Faculty of Aerospace Engineering

# Changing behavior during teleoperation by tricking the brain?

*Exploring a practical application of body illusions*

L. V. Wajon, BSc

19th August, 2015

Delft University of Technology

Challenge the future

# Changing behavior during teleoperation by tricking the brain?

## Exploring a practical application of body illusions

Master of Science Thesis

For obtaining the degree of Master of Science in Aerospace Engineering
at Delft University of Technology

L. V. Wajon, BSc

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DELFT UNIVERSITY OF TECHNOLOGY
DEPARTMENT OF
CONTROL AND SIMULATION

The undersigned hereby certify that they have read and recommend to the Faculty of Aerospace Engineering for acceptance a thesis entitled **"Changing behavior during teleoperation by tricking the brain?"** by **L. V. Wajon, BSc** in partial fulfillment of the requirements for the degree of **Master of Science**.

Dated: 19$^{\text{th}}$ August, 2015

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Shyrill Pacio, I love you!

Delft University of Technology,
August 19$^{\text{th}}$, 2015

Lloyd Vincent Wajon BSc.

# Contents

# List of Figures

# List of Tables

# IEEE paper

# Applying Body Illusions During Teleoperation May Influence Teleoperation Accuracy

Lloyd V. Wajon, David A. Abbink, René M. van Paassen, Max Mulder, and Erwin R. Boer

***Abstract*—Teleoperation is widely used in human-hostile or otherwise inaccessible environments. However, using teleoperation to perform a task is more difficult than performing the task directly. A main factor for this is limited telepresence due to the absence or distortion of natural sensory feedback.**

**An interesting possibility to increase telepresence and enhance teleoperation performance is inducing a Body Illusion which may give human operators the sensation that the remote tool belongs to their own body. This study investigated the possibility of inducing the Projected Hand Illusion during a teleoperated reaching task, and its effects on accuracy. The participants (n=16) reached for targets while avoiding stationary obstacles, by manipulating a master device coupled to a slave device. Three conditions were randomly presented: the Direct Control (DC) condition, showing the master device with the participants' own hand, 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 similar shape designed to not induce a Body Illusion. A questionnaire was used to assess the subjective feeling of the Projected Hand Illusion. Based on the questionnaire responses, participants were grouped in the qualifying group (n=5) or the non-qualifying group (n=11). It was found that the Projected Hand Illusion was consistently induced in both conditions, and for both groups. Also, a significant difference in distance to target in the y-direction and x-direction was found between conditions PHI and nPHI; in the nPHI condition, participants kept more distance to the obstacle than in the PHI condition. This may suggest an increased perception of risk due to a difference in visual perception or due to the Body Illusion. However, as the Body Illusion was present in both conditions according to the metric used, and the differences between conditions were found for both groups, these findings cannot be attributed to the presence of the Body Illusion with certainty. Therefore, more in-depth studies investigating the possible causes are recommended.**

**This research shows that a Body Illusion can be evoked during teleoperation, and possibly affect its performance. Therefore, this exploratory study gives rise to further research into the practical application of Body Illusions in teleoperation.**

***Index Terms*—Teleoperation, task performance, telepresence, Body Illusion, Projected Hand Illusion, multisensory illusion, body ownership, psychophysics**

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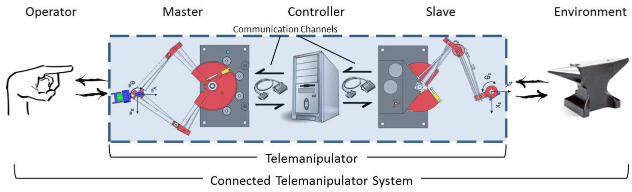


Fig. 1. All of the components of the telemanipulator and the connected telemanipulator system. From [49], which adapted it from [11].

## I. Introduction

TELEOPERATION enables humans to interact with a remote environment, while preserving their capability of adapting to and coping with dynamic and unpredictable situations. Therefore, despite automation, teleoperation has a lot of different applications. However, teleoperation is not without flaws or shortcomings. Many ways to improve teleoperation have been developed and tested extensively in literature. Yet, there is still room for innovation to further increase performance of teleoperation.

A teleoperation system, or telemanipulator, consists of three main components connected through communication channels only: a master-side manipulator, a slave-side manipulator and a controller. The human operator directly operates the master-side manipulator. All forces and movements are translated by the controller and passed to the slave-side through the communication channels. The slave-side manipulator acts according to the input generated by the operator at the master-side, and interacts with the remote environment. Forces generated by the interaction of the slave-side manipulator with the remote environment are translated by the controller and passed back to the master-side. The master-side manipulator provides force feedback accordingly to the human operator, completing the loop of teleoperation. The telemanipulator together with the human operator and the remote environment, forms the connected telemanipulator system. Each of the components of the telemanipulator and the connected telemanipulator system are depicted in Fig. 1. Using this technology, the human can be "virtually present" at the remote environment, which is commonly referred to as "telepresence" in literature [37].

