to be experienced not only in relation to our body but also relating to objects in the external world (Botvinick and Cohen, 1998; Tsakiris, 2010), therefore it is plausible that including a sense that is integral to our bodily experience such as tactile input, would have a greater effect on body illusions compared to less embodied senses such as auditory input.

Regarding performance findings, positive control analyses showed that there was a significant difference between baseline and experimental conditions for left and right dot touch tasks, with participants accurately placing their finger on the dot in the baseline condition for the right dot task, and then touching around a centimetre too close to their bodies in both experimental conditions due to the perceived elongation of the finger in the experimental conditions. For the left dot touch data, participants were less accurate in their finger placement in the baseline condition, but still placed their finger significantly closer to their bodies on both experimental conditions, indicating a perceived elongation of their finger in both right and left dot touch tasks. Additionally, in the ruler judgement task, participants reported the tip of their finger to be significantly further away in both experimental conditions compared to the baseline condition, indicating an experience of their finger being longer in experimental conditions compared to the baseline non-illusion condition. These findings indicate success of the positive control analyses, showing that these performance tasks can highlight the differences between baseline and experimental conditions.

Referring to the confirmatory analyses regarding the dot touch data, findings showed no significant effect of group or condition for the right dot touch task, and there was no effect of group for the left dot touch task, however there was an effect of condition, with participants placing their finger significantly closer to their bodies in the conditions without touch (V/VA) compared to the conditions with tactile input (VT/VTA). This finding of a significant effect of condition for the left dot touch data could be described through a transference effect of stretching from the manipulated hand (right) to the non-manipulated hand (left). Petkova et al. (2011) found whilst using a full body illusion and fMRI, evidence for a spread of ownership across connected body parts. Therefore, the resizing of the right hand could likely spread to the left unmanipulated hand, meaning participants felt as though this hand had also been resized, which is supported by the positive control analyses for the left dot touch task finding a significant effect of the illusion in the experimental conditions without manipulation to this hand. It is possible that the tactile inputs in the VT/VTA illusion could provide a grounding effect, wherein the participant's hand is grounded to the spatial location within the augmented reality system, which does not occur for visual only or visual audio manipulations. This spatial grounding in conjunction with the transference effects mentioned previously, could explain why we see a significant difference between experimental conditions in the left dot touch task. This is however speculative, and further research would be needed to assess the replicability of this effect. Finally, ruler judgement data also showed no significant effect of condition or group, indicating that the addition of non-naturalistic auditory input showed no facilitatory effects for either performance task.

The rationale for including two performance tasks in the present study came from previous discordance in the literature with Kammers et al. (2009) finding an impact on body image, but not body schema, in the rubber hand illusion, whereas Newport et al. (2010) found distortions in body schema using the rubber hand illusion and supernumerary limbs. The use of differing measures of body representations in previous literature often results in different findings, and this discordance between body image and body schema is one example of when this occurs regarding body illusions. Here, we see evidence for an impact of resizing illusions on body schema and body image as evidenced through the positive control analyses, showing that resizing illusions affect one's percept of the body (body image) in addition to the control of the body in an external environment (body schema). The rubber hand illusion differs from the resizing illusion used here, in that the present manipulation does not attempt to relocate the hand, but rather attempts to change the representation of the finger to be longer. Therefore, it could be that when changing an existing part of one's body, both body image and body schema are affected, whilst when attempting to create a new sensation of one's body in a different location, impact on body schema is dependent on the experimental manipulations being used.

The increasing pitch tone that was used as the non-naturalistic auditory input in the current study was chosen as it closely reflected that used by Tajadura-Jiménez et al. (2017), who previously found increases in estimations of finger length when accompanied by an increasing pitch tone compared to a decreasing or constant tone. However, in the current experiment, we cannot claim that the effect found of an increase in subjective experience of the resizing illusion when this non-naturalistic auditory input is added, is unique to a rising pitch tone. It is possible that other auditory inputs, such as naturalistic inputs, perhaps of the bones in the finger creaking as it is stretched, akin to the auditory inputs heard during chiropractic treatments, or an unrelated auditory input, such as a constant tone during the resizing conditions, could elicit similar effects of increases in subjective experience. It is also possible that the increasing pitch tone that was used in the current study could be manipulated to be presented in steps rather than a constant tone, to assess if the same effects of increasing illusory experience are seen in different presentations of a rising pitch tone, or of the addition of any tone would increase subjective illusory experience through directing attention towards the illusory manipulation. The findings from the current study enhance our understanding of the role that auditory input can play in resizing illusions, however further research into the efficacy of alternate auditory inputs is needed to consolidate current findings.

