

Mirror-Brush Illusion: Creating Phantom Tactile Percepts on Intact Limbs

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Abstract—Haptic illusions provide unique insights into how we model our bodies separate from our environment. Popular illusions like the rubber-hand illusion and mirror-box illusion have demonstrated that we can adapt the internal representations of our limbs in response to visuo-haptic conflicts. In this manuscript, we extend this knowledge by investigating to what extent, if any, we also augment our external representations of the environment and its action on our bodies in response to visuo-haptic conflicts. Utilizing a mirror and a robotic brushstroking platform, we create a novel illusory paradigm that presents a visuo-haptic conflict using congruent and incongruent tactile stimuli applied to participants' fingers. Overall, we observed that participants perceived an illusory tactile sensation on their visually occluded finger when seeing a visual stimulus that was inconsistent with the actual tactile stimulus provided. We also found residual effects of the illusion after the conflict was removed. These findings highlight how our need to maintain a coherent internal representation of our body extends to our model of our environment.

Index Terms—Haptic illusion, rubber-hand, mirror-box.

I. INTRODUCTION

FOR most of our daily lives, our internal body representation is formed through a dynamic integration of auditory, visual, and haptic information [1], [2], [3]. This process plays a key role in creating a sense of ownership of our body, agency over its actions, and a sense of awareness of the self, separate from our environment, referred to as embodiment [4]. With advances in technology, particularly in robotics and virtual reality, there is a growing interest in the ability to extend our internal representations outside the human body, onto physical systems like prostheses and telepresence robots, and digital systems like virtual reality avatars and holograms [5], [6], [7].

It has been shown that the sense of embodiment is not limited to the boundaries of the physical body. Humans can extend

the borders of their physical body to temporarily incorporate external objects into their body schema [3], [4]. The rubber hand illusion, for example, is a popular haptic illusion wherein participants incorporate an artificial rubber hand into their body schema. The illusory effects are elicited by synchronously stroking, at the same location, the participant's real hand and the artificial hand with a brush [8]. Participants do not receive direct visual feedback of their real hand, instead, the artificial hand is visible and placed in a manner that is anatomically congruent, with respect to the position of the obstructed hand.

Another popular illusion that demonstrates the ability to adapt the body schema is the mirror-box illusion [9]. In this illusion, a mirror is placed between the participant's limbs in a manner that visually obstructs direct view of one of the limbs. Participants are asked to focus on a reflection of their unobstructed limb in the mirror while they synchronously move both limbs. As a result, participants begin to embody the unobstructed limb's reflection in the mirror as their real limb, which remains visually obstructed behind the mirror. If the two limbs are positioned across the mirror asymmetrically, the participant's estimate for the position of their obstructed limb approaches the position of the unobstructed limb's reflection in the mirror (i.e., equidistant across the mirror), a phenomenon known as proprioceptive drift [10].

Both the rubber hand illusion, and the mirror-box illusion rely on the participant resolving a visuo-haptic conflict by trusting information from their visual sense over their cutaneous and proprioceptive senses [9], [11], [12], [13], [14], [15]. This trust in visual information can be so powerful that the mirror illusion has even been used as a tool to treat phantom limb pain in individuals with limb loss [16], [17], [18]. A common theme across these illusions and their variations is our willingness to change the internal representation of our own bodies in response to a visuo-haptic conflict. Visuo-haptic conflicts, however, have also been used to influence human tactile perception. The manner in which visual and haptic information is integrated can have significant impact on our estimates of properties like object shape and size [19], [20].

In this manuscript, we question whether the need to maintain a coherent internal representation extends beyond the perception of one's self to that of the environment and the stimuli it presents. We ask to what extent, if any, do individuals adapt their perception of stimuli originating from the environment in response to visuo-haptic conflict. To answer this important question, we developed a custom robotic platform (see Fig. 1) that allows us to provide congruent and incongruent

Manuscript received 16 December 2022; revised 12 April 2023; accepted 11 May 2023. Date of publication 26 May 2023; date of current version 19 December 2023. This work was supported by the National Science Foundation under Grant 1910939. This paper was recommended for publication by Associate Editor M. Di Luca.

This work involved human subjects or animals in its research. Approval of all ethical and experimental procedures and protocols was granted by Johns Hopkins School of Medicine Institutional Review Board under Application No. IRB00263386.