The characteristics of teleoperation make this technology exceptionally suitable to let humans perform tasks at locations otherwise inaccessible or even hostile (e.g., [37]). For example, exploration of space [2], [30], deep-sea and the airspace [10] are common fields for teleoperation. Assisting in providing aid in case of nuclear disasters [48] or collapsed buildings (e.g., [42], [9], [10]) is one of the main uses for teleoperation as well. Surgery (e.g., [21], [17], [32], [5], [10]) and micro-assembly [50] are other examples of applications in which teleoperation has been successfully implemented. The advantages in these examples are of great value; the human operator is physically separated from hostile environments (e.g., space, deep-sea, nuclear disasters, collapsed buildings) and can act more precisely and on a smaller scale than normally possible (e.g., surgery, micro-assembly).

However//Unfortunately, the natural perception of the human operator is physically decoupled from the remote environment. This causes problems with (remote) perception; for example, scale ambiguity [42], [51], lack of motion feedback and a camera viewpoint not matching with the natural viewpoint of the human eyes can render simple tasks rather challenging. As a result, spatial awareness is usually poor, which has a negative effect on performance during teleoperation [10].

Various solutions and improvements have been proposed and elaborately assessed in different studies. For example, by providing more information visually to the operator (e.g., multiple camera viewpoints, stereoscopic vision, augmented reality, other sensors such as radar or accelerometers [10], [4]) or automating tasks where possible. Other developments have been made in the field of haptic feedback, such as event-based haptic feedback [25], shared control [41] or aiming for transparency [30], a representation of forces and contacts with objects and surfaces as accurately as possible.

Despite these improvements, performance of teleoperated tasks is lower than performance of the equivalent directly-manipulated tasks – even aiming for complete transparency does not seem to improve performance substantially compared to less complex forms of haptic feedback [49]. Innovative concepts can possibly enhance teleoperation performance in different ways, perhaps by altering the way the remote environment and manipulator are perceived.

Normally, humans perceive the world and their body by a process called sensory processing. This process estimates the (state of the) body and the surrounding environment. This enables humans to (safely) navigate and interact with their environment. Sensory processing combines two general strategies, sensory combination and sensory integration [15].

Through 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 [20].

Sensory integration integrates redundant signals from different sensory modalities such that “a coherent multisensory percept is formed” [15]. During this process, weighting of the modalities happens according to how reliably an estimate can be derived from a specific modality [14]. In other words, weighting depends not solely on a particular modality, but also on the specific circumstances under which a modality provides an estimate. For instance, the visual modality becomes less reliable when there are poor lighting conditions or visual noise and thus, its assigned weight decreases. Therefore, Ernst & Bülthoff coined the term “estimate precision” [15].

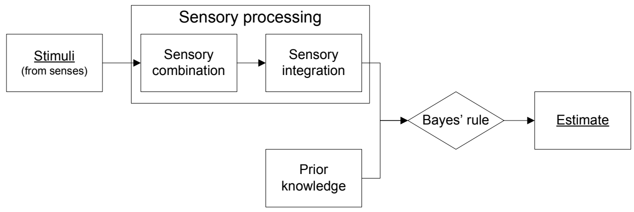


Fig. 2. Schematic diagram depicting the process of going from stimuli to estimate. Based on [15].

Together, these processes make up the sensory processing. This is a so-called bottom-up process; an estimate of the body or environment is constructed solely from sensory information. However, it is impossible to fully construct a mental representation of body and/or environment from these estimates alone. Prior knowledge, built up over the years of one’s life, provides a logical framework to make sense of the incoming signals. This is a top-down process. The top-down process is combined with the bottom-up process using Bayes’ rule to construct a meaningful estimate of a particular property of either body or environment. See Fig. 2 for a schematic overview of this complete process.

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 [40], and surprisingly easily as well. Body Illusions are one way to achieve this. During a Body Illusion, one experiences an illusory ownership over a fake limb, or even a complete fake body (e.g., [7], [13], [40]). A Body Illusion is invoked by “altering the normal association” between two or more modalities [40]. 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 [7]. 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 [12], [35].

In-depth studies revealed more information regarding the boundaries and required conditions of inducing the RHI. For instance, it is only possible to induce the illusion if there is sufficient coherence to the natural situation in terms of synchronicity of stimulations (e.g., [7]), similar aesthetics, a congruent posture and a congruent identity [43]. However, there is some toleration of incongruence, which grows with stronger experiences of a Body Illusion [27].