Resizing illusions have been found to reduce pain in chronic pain conditions affecting the hands (Preston and Newport, 2011), back (Diers et al., 2013) and knees (Stanton et al., 2018). Findings from the present study enhance our understanding of the conditions under which these manipulations affect personal experience of the illusions. Previously it has been found that around 30% of participants experience an effective unimodal visual condition for resizing illusions (Hansford et al., 2023). Here, we show that experience of the illusion in the traditional unimodal visual presentation can be increased through the addition of non-naturalistic auditory input. Therefore, it is possible that when using resizing illusions for the treatment of chronic pain, it could be beneficial to include non-naturalistic auditory input to give patients an increased experience of the illusion, and consequently, potential increased attenuation of pain. The traditional unimodal visual condition has been mentioned as the most accessible version of resizing illusions [hansford2023a] as it has the potential to be delivered via a mobile phone application without the need for a researcher to add the tactile inputs to the illusion. The addition of auditory inputs also requires no researcher presence, and therefore arises as a way of incorporating the principles of multisensory integration into traditional unimodal visual applications of the illusion, which could have implications for increased analgesic effect of these illusions in a chronic pain sample. Future research is however needed to assess if the addition of auditory input has a similar enhancing effect of the illusion in chronic pain patients as has been seen here in a healthy sample.

5. Conclusions

We found that the addition of non-naturalistic auditory input can enhance subjective experience of resizing illusions, however we found no facilitatory effects of the auditory input for performance measures of illusion strength. We address previous discordance in the literature surrounding the impact of hand-based illusions on body image and body schema, showing that in a resizing hand-based illusion, the manipulation affects both concepts of the bodily self. Additionally, this study highlights the potential for non-naturalistic auditory input to be included in resizing illusions used for the treatment of chronic pain, whilst inviting further research to assess the impact of non-naturalistic auditory input in chronic pain patient samples, in addition to researching the uniqueness of a rising pitch tone as the presentation of the non-naturalistic auditory input, to assess if this alone causes an increase in subjective illusory experience. Finally, we highlight the difference between conscious subjective experience of resizing illusions and unconscious performance-based measures, enhancing our understanding of the mechanisms behind the experience of these bodily manipulations.

Acknowledgements

The authors would like to acknowledge B.P.A. Quinn, for creation of the schematic in Figure 1, and the Pain Relief Foundation studentship and BBSRC grant BB/V007580/1, for funding this work.

References

Banakou D, Groten R, Slater M. 2013. Illusory ownership of a virtual child body causes overestimation of object sizes and implicit attitude changes. *Proceedings of the National Academy of Sciences* **110**:12846–12851. doi:10.1073/pnas.1306779110

Botvinick M, Cohen J. 1998. Rubber hands "feel" touch that eyes see. *Nature* **391**:756–756. doi:10.1038/35784

Davies AMA, White RC, Davies M. 2013. Spatial limits on the nonvisual self-touch illusion and the visual rubber hand illusion: Subjective experience of the illusion and proprioceptive drift. *Consciousness and Cognition* **22**:613–636.

Diers M, Zieglgänsberger W, Trojan J, Drevensek AM, Erhardt-Raum G, Flor H. 2013. Site-specific visual feedback reduces pain perception. *Pain* **154**:890–896. doi:10.1016/j.pain.2013.02.022

Frassinetti F, Bolognini N, Làdavas E. 2002. Enhancement of visual perception by crossmodal visuo-auditory interaction. *Experimental brain research* **147**:332–343.

Hansford KJ, Baker DH, McKenzie KJ, Preston CE. 2023. Distinct neural signatures of multimodal resizing illusions. *Neuropsychologia* **108622**.

Hubbard TL, editor. 2018. Spatial biases in perception and cognition. Cambridge University Press.

Kammers MP, Vignemont F, Verhagen L, Dijkerman HC. 2009. The rubber hand illusion in action. *Neuropsychologia* **47**:204–211.

Kilteni K, Maselli A, Kording KP, Slater M. 2015. Over my fake body: Body ownership illusions for studying the multisensory basis of own-body perception. *Frontiers in human neuroscience* **9**:141.