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Digital Object Identifier 10.1109/TOH.2023.3279012

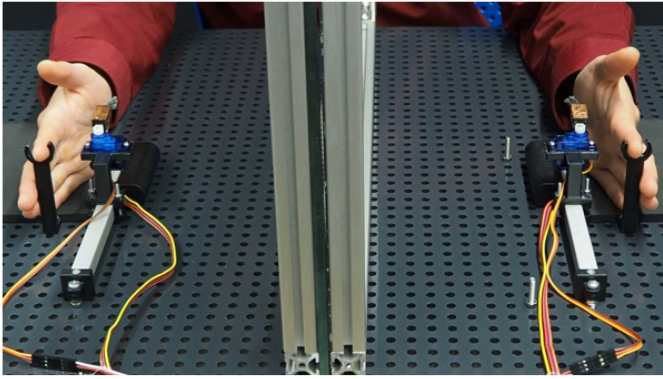


Fig. 1. Experimenter view of the experimental setup which includes identical brushstroke devices consisting of linear actuators and rotary servos, placed symmetrically across a mirror. The participants' hands are placed on vibration damping pads and their index fingers are placed on 3-D printed supports.

cutaneous stimuli to both hands of a participant. We placed participants' hands symmetrically across a mirror, limiting them to see only their right hand and its reflection in the mirror. The visuo-haptic conflict was created by stroking the index finger of participants' visually unobstructed hand with a brush while simultaneously tapping, for the same time duration, the base of the index finger of their visually obstructed hand with an identical brush. We investigated how participants resolved the conflict in comparison to a condition where the mirror was covered, removing the visuo-haptic conflict. We also tested for residual effects of the illusion, wherein participants were first primed with the illusory visuo-haptic conflict (mirror uncovered) before removing the conflict (mirror covered).

We hypothesized that the mirror would induce participants to embody the unobstructed hand's reflection and thereby perceive a cutaneous brushstroke along the length of their real obstructed finger, despite the actual stimulus being a cutaneous tap at the base of the finger. More specifically, use of the mirror would result in participants adapting their perception of the environmental cutaneous stimulus to maintain a representation of the obstructed hand that is consonant with the visual feedback of the unobstructed hand's reflection in the mirror. As a secondary hypothesis, we expected to find that priming participants with the illusory percept would result in a residual percept wherein participants would continue to feel a stroke-like illusory percept on their visually obstructed finger after the visual conflict was removed.

In what follows, we provide an overview of our experimental setup and a discussion of our results in the broader context of other visuo-haptic illusions. For the purposes of this manuscript a tap is defined as a haptic stimulus where only a static contact is made between the brush and the finger (for 1200 ms), while a stroke is defined as a haptic stimulus where a dynamic contact is established between the brush and the surface of the finger.

II. METHODS

A. Participants

We recruited $N = 14$ individuals (8 female, 6 male, age = 25 ± 5 years) for this study. All participants provided

written informed consent according to a protocol approved by the Johns Hopkins School of Medicine Institutional Review Board (Study# IRB00263386). Each experimental session lasted approximately 30 minutes.

B. Experimental Setup

The experimental apparatus consisted of a custom robotic device designed to deliver brushstrokes to the participant's index fingers (two identical apparatus were used, one for each index finger). This was achieved using an SG90 hobby rotary servo which was mounted on the carriage of an Actuonix T16-P linear track actuator (stroke length of 100 mm with 22:1 gear ratio). A brush was attached to the rotary servo. The servo motor controlled the angle at which the brush was placed, relative to the participant's finger, allowing the experimenter to control when the brush made or broke contact with the finger. The linear actuator was controlled using a compatible Actuonic LAC controller and was used to move the brush along the finger, thereby providing a stroking sensation to the participant's index fingers.

A Quanser QPIDE PCI data acquisition card was used for data acquisition and control via a MATLAB/Simulink and Quarc real-time software interface. The setup was run at a sample rate of 1 KHz on a Dell Precision 5810 desktop. The cutaneous stimulus could be varied by modulating where the brush made contact with the finger, how far it travelled along the finger, and the direction of travel.

Two brushstroke devices were placed symmetrically across a mirror on top of a platform where participants rested their hands and forearms. The reflective side of the mirror faced the participant's right hand. The participant was seated towards the right and their view of their left hand was obstructed by the mirror. A black curtain was placed on both sides of the setup to limit any discernible visual cues in participants' peripheral vision. Two 3D printed supports were used to properly position participants' fingers with respect to the brushstroke devices and limit movement during the experimental trials.

The two primary brushstroke devices were programmed to provide three distinct stimuli on the finger- Nothing, Tap and Stroke. For all trials throughout the experiment, the unobstructed (right) finger received only the Stroke stimulus, while the obstructed (left) finger received each of the three stimuli, based on the experimental procedure. Thus, trials are defined by the stimulus provided to the obstructed (left) finger: *Nothing trial*, *Tap trial*, and *Stroke trial*. Brushstrokes on both fingers were always unidirectional, from the base of the finger to the tip.

The mechanical action for the three stimuli is explained in detail below:

- 1) *Nothing* – neither the rotary servo nor the linear actuator moved, producing no stimulus on the finger.
- 2) *Tap* – only the rotary servo turned such that the attached brush made contact with the finger for 1200 ms, and then broke contact by returning to its original state. The linear actuator was inactive for this stimulus and stayed at the home position.
- 3) *Stroke* – 1) the rotary servo turned such that the brush made contact with the finger; 2) the linear actuator moved the

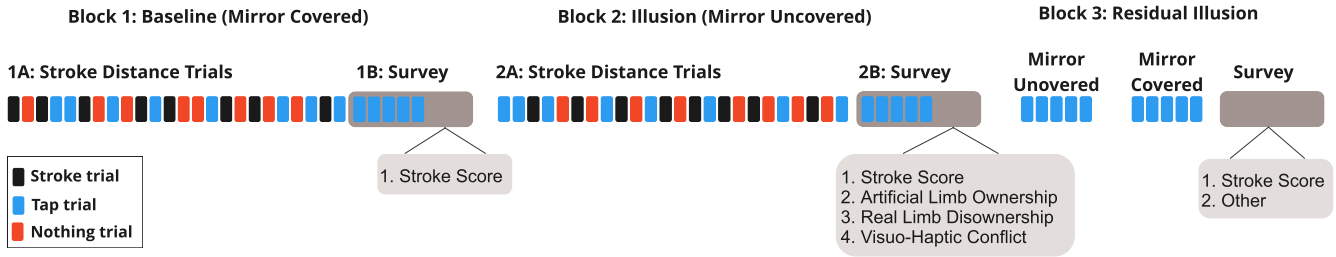


Fig. 2. Experiment timeline showcasing the different experiment blocks with the experiment conditions and surveys performed within the blocks.

brush along the palmar surface of the finger for 1200 ms while still maintaining contact; 3) the rotary servo returned to its original state, breaking contact with the finger; 4) the linear actuator moved the brush back to the home position.

An additional brushstroke device was fixed underneath the platform (out of view) directly under the brushstroke device for the obstructed (left) hand. This device was used to mask any auditory and mechanical vibration cues that were generated when the two primary devices presented incongruent stimuli.

C. Procedure

The experimenter covered the mirror with an opaque screen before the participant was seated. The participant was then requested to place their hands symmetrically across the mirror (using the 3D printed supports). Participants placed their hands resting on their sides in an open palm pose, with their thumbs pointing up and palms facing the mirror. The hands were placed on vibration damping pads of different heights to ensure that the fingers were aligned to the stroking axis of the brushstroke device.

A calibration session was performed (with the mirror covered), where the right unobstructed finger received sequential brushstrokes while the left obstructed finger received three trials for each of the three different stimulus types in a randomized order. The participant was asked to identify the *stroke distance*: on a “0–10” scale, the farthest point on their obstructed (left) index finger where they felt anything, with “1” referring to the base of their finger, “10” referring to the tip of their finger, and “0” referring to feeling nothing. The calibration period allowed participants to get comfortable with the response variable, and allowed the experimenter to position their fingers appropriately.

The calibration session was followed by three experimental blocks and each block included a set of experimental trials and survey (see Fig. 2):

Block 1 A (Baseline – Stroke Distance): With the *mirror covered* (Fig. 3(a)), the participant was presented with 24 trials, eight for each of the three trial types, in a randomized order. The participant reported the *stroke distance* after each trial for their obstructed (left) index finger. This block was used to obtain a baseline for the participant’s perception of the stimuli presented to their obstructed (left) index finger.

Block 1B (Baseline – Survey): With the *mirror covered* (Fig. 3(a)), the participant was presented with five consecutive

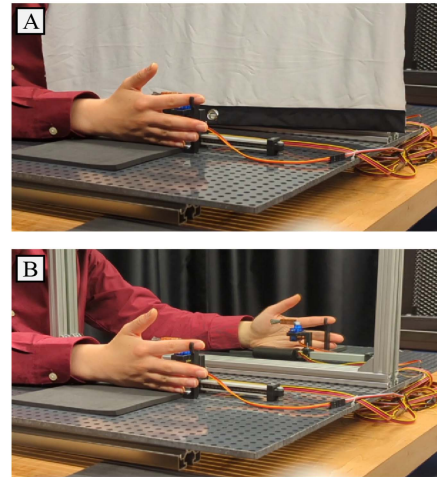


Fig. 3. Perspective view of experimental setup showing: (a) Participant’s unobstructed hand with the mirror covered, (b) Participant’s unobstructed hand and its reflection with the mirror uncovered.

TABLE I
BLOCK 1B (BASELINE) SURVEY

| | | |
|----|--------------|---|
| Q1 | Stroke Score | I seemed to feel a stroke on my left index finger |
| Q2 | | I seemed to feel only a tap on my left index finger |

Tap trials. The participant was then instructed to respond to the survey questions listed in Table I on a scale of -3 (Strongly Disagree) to +3 (Strongly agree).

Block 2 A (Illusion – Stroke Distance): With the *mirror uncovered* (Fig. 3(b)), the participant was presented with 24 trials, eight for each of the three trial types, in a randomized order (different from Block 1 A). The participant reported the *stroke distance* after each trial for their obstructed (left) index finger. This block was used to evaluate the effects of the illusory visuo-haptic conflict on the participant’s perception of the stimuli on their left index finger.

Block 2b (Illusion – Survey): With the *mirror uncovered* (Fig. 3(b)), the participant was presented with five consecutive *Tap trials*. The participant was asked to respond to the survey questions listed in Table II (next page) on a scale of -3 (Strongly Disagree) to +3 (Strongly agree).

Block 3 (Residual Illusion-Survey): With the *mirror uncovered* (Fig. 3(b)), the participant was presented with five *Tap trials*. Then, with the *mirror covered* (Fig. 3(a)), the participant

TABLE II
BLOCK 2B (ILLUSION) SURVEY

| | | |
|----|--|---|
| Q1 | Stroke Score | I seemed to feel a stroke on my left index finger |
| Q2 | | I seemed to feel only a tap on my left index finger |
| Q3 | Ownership of artificial reflected limb | It seemed as if I was looking at my left hand |
| Q4 | | It seemed as if the reflected hand was a part of my body |
| Q5 | | It seemed as if the reflected hand was my left hand |
| Q6 | Disownership of real limb | It seemed as if I had more than one left index finger |
| Q7 | | It seemed as if my natural left index finger was turning numb |
| Q8 | | It seemed as if I no longer had a natural left hand, as if my natural left hand had disappeared |
| Q9 | Visuo-haptic conflict | It seemed as if there was a conflict between the visual feedback and the touch feedback |

TABLE III
BLOCK 3 (RESIDUAL ILLUSION) SURVEY

| | | |
|----|-----------------|---|
| Q1 | Stroke Score | I seemed to feel a stroke on my left index finger |
| Q2 | | I seemed to feel only a tap on my left index finger |
| Q3 | Other questions | It seemed as if I wanted to feel a stroke |
| Q4 | | It seemed as if my finger was being stroked, but only at one location |
| Q5 | | My perception changed between trials |

was presented with another five *Tap trials*. In this way, the participant was first primed with the illusion before the visuo-haptic conflict was removed. Participants were asked to respond to the survey questions listed in Table III (next page) on a scale of -3 (Strongly Disagree) to $+3$ (Strongly agree). This block was used to test for residual illusory effects.