Studies into different kinds of Body Illusions have also been performed. These studies demonstrated that Body Illusions are not only possible in the physical environment, but also through a camera-monitor setup (e.g., [46], [45], [16]) or even in Virtual Reality [35], [24]. Furthermore, literature shows that not only a specific body part can be experienced as one’s own, but even an entire body (e.g., [13], [31], [36], [40]).

Body Illusions have known various successful, mostly medically related, applications: enhancing experience of upper-limb amputees with prostheses [34], investigating and authenticating vision-touch synaesthesia [1], investigating and possibly treating patients with anorexia nervosa [23], investigating (patients experiencing) the phenomenon of phantom limbs and phantom pains [19], [36], fundamental research into the working of the brains (e.g., [44], [22], [8]) and processes like estimating scale [47]. Although less commonly reported, there are studies with a less successful than desired outcome, such as investigating Body Illusions as a way to relieve clinical pain [29].

This study proposes the following concept: 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 [37] (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 [37] (p. 497).

Therefore, the research question the current study aims to answer is: "Is there any difference in performance between teleoperation with or without Body Illusion?"

This article will first discuss the method of the study in Section II, describing the experimental details. The most important results of the experiment are presented in Section III. The results will be elaborately discussed and analyzed in Section IV, which also contains recommendations regarding the experiment. Finally, this article ends with the conclusions drawn from the current study in Section V.

## II. Methods

### A. Participants

Initially, 19 participants entered the experiment. However, due to a change in setup after the first 3 sessions of the experiment, the first 3 participants were excluded, leaving 16 participants. The remaining participants were all male, and aged between 20 and 54 ($\text{mean} \pm \text{SD} = 25.8 \pm 7.8\,\text{years}$). The analyses reported in this article refer to the 16 remaining participants. One participant was left-handed (5.3%), but stated to control a computer mouse with the right hand. No participant had any relevant allergies (e.g., to nitrile), but one participant experienced back pain, while another participant was known to occasionally suffer from RSI-related complaints. All participants signed an informed consent form. The experiment was approved by the Human Research Ethics Committee of Delft University of Technology in accordance with the Declaration of Helsinki.

### B. Experimental setup

The teleoperation device used in the setup is the Munin, a 3-DoF planar teleoperation system, custom-built by a former PhD. student of the Haptics Lab at the department of Mechanical Engineering of Delft University of Technology (see [11]. It consists of a parallel, non-compliant master and a serial, compliant slave. Its controller runs on a MathWorks xPC Target at 1kHz, resulting in an estimated delay of 1.5 [ms] between master and slave. More detailed information regarding the system, including a system analysis, can be found from [11].

The master and slave of the Munin were each mounted on the base of two separate, custom-built wooden setups. On both setups was mounted a webcam and a transparent acrylic plate holding three obstacles and a cloth curtain is spanned over the width of the setup. The master-setup incorporates a mouse, with which the participants were asked to fill out the questionnaire when presented.

The webcams (Logitech HD Pro Webcam C920) were used to capture a video-feed of the workspace on either the master or slave side. Using MATLAB, the video-feed was displayed on a 17" monitor (HP 1740), which was placed on a stand behind the master setup. This monitor also displayed the experiment-specific instructions during measurements and the questionnaire after conditions.

The obstacle plates both hold three obstacles. The plates' position of mounting 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 obstacles actually are bolts attached to the plate. The head of the bolts is wrapped with soft foam, to eliminate contact noises which could give auditory cues during the experiment.

The cloth curtain was spanned across the width of the master-setup to provide tactile input to the participant's hand during the experiment. This was deemed desirable, to increase visuotactile congruence and increase the probability that one is able to induce the Projected Hand Illusion using this setup. For visual consistency between both setups, the curtain is also present in the slave setup.

The front view of the master setup is shown in Fig. 3. Note that this picture depicts an intermediate (but near final) version of the setup. The final version has a slightly different, smaller obstacle plate with just the three obstacles and no extra holes (this can be seen in Fig. 4), and the targets shown on-screen have been changed (more about the lay-out of the targets follows below). Also note that the Munin itself is obscured from view by the back plate.

Participants are seated in front of the master setup. The view on the master setup is obscured by means of a black curtain at the front of the setup. Participants can stick their hand underneath the curtain, but cannot view the setup directly – only via the camera-feed shown on the monitor. To obscure the view on the neighboring slave setup, a plate was placed in-between both setups.

Three different attachments were 3D-printed; 1 for the master setup, and 2 for the slave setup. All attachments consist

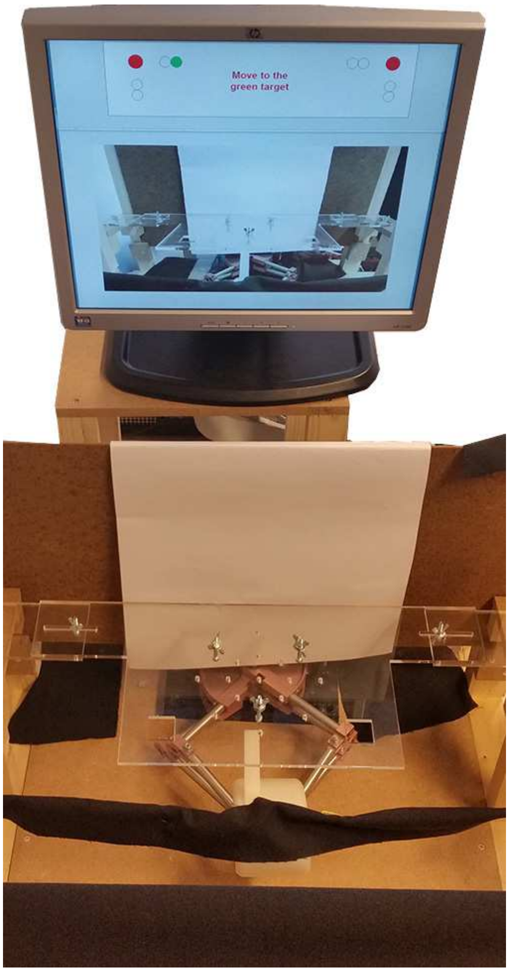


Fig. 3. Front view of the master-side setup. At the bottom the attachment and the small cloth curtain are visible, with right above the attachment the transparent obstacle plate, holding the three obstacles. The monitor with the visuals presented to the participant during the experiment is visible at the top.

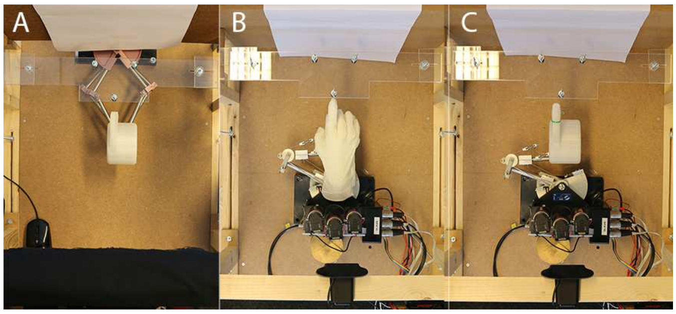


Fig. 4. All three attachments, as mounted on the setup. A: attachment for the participants to hold, mounted on the master-side; B: attachment with the realistic hand, mounted on the slave-side; C: attachment with the finger-like boom, mounted on the slave side

Fig. 5. Attachments used in conditions PHI (left) and nPHI (right). Note that the attachment of the nPHI-setup does not include a hand and that a tie-wrap is strapped around the finger-like boom; both to accentuate the non-human physique.

of a base mesh, which is similar to a computer mouse. On top of this part is an elevated ramp, on which the participants can rest their index finger. The attachments are made for right-handed use only.

The first attachment for the slave setup includes a realistic 3D-printed hand, which is attached to the mouse-like part. The hand holds the attachment like the participants are instructed to; that is, like a computer mouse and with their right index finger resting on the ramp. The fake hand is posed as anatomically correct as possible. 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. This attachment is used in the PHI-condition (more about this later).

The second attachment for the slave setup does not include a hand, but rather just a rod attached to the ramp, as if it were a somewhat featureless cut-off finger. A green tie-wrap is strapped around this finger-like "boom", to further accentuate the non-human physique. This attachment is used in the nPHI-condition (more about this later).

See Fig. 4 for all three attachments, as mounted on the setups. Fig. 5 shows a close-up picture of the attachment of the PHI condition (left) and the attachment of the nPHI condition (right).

The experiment took place in a closed, private room. Both visual and auditory distractions from outside were minimized. A closed sunscreen provided controlled lighting conditions and obstructed the view outside. Participants wore a pair of closed-ear headphones (Sennheiser HD 201) playing brown noise. The volume was adjusted to the participants' comfort, but was loud enough to cancel out distracting sounds from outside and possible auditory cues of the setup itself (e.g., touching of the obstacles). Participants wore a nitrile glove for consistency with the image of the fake hand. Participants filled out the questionnaire with their left hand, to minimize movements of the right hand which might influence the induction of the PHI.

The complete experiment took about 100 to 120 minutes per participant.

As a side-note, before the experiment, participants were subjected to two short experiments. These were originally meant as inclusion criteria and to test the participants for their sensitivity to the Rubber Hand Illusion and the Projected Hand Illusion. However, the inclusion criteria were dropped due to the fact that it is how the experience of the RHI or PHI in these short experiments relate to the experience of the PHI in the actual experiