DOES THE PROJECTED-HAND ILLUSION HELP IN TELEOPERATION?

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A body illusion, commonly known in the form of the "Rubber Hand Illusion", is an illusion wherein visual inputs on an inanimate object and simultaneous tactile inputs on a part of the body lead to a situation where the inanimate object is identified as the body part. This study investigated the possibility of inducing a body illusion during a teleoperated reaching task, to see if this leads to increased telepresence and improved accuracy. Three conditions were presented in random order; the Direct Control (DC) condition, where the participant's hand is shown on the screen, the Projected Hand Illusion (PHI) condition, showing the slave device consisting of a 3D-printed hand designed to induce a body illusion, and the no Projected Hand Illusion (nPHI) condition, showing the slave device consisting of a 3D-printed object of appropriate shape but designed to not induce a body illusion. Reaching performance was interpreted in terms of position error, for which a significant difference was found between conditions PHI and nPHI. In the nPHI condition, participants kept more distance to the obstacle than in the PHI condition. Potential causes for this difference are an increased perception of risk due to a difference in visual perception, or subtle visual differences in between the two conditions.

Introduction

Teleoperation enables humans to interact with a remote or hostile environments, while preserving their capability of adapting to and coping with dynamic and unpredictable situations. The ideal for teleoperation is to reach optimal "telepresence" (Sheridan, 1989), so that tasks can be performed as if the human were physically in the remote environment. However, limitations in communication bandwidth, time delays and other restrictions make that in teleoperation, simple tasks can be made more challenging, as spatial awareness is degraded (Chen, Haas, Pillalamarri, & Jacobson, 2006). Solutions and improvements include the presentation of additional visual information (Azuma, 1997), aid from automation with shared control (Boessenkool, Abbink, Heemskerk, van der Helm, & Wildenbeest, 2013) or techniques to enhance teleoperation transparency (Okamura, 2013). This study investigates whether Body Illusions (BI) can play a role in improving teleoperation.

Normally, humans perceive the world and their body by a process called sensory processing. Two types of sensory processing are distinguished (Ernst & Bülthoff, 2004), sensory combination and sensory integration. In sensory combination, non-redundant information from different modalities regarding some environmental property are combined to provide a more robust estimate of the property in question. For instance, visual and haptic information about the shape of an object can be combined to provide a better estimate than information from either of the modalities alone could (Helbig & Ernst, 2007). Sensory integration integrates redundant signals from different sensory modalities such that "a coherent multisensory percept is formed" (Ernst & Bülthoff, 2004).

Sensory processing can be seen as a bottom-up process; an estimate of the body or environment is constructed solely from sensory information. However, this is complemented by a top-down process. Prior knowledge provides a logical framework to make sense of the incoming signals. Even though one's prior knowledge is built up over all the years of one's life, it is possible for "bottom-up perceptual mechanisms" to temporarily override it (Slater, Spanlang, Sanchez-Vives, & Blanke, 2010). Body illusions are one example of this phenomenon. During a BI, one experiences an illusory ownership over a fake limb, or even a complete fake body (e.g., (Botvinick & Cohen, 1998), (Ehrsson, 2007), (Slater et al., 2010)). For instance, in the original Rubber Hand Illusion, congruent visuotactile stimulation applied with a paintbrush on a fake hand and one's own unseen hand invokes the illusory perception that the fake hand is actually one's own hand (Botvinick & Cohen, 1998). It has also been proven that a visuomotor correlation (i.e. through initiating active movement and visually perceiving an identical and congruent movement in a fake limb or body) can induce a similar illusion (Dummer, Picot-Annand, Neal, & Moore, 2009), (Sanchez-Vives, Spanlang, Frisoli, Bergamasco, & Slater, 2010).

This study proposes the concept of applying the unique properties of body illusions (e.g., feeling of ownership over fake limbs or body) to the field of teleoperation, to try and enhance teleoperation performance by increasing spatial awareness. This concept is in accordance with Sheridan's supposition: "Identifying with remote arms, eyes or body, especially when there is geometric correspondence, would seem to have advantages", from

(Sheridan, 1989, p. 497). But, as Sheridan also stated: “However, it is not well understood why, or even whether, a feeling of presence enhances observing or acting, whether remotely or not”, also from (Sheridan, 1989, p. 497).

To find an answer to this question, a simplified teleoperation set-up was created in which an added tactile stimulus was introduced to increase the induction of the body illusion. In different conditions, the performance of teleoperation with this set-up was evaluated.

Method

Participants

Sixteen participants, aged between 20 and 54, all male, participated in the experiment. One of the participants was left handed, but stated to normally control a computer mouse with the right hand, indicating that he would not have a problem performing the teleoperation task with the right hand.

Experimental set-up

The experimental set-up used a 3-DoF custom-built planar teleoperation system at the department of Mechanical Engineering of Delft University of Technology (Christiansson, 2007). It consists of a parallel, non-compliant, master and a serial, compliant slave. The master and slave were mounted on the base of two separate, custom-built wooden set-ups. These were each equipped with a webcam (Logitech HD Pro Webcam C920), a transparent acrylic plate holding three target obstacles and a cloth curtain. The webcams were used to provide a video-feed of the workspace on either the master or slave side, which was then displayed on a 17" monitor (HP 1740), on a stand behind the master set-up.

The obstacle plates both held three obstacles. The plates’ position can be adjusted, to accommodate for different-sized hands and fingers. In the same way, the relative position between the manipulators and the obstacles of both sides can be properly adjusted to match the master and slave teleoperation set-ups. A cloth curtain was spanned across the width of the master-setup to provide tactile input to the participant’s hand during the experiment. For visual consistency between both setups, the curtain is also present in the slave setup.

Paricipants were seated in front of the master setup, and placed their right hand on the computer mouse-like manipulator attached to the master end of the teleoperator. Their hand was never directly visible; depending on the experiment condition, either the webcam image of the hand and master side, or the webcam image of the slave side was shown (Fig. 4).

Three different attachments were created with a 3D printer, these were: (1) A mouse-like manipulator for the master side, with a ramp for the finger of the participant’s hand; (2) A realistic hand, with the index finger extended and mounted on top of the same mouse-like manipulator. A nitrile glove is wrapped around the hand, to obscure its plastic nature and increase the visual similarity between the attachment and the participants’ own hand, for this participants wore an identical glove during the experiment. This attachment was used for the slave side; (3) A second mouse-like shape for the slave side, with a rod attached to the ramp to have the same effective dimensions as the manipulator, but made to not resemble the participant’s own hand. For added distinction, a plastic tie-wrap was tied around the rod. The different attachements as fixed to the manipulator are shown in Fig. 1.

Task description

The task environment contained three obstacles which needed to be avoided, suspended slightly above the participant’s hand, with the obstacles’ heads at about the same height as the participants’ fingertips. The front target is the base (or B), the latter targets are called L and R, for left and right obstacle. See Fig. 3. Four targets were defined relative to the L and R obstacles, two lateral targets (located left of the obstacles) and two longitudinal targets in front of the obstacles. The targets are strictly virtual and they are not visible on the video-feed. The targets were numbered from 1 to 4 for analysis purposes. During the experiment, targets were indicated on the upper part of the screen, above the webcam view, and participants were asked to quickly move from the base position to the target, without hitting or touching any of the obstacles.

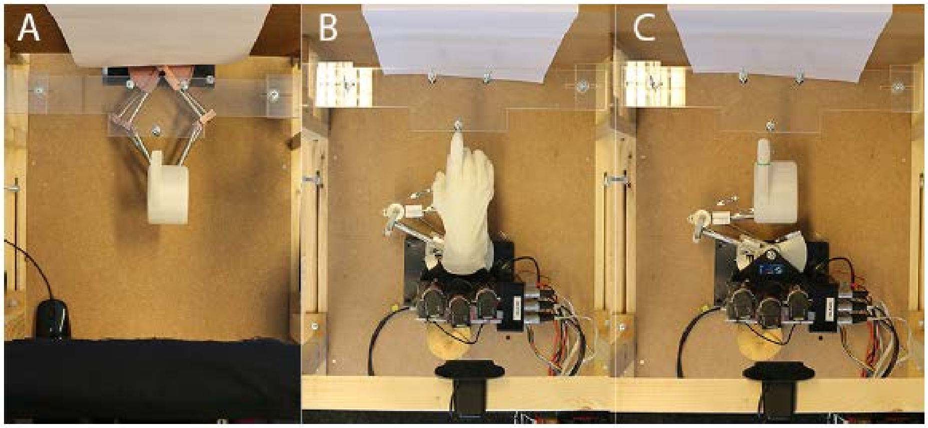

Figure 1: All three attachments, as mounted on the setup. A: attachment for the participants to hold, mounted on the master-side; B: attachment with the realistic hand, mounted on the slave-side; C: attachment with the finger-like boom, mounted on the slave side

Experiment Design

The experiment started with a training consisting of three parts. During the first part subjects received on-screen feedback on the registered position relative to the target and were asked to touch the L or R obstacle before moving to the target. In the second part of the training, the obstacle was not to be touched, but feedback was still provided. The third training set had no feedback out the questionnaire. Then 9 measurement sets (of 4 movements each) were performed (DT). Subjects were shown the master setup and their own hand on-screen. This, in combination with the movement, and the sensation from the curtain should induce the Projected Hand illusion.

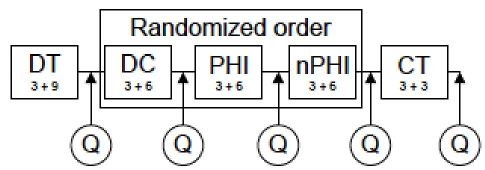

Figure 2: Schematic overview of the order of conditions. The numbers below the abbreviated condition names indicate the training and measurement sets, respectively. The Q's represent the moments of filling out the questionnaire.

The measurement conditions, Direct Control (DC), with view of the master side and the subject's hand, Projected Hand Illusion (PHI), with view of the slave side and the fake hand, and non-Projected Hand Illusion (nPHI), with view of the slave side and fake finger, were offered in randomized order, each of these consisted of 3 training sets and 6 measurement sets. The experiment was closed off with a control condition (CT), equal to the DT condition, to check for learning during the experiment. A questionnaire on the strength of the body illusion was taken after each condition (Fig. 2).

Hypotheses and metrics

A 20 item questionnaire on the body illusion, adapted from (Graham, Martin-Iverson, Holmes, & Waters, 2014; Longo, Schüür, Kammers, Tsakiris, & Haggard, 2008), was answered after each condition. From this questionnaire, the question that most seemed to define the occurence of the body illusion, "It felt like . . . the wooden hand was my hand." was used to divide the participants into two groups. The 5 participants who scored higher on this question for the PHI condition compared to the nPHI condition were grouped in a qualifying group (Q), the remaining 11 participants were assigned to the non qualifyng (nQ) group. It was hypothesized that the sensation of ownership of the artificial hand would affect performance on the task, and that would make performance in the DC and PHI conditions similar, and different from the nPHI condition, while for the nQ group the performance in the PHI and nPHI condition is expected to be similar. Data were recorded on the slave and master positions, and performance on reaching the target position was calculated. Data on timing proved to be not consistent enough for further analysis.

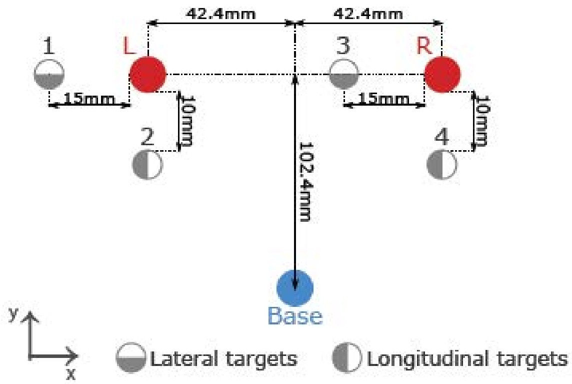

Figure 3: Schematic lay-out of the 3 obstacles and the 4 targets as seen from the top, including dimensions and target numbering. The diameter of the obstacles is 6.5mm. Note: figure not to scale.

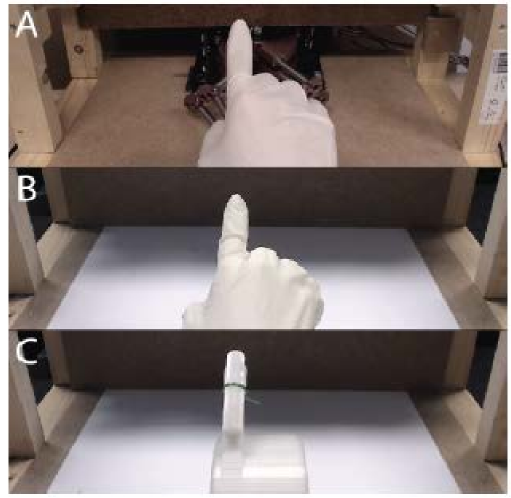

Figure 4: Screenshots (cropped) showing what participants saw on the monitor during the experiment fc the different conditions. A: DT condition, DC condition and CT condition (own hand, master side); B: PHI condition (fake hand, slave side); C: nPHI condition (fake finger, slave side).

Results

On the basis of the questionnaire only 5 participants were grouped in the Q-group. However all but one of the participants in the Q-group judged the experience of the BI as "neutral" or "positive" in condition nPHI as well. As condition nPHI was designed not to induce the Projected Hand Illusion, this is an unexpected result. This was not limited to the Q group, most participants actually did not experience a real difference in BI between conditions PHI and nPHI, based on their responses and the used rules for assessment (BI is present when score is 0 or higher); of the 16 total participants, 11 participants filled out a score of 0 or higher in both PHI and nPHI, and 2 participants filled out a score lower than 0 for both conditions. This means that only 3 participants noticed an actual difference in BI between the two conditions; only 1 participant experienced the BI only in the PHI condition (in accordance to the design of the experiment), while 2 other participants experienced the BI only in the nPHI condition (the opposite of what was designed to happen).

Fig. 5 shows the deviation between the position of reached and intended target in y-direction (longitudinal direction from the participant's point of view), for all trials of the participants in the qualifying group (Q-group, n=5). The four targets and the three conditions of interest (i.e. DC, PHI, nPHI) are depicted separately. The positive direction is defined as being directed away from the participant. Each participant completed each target 6 times during each condition, except for one participant who completed each target 5 times in the DC condition due to an error during measurements.

A one-way analysis of variance (ANOVA) was performed over all three conditions for each target separately. Therefore, a Bonferroni correction was applied, reducing the alpha level to 0.0125 instead of 0.05. A significant difference was found for target 2 ($\mathbf{F}(2, 84) = 19.36$, $\mathbf{p} < 0.001$) and target 4 ($\mathbf{F}(2, 84) = 11.61$, $\mathbf{p} < 0.001$). Subsequently, dependent t-tests were performed over conditions PHI and nPHI for target 2 and target 4, confirming significant differences in performance between these conditions.

Similarly, Fig. 6 depicts the deviation between the position of reached and intended target in y-direction, but now for all trials of the participants in the non-qualifying group (nQ-group, n=11). Again, the four targets and the three conditions of interest (i.e. DC, PHI, nPHI) are depicted separately, and the positive direction is defined as being directed away from the participant. Each participant completed each target 6 times during each condition.

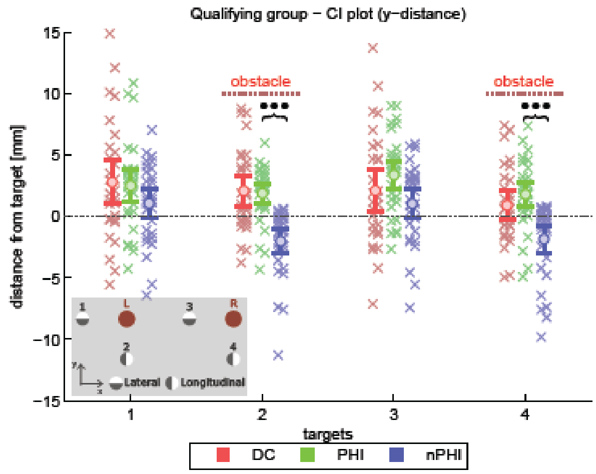

Figure 5: Distance in y-direction between reach and intended target, for the Q-group (n=5). Each cross represents the result of one trial, while the circles show the mean of all trials and the error bars indicate the 95% confidence intervals. Significance is denoted by "•", "••" and "• • •", representing $p \leq 0.05$, $p \leq 0.01$ and $p \leq 0.001$, respectively.

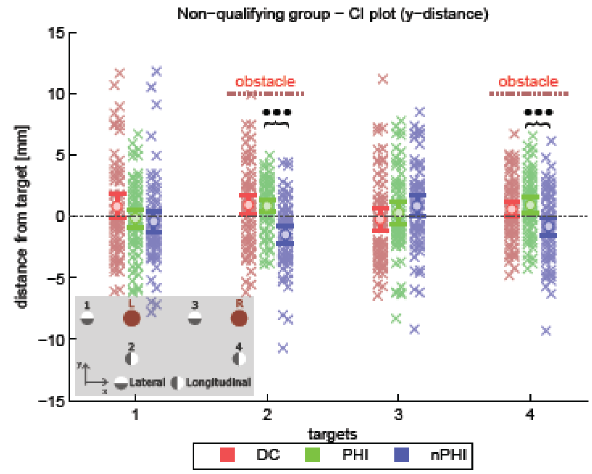

Figure 6: Distance in y-direction between reach and intended target, for the nQ-group (n=11). Each cross represents the result of one trial, while the circles show the mean of all trials and the error bars indicate the 95% confidence intervals. Significance is denoted by "•", "••" and "• • •", representing $p \leq 0.05$, $p \leq 0.01$ and $p \leq 0.001$, respectively.

An ANOVA over all three conditions for each target separately (again, a Bonferroni correction was applied, such that _ = 0:0125) showed that there is a significant difference for target 2 ($F(2, 195) = 15.18$, $p < 0.001$) and target 4 ($F(2, 195) = 7.47$, $p < 0.001$). Post-hoc dependent t-tests again showed the differences in between conditions PHI and nPHI.

Data for lateral direction were also analysed, and showed a significant difference between the PHI and nPHI conditions for targets 2 and 3, with small offsets to the left and to the right respectively (these data are not presented in this paper).

Discussion

Differences between performance in the PHI and nPHI conditions were found for two of the targets. However, the differences do not directly indicate an effect of the BI on teleoperation performance, since both the Q- and nQ- groups showed a similar effect. It can be argued that the manipulation – nPHI versus PHI condition – was ineffective in controlling the BI. The questionnaire results indicate that in many cases the judgment of BI was independent of the type of slave device shown, possibly due to a lack of sensitivity in the questionnaire, or possibly a gloved hand versus the more abstract computer mouse-like shape did not provide enough differentiation in sense of ownership of the controlled and visible device.

Indeed, the majority of participants verbally reported that after a while, controlling the finger-like boom felt natural and similar to controlling the fake hand or their own hand – even though they clearly noticed and reported that the finger-like boom did not look like a hand. Thus, despite clear visual discrepancies, participants may have accepted the fake finger as being their own, see again Fig. 4 for a visual comparison of the conditions as seen by the participants.

The remaining persistent differences between the nPHI and PHI conditions might also be attributable to other factors. To avoid systematic errors in the movement, the master and slave set-up were calibrated as accurately as possible to match up the distances to the target positions. For instance, a difference in end-point of the "fingertip" of the attachments used in conditions PHI and nPHI can easily cause a bias in the y-direction, and despite the calibration, these differences cannot be completely excluded. Also, as the attachments of conditions PHI and nPHI show quite some geometrical differences, making visual references provided by the attachments different. This difference can also influence the distance estimation by the participants. In addition, the attachments are not symmetrical and thus the left and right side of the attachments can provide differing visual references, which can specifically influence spatial estimations laterally.

Conclusion

The effect of Body Illusions (BI) on tele-operated reaching performance under three different conditions: Direct Control (DC, showing the own hand on the master side, gloved and visible on-screen), the Projected Hand Illusion (PHI, with 3D printed gloved hand visible on the slave side) and the no-Projected Hand Illusion (nPHI, with a mouse-like shape on the slave side). Based on differences in subjective responses to a question on how the virtual hand was experienced for the nPHI and PHI conditions, participants were assigned to a qualifying group or a non qualifying group, that experienced less or no body illusion sensation. Errors between target and final position after reaching were used as performance measure.

Consistent longitudinal differences in movement to the target position were found for the two positions where the finger longitudinally approached the target (complicated by limited depth perception), for the nPHI and PHI conditions. No significant differences were found between the DC and PHI condition. The results could not be unequivocally attributed to BI effects. Participants did indicate in the majority of the cases (80%) “ownership” of the shown device, both in the nPHI and PHI conditions, suggesting that the effect of a body illusion might already be present in situations where the manipulated device cannot be mistaken for a body part.

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