In the trials where the mirror was covered, participants were instructed to focus on the opaque screen covering the mirror. In trials where the mirror was uncovered, participants were instructed to focus on the reflection of their unobstructed hand in the mirror. In addition, the experimenter monitored participants for non-compliance. To maintain consistency in survey responses, participants were informed that the term “tap” refers to any cutaneous stimulus they perceive that is static, whereas the term “stroke” refers to any cutaneous stimulus they perceive that has a component of motion to it.

D. Metrics

Data from Block 1 A and Block 2 A was used for analysis of the strength of the illusion. The primary metric of interest was the Stroke Distance: the farthest point at which the participant felt a sensation on their obstructed (left) finger, averaged across the 8 trials for each of the three stimuli. A Stroke Distance greater than 1 suggests that the participant felt a stroke on their obstructed index finger. Stroke Distance was separately calculated for all three trial types for the Baseline (1 A) and Illusion (2 A) blocks.

The self-reported strength of the illusion, Stroke Score, was obtained by subtracting the participants response to survey question 2 (feeling of a tap on the left finger) from the response to question 1 (feeling of a stroke on the left finger), with a maximum score of 6 and a minimum score of -6 . A net positive score indicates that the participant perceived the stimulus as being more like a stroke than a tap, and a net negative score suggests that the stimulus was perceived more as a tap. The Stroke Scores were computed from survey responses for Block 1B (Baseline), Block 2B (Mirror) and Block 3 (Residual Illusion), separately.

Ownership scores (of the unobstructed finger’s reflection) were calculated by taking the average response from survey questions Q3, Q4, and Q5, for Block 2B (Illusion). Disownership scores (of the real obstructed hand) were calculated by taking the average response from survey questions Q6, Q7, and Q8, for Block 2B (Illusion).

E. Statistical Analysis

The data was first cleaned to account for any missing or repeated trials. Missing data was treated on a case by case basis. Checks for outliers, normality, and sphericity were performed as needed. Bonferroni corrections were also applied to correct for multiple comparisons.

Data from one *Tap trial* was missing for one participant in Block 2 A (Illusion Block), and data from three *Stroke trials* was missing for one participant in Block 1 A (Baseline Block). The stroke distance in these two cases were computed as an average of their response for the remaining trials. This was done since both the participants reported the same Stroke Distance for all their remaining trials (seven trials and five trials, respectively), and unit imputation of the missing values resulted in the same average using either the mean or median value.

The Stroke Distance data for the Baseline (1 A) *Tap trials* and Illusion (2 A) *Tap trials* data were not normally distributed, as assessed by Kolmogorov-Smirnov tests with $p = .043$ and $p = .003$, respectively. The distribution of the differences between the Baseline and Illusion stroke distance data were not symmetric, based on visual inspection of histograms. Hence, an exact sign-test was performed to compare the Stroke Distance for the Baseline (1 A) *Tap trials*, with Stroke Distance for the Illusion (2 A) *Tap trials*. This analysis provides insight into the strength of the illusory percept.

A separate exact sign-test was also performed to compare the Stroke Distance for the Illusion (2 A) *Tap trials*, with the Stroke Distance for the Baseline (1 A) *Stroke trials*. This analysis provides insight into the relative difference between the illusory percept and a real stroke percept.

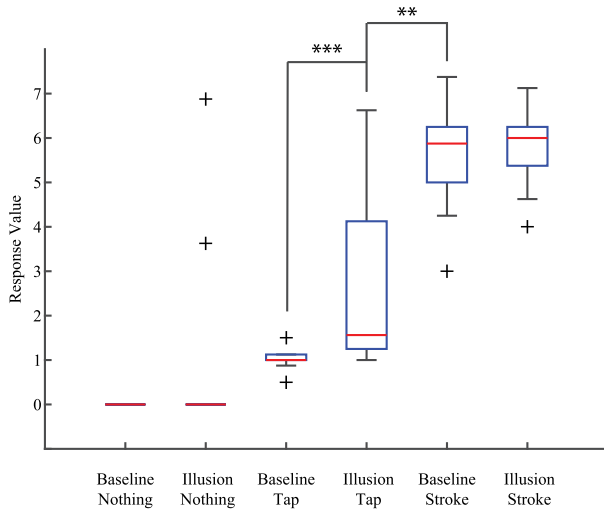


Fig. 4. Stroke distance for the *Nothing*, *Tap*, and *Stroke* stimulus trials in Baseline (1 A) and Illusion (2 A) blocks. A score of 1 indicates that the participant felt a tap sensation at the base of their index finger and a higher score indicates that the participant perceived a “stroke” sensation further along their index finger.

A Friedman test was performed to compare the participants’ self-reported strength of the illusion from survey responses of the Baseline Block (1B), Illusion Block (2B) and Residual Illusion Block (Block 3). Post-hoc pairwise comparisons were performed with a Bonferroni correction for multiple comparisons.

A Wilcoxon signed-rank test was performed to compare the scores for the Ownership and Disownership scores based on survey responses for Block 2B.

III. RESULTS

A. Stroke Percepts

13 out of the 14 participants showed an increased Stroke Distance for the Illusion (2 A) *Tap trials* compared to the Baseline (1 A) *Tap trials*, and one participant showed no change. Results of the sign test revealed a statistically significant median increase in the Stroke Distance (0.5), $z = 3.328$, $p < 0.001$ for the *Tap trials* in the Illusion Block (2 A) compared to the *Tap trials* in the Baseline Block (1 A), as illustrated in Fig. 4.

13 out of the 14 participants showed a decreased Stroke Distance for Illusion (2 A) *Tap trials* as compared to the Baseline (1 A) *Stroke trials*. Results of the sign test revealed a statistically significant median decrease in the Stroke Distance (4.31), $z = 2.94$, $p = 0.003$ for the *Tap trials* in the Illusion Block (2 A) compared to the *Stroke trials* in the Baseline Block (1 A), as illustrated in Fig. 4.

Results of the Friedman test revealed that the Stroke Scores were significantly different for Baseline (1B), Illusion (2B), and Residual Illusion (Block 3) trials $\chi^2(2) = 18$, $p < 0.001$. Results from the post-hoc analysis revealed that the Stroke Scores were significantly greater in the Illusion Block (Mdn = 6), compared to the Baseline Block (Mdn = -5) ($p < 0.001$). The Stroke Scores were significantly greater for the Residual Illusion Block

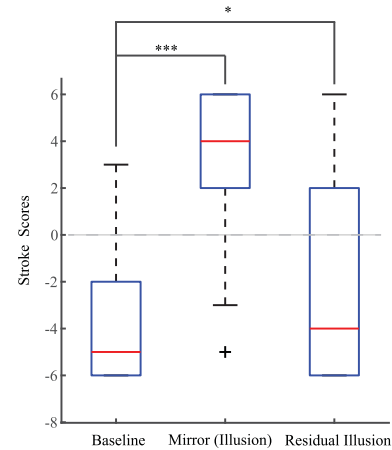


Fig. 5. Stroke Scores for the Baseline (1B), Illusion (2B), and Residual Illusion (3) blocks. A positive Stroke Score indicates that the participants were more likely to characterize their percept as a stroke, than a tap.

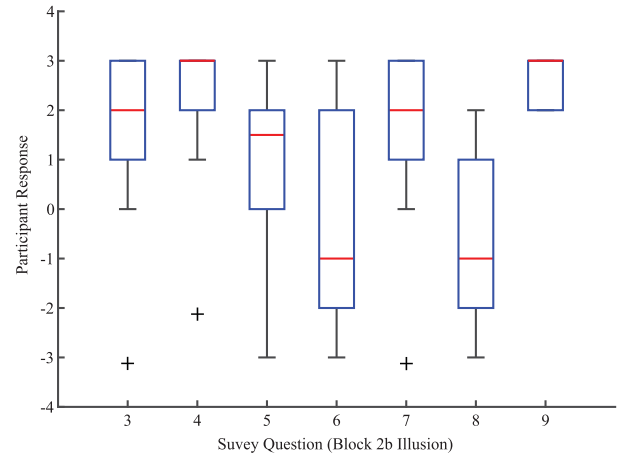


Fig. 6. Responses for Questions 3-9 in Block 2b Illusion survey. A score of positive 3 indicates a strong agreement, while a score of negative 3 indicates a strong disagreement with the respective statement (see Table II).

(Mdn = -4), compared to the Baseline Block (Mdn = -5), $p = 0.014$ (see Fig. 5).

B. Ownership

Results of the Wilcoxon signed-rank test revealed a statistically significant difference in agreement, where participants were more likely to agree with statements that indicated ownership of the unobstructed right hand’s reflection (Mdn = 2, Range = [-1.3, 2.67]) than statements that indicated disownership of their obstructed left hand (Mdn = 0.5, Range = [-2.0, 2.3]), $z = 11$ and $p = 0.028$ (see Fig. 6 and Table II).

C. Visuo-Haptic Conflict

All participants agreed with the statement that there was a conflict between the visual and touch feedback during the *Tap trials* in the Illusion Block; Mean = 2.64 ± 0.48 (out of 3) (see Fig. 6, Q9).

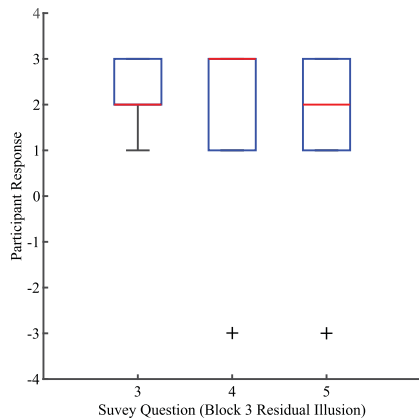


Fig. 7. Responses for Questions 3 through 5 in Block 3 Residual Illusion survey. A score of positive 3 indicates a strong agreement, while a score of negative 3 indicates a strong disagreement with the respective statement.

D. Residual Illusion Survey Response

All participants agreed that they wanted to feel a stroke during the five Residual Illusion (mirror covered) trials; Mean = 2.36 ± 0.6 (out of 3), with Md = 2, Range = [1,3], see Fig. 7, Q3.

12 out of the 14 participants agreed that during the five Residual Illusion (mirror covered) trials, they felt as if their finger was being stroked but only at one location, consistent with a sweeping motion at the base. Two participants strongly disagreed with this statement; Mean = 1.64 ± 2.05 (out of 3), with Mdn = 3, Range = [-3,3], see Fig. 7, Q4.

11 out of the 14 participants agreed that their perception changed during the five Residual Illusion (mirror covered) trials. Three participants strongly disagreed with the statement and two of these participants also disagreed with the previous statement regarding stroking at one location; Mean = 1 ± 2.21 (out of 3), with Mdn = 2, Range = [-3,3], see Fig. 7, Q5.

IV. DISCUSSION

Historically, it was believed that vision acts as the dominant sensory modality when processing visuo-haptic information as a self-contained unit, unaffected by other senses. However, recent studies have used haptic illusions to show that this is not always the case and that our haptic perception is shaped through integration of visual and haptic sensory information [19], [20]. In this manuscript, we tried to exploit this process of sensory integration to create a novel haptic illusion.

We investigated to what extent visuo-haptic conflicts can be used to create illusory haptic effects in the form of phantom environmental stimuli. To accomplish this, we utilized a mirror to flip the traditional rubber-hand illusion paradigm. We asked participants to look at the reflection of their right index finger in the mirror while we provided congruent and incongruent cutaneous stimuli to their right finger and their left finger, which was visibly obstructed by the mirror. The visuo-haptic conflict here was generated by providing a tapping stimulus to the participants' obstructed left finger while they visually observed their unobstructed right index finger being stroked in

the mirror. Overall, we found that participants experienced the illusory percept of a stroking stimulus on their obstructed left finger when presented with the visuo-haptic conflict. While the strength of the illusory stroke was weaker than a real stroke provided at baseline, the illusion was still strong enough that most participants continued to experience it to varying degrees even when the visuo-haptic conflict was removed. These findings therefore represent a novel visuo-haptic illusion that is consistent with other illusions previously presented in the literature [8], [11], [12].

Unlike the rubber-hand [8] and mirror-box [9] illusions, the visual-haptic conflict in our illusory paradigm is not proprioceptive in nature. Here, the location of the unobstructed hand's reflection in the mirror coincides with that of the obstructed hand due to their symmetrical placement across the mirror. For the illusion used in this study, we varied the tactile stimulus provided to the finger of the obstructed hand to create a conflict that was cutaneous in nature. To capture the existence of this illusory percept, we created a new metric, Stroke Distance, which measures participant's willingness to ignore the actual tactile stimulus provided to the obstructed finger (the tap) in favor of one that better aligns with the visual feedback of the unobstructed finger's reflection (a stroke). In this way, Stroke Distance closely resembles the proprioceptive drift metric [10], which is popular in other illusions and measures participants' willingness to ignore the actual location of their limb in favor of one that more closely aligns with their visual observation. Like proprioceptive drift, Stroke Distance allows us to measure the intensity of our illusion based on the difference between the cutaneous stimulus provided to the participant, and the cutaneous percept formed by the participant.

Although survey based questionnaires are very common in visuo-haptic illusion research, they are prone to response bias. To mediate this bias, our Stroke Score metric was designed to be robust to participants' indecision of what they categorized as a stroke or a tap. By subtracting participants' responses to the question of a perceived tap on the obstructed left finger from their responses to the question of a perceived stroke on the obstructed left finger, we are able to capture how likely the participant is to categorize the percept they experienced during the visuo-haptic conflict as a stroke or a tap. The significant increase in the Stroke Scores following the *Tap trials* in the Illusion (mirror uncovered) block (Block 2B) compared to the *Tap trials* in the Baseline (mirror covered) block (Block 1B) further supports the claim that participants formed illusory stroke percepts when the mirror was uncovered.

Our survey analysis also provided useful insight into participants' ownership and disownership of their reflected and obstructed hands. Modeled after the work of Kalckert and Ehrsson [21], our responses indicate that participants tend to agree more with statements that pertain to them feeling an increased ownership of the reflected hand as opposed to a reduced ownership of their obstructed hand. We believe this observation points to a possible mechanism underlying the illusory experience of our participants, whereby participants are likely embodying the reflection of the unobstructed hand, as expected from the mirror-box illusion. We suspect that the mostly neutral response

to the questions pertaining to disownership of their real hand may stem from participants' limited willingness to accept the presence of discrepancies in the normal functioning of their hand.

Another interesting aspect of an illusion is the degree to which it persists after the catalyst has been removed. While piloting our experimental protocol, we anecdotally observed some participants experiencing a sensation of a sweeping motion at the base of their finger during non-illusion *Tap trials* (mirror covered) that immediately followed illusion *Tap trials* (mirror-uncovered). We therefore designed Block 3 of our experimental protocol to evaluate if these residual percepts were significant. After priming participants with five illusion *Tap trials*, we found that in the subsequent five non-illusion *Tap trials*, participants reported a significant increase in the Stroke Score. Furthermore, participants strongly agreed that they felt as if they wanted to feel a stroke and that they felt as if the brush was sweeping them in one spot. The existence of the residual effects also suggests that the ordering of Baseline Block before the Illusion Block in our study may not have played a significant role in the development of the primary illusory stroke percept.

The difference between the percepts in the primary Illusion Block and the Residual Illusion Block also raises an important question for future investigation. Namely, to what extent does participants' perception reflect an attenuated stroke during the illusion versus a distortion of the actual tap sensation being presented? In addition, future work can aim to better understand the effects that the direct visualization of the right hand may have hand on the illusion. One variation of interest that may help understand this behavior is the replacement of the physical brush with an air brush (driven by a pneumatic actuator). It is possible that replacing physical bristles with air can attenuate the visual component of the visuo-haptic conflict while still retaining the tactile sensation. Similarly, direct view of the right hand can be obstructed while still allowing the participant to see its reflection. Alternatively, the mirror can be replaced with a video monitor displaying videos of pre-recorded stimuli that are incongruent with the haptic stimuli provided during the experiment. Any resulting changes in participants' response in either of these scenarios would help in better understanding the role that the direct visuo-haptic feedback of the right hand may play in creation of this illusion.

While the underlying mechanism behind this illusion may not be completely understood, it is important to consider how reliably our illusion worked for almost every participant. To the best of the authors' knowledge, this is the first demonstration of participants creating percepts of a phantom stroking stimulus originating from the environment on their body to resolve a visuo-haptic conflict. It may be possible that the current results are specific to the visuo-haptic conflict we created. Still, our study serves as a novel demonstration of the way human haptic

perception can be augmented by visual information. We believe that these findings will be of interest to researchers investigating sensory perception and haptic researchers designing novel visuo-haptic interfaces.

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