Kilteni K, Normand JM, Sanchez-Vives MV, Slater M. 2012. Extending body space in immersive virtual reality: A very long arm illusion. *PloS one* **7**:40867. doi:10.1371/journal.pone.0040867

Lovelace CT, Stein BE, Wallace MT. 2003. An irrelevant light enhances auditory detection in humans: A psychophysical analysis of multisensory integration in stimulus detection. *Cognitive brain research* **17**:447–453.

Newport R, Pearce R, Preston C. 2010. Fake hands in action: Embodiment and control of supernumerary limbs. *Experimental brain research* **204**:385–395.

O'Mera B. 2014. Auditory information in the form of a scratching sound enhances the effects of the rubber hand illusion.

Paillard J. 1999. Body schema and body image-a double dissociation. *Motor control, today and tomorrow* 197–214.

Petkova VI, Björnsdotter M, Gentile G, Jonsson T, Li TQ, Ehrsson HH. 2011. From part-to whole-body ownership in the multisensory brain. *Current Biology* **21**:1118–1122.

Preston C, Gilpin HR, Newport R. 2020. An exploratory investigation into the longevity of pain reduction following multisensory illusions designed to alter body perception. *Musculoskeletal Science and Practice* **45**:102080. doi:10.1016/j.msksp.2019.102080

Preston C, Newport R. 2011. Analgesic effects of multisensory illusions in osteoarthritis. *Rheumatology* **50**:2314–2315. doi:10.1093/rheumatology/ker104

Radziun D, Ehrsson HH. 2018. Auditory cues influence the rubber-hand illusion. *Journal of Experimental Psychology: Human Perception and Performance* **44**:1012.

Senna I, Maravita A, Bolognini N, Parise CV. 2014. The marble-hand illusion. *PloS one* **9**:91688.

Stanton TR, Gilpin HR, Edwards L, Moseley GL, Newport R. 2018. Illusory resizing of the painful knee is analgesic in symptomatic knee osteoarthritis. *PeerJ* **6**:5206. doi:10.7717/peerj.5206

Tajadura-Jiménez A, Basia M, Deroy O, Fairhurst M, Marquardt N, Bianchi-Berthouze N. 2015. As light as your footsteps: Altering walking sounds to change perceived body weight, emotional state and gaitProceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems. pp. 2943–2952.

Tajadura-Jiménez A, Vakali M, Fairhurst MT, Mandrigin A, Bianchi-Berthouze N, Deroy O. 2017. Contingent sounds change the mental representation of one's finger length. *Scientific reports* **7**:1–11.

Tajadura-Jiménez A, Väljamäe A, Toshima I, Kimura T, Tsakiris M, Kitagawa N. 2012. Action sounds recalibrate perceived tactile distance. *Current Biology* **22**:516–517.

Tsakiris M. 2010. My body in the brain: A neurocognitive model of body-ownership. *Neuropsychologia* **48**:703–712.

Zampini M, Spence C. 2004. The role of auditory cues in modulating the perceived crispness and staleness of potato chips. *Journal of sensory studies* **19**:347–363.

Supplementary Materials

S1. Video of finger stretching

A video of a participant undergoing a visual-tactile illusion can be seen at the following OSF link: https://osf.io/ek8cd

S2. Ownership Data

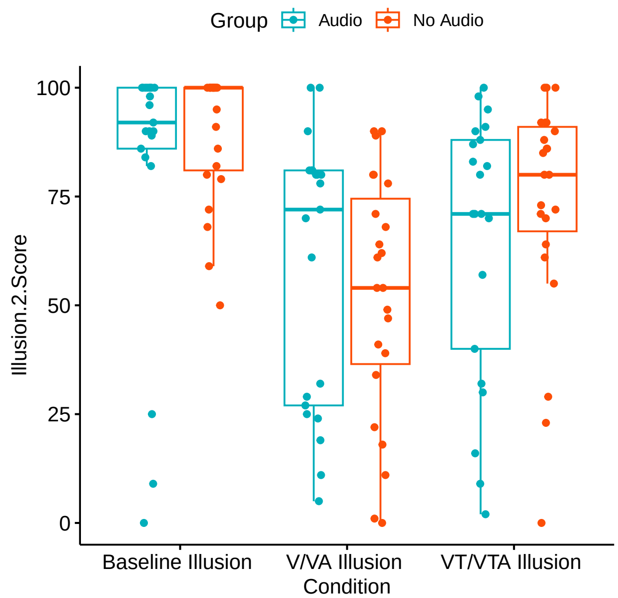

Figure 5: Ownership data for participants across all conditions. Each mean rating is above 50 indicating experience of ownership of the hand during the illusion (Baseline Audio: M = 82.4, SD = 30.6, Baseline Non-audio: M = 89.7, SD = 15.1, V/VA Audio: M = 58.4, SD = 31.3, V/VA Non-Audio: M = 52.3, SD = 27.9, VT/VTA Audio: M = 64.9, SD = 30.8, VT/VTA Non-Audio: M = 73.4, SD = 25.8).

S3. Disownership Data

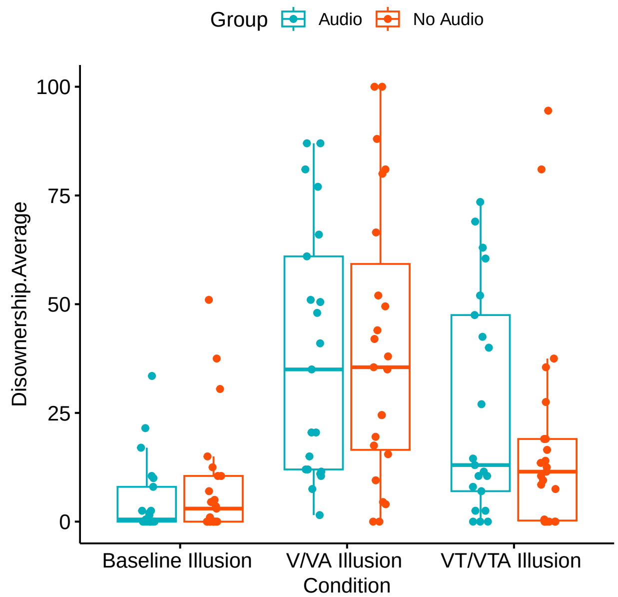

Figure 6: Disownership average data for participants across all conditions. Each mean rating is below 50 indicating experience of no experiences of disownership of the hand during the illusion (Baseline Audio: M = 5.21, SD = 8.93, Baseline Non-audio: M = 8.33, SD = 13.6, V/VA Audio: M = 38.4, 29.0, V/VA Non-Audio: M = 40.5, 32.0, VT/VTA Audio: M = 26.4, SD = 25.6, VT/VTA Non-Audio: M = 18.2, 24.6).

S4. Control Data

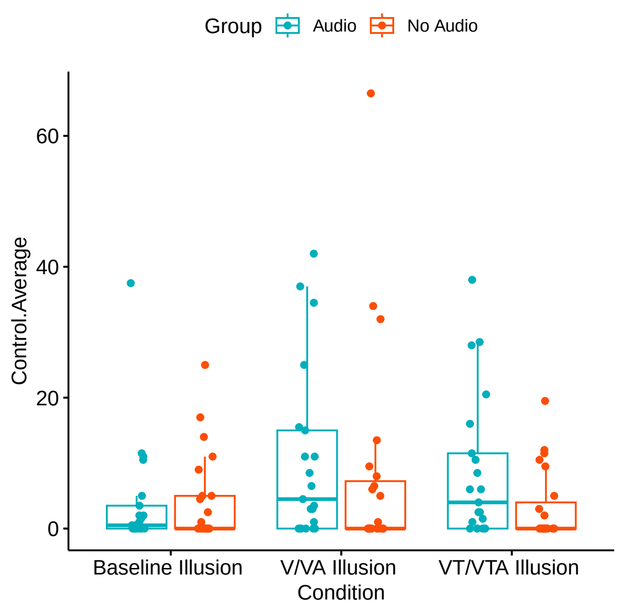

Figure 7: Control average data for participants across all conditions. Each mean rating is below 50 indicating no violation of control statements during the illusion (Baseline Audio: M= 4.12, SD = 8.55, Baseline Non-audio: M = 4.09, SD = 6.76, V/VA Audio: M = 10.5, SD = 13.2, V/VA Non-Audio: M = 7.91, SD = 16.0, VT/VTA Audio: M = 8.81, SD = 11.2, VT/VTA Non-Audio: M = 3.17, SD = 5.49).

S5. Positive Control Right Dot Touch

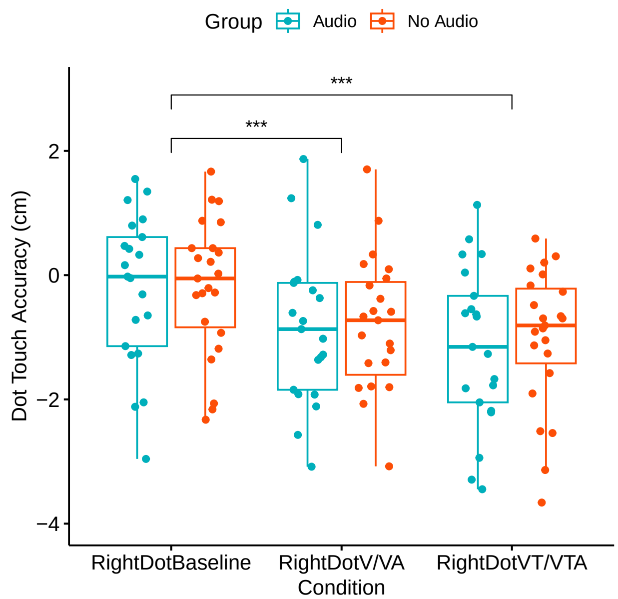

Figure 8: Dot Touch Data in centimetres for Baseline, V/VA, and VT/VTA conditions for right hand data. Group is indicated by colour, with red showing the no audio group and blue showing the audio group.

S6. Positive Control left Dot Touch

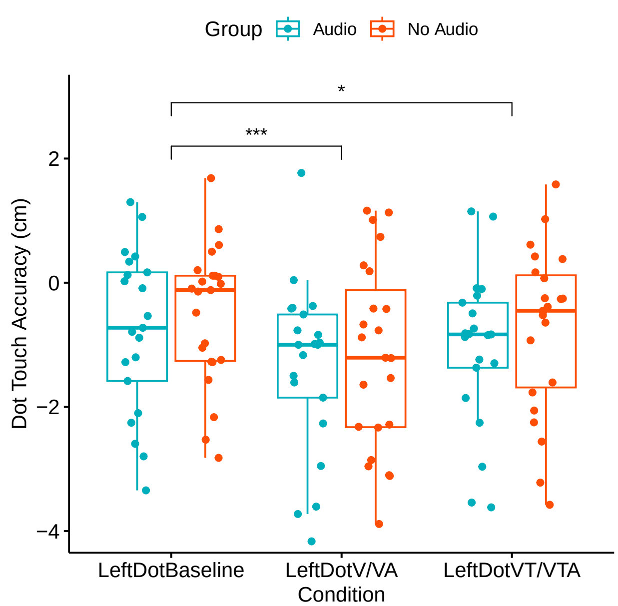

Figure 9: Dot Touch Data in centimetres for Baseline, V/VA, and VT/VTA conditions for left hand data. Group is indicated by colour, with red showing the no audio group and blue showing the audio group.

S7. Positive Control Ruler Judgement

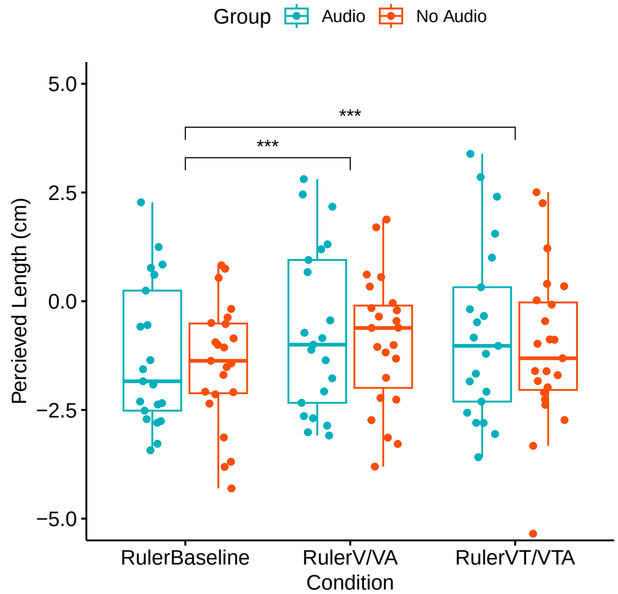

Figure 10: DRuler Judgement data in centimetres for baseline, V/VA, and VT/VTA conditions. Group is indicated by colour, with red showing the no audio group and blue showing the audio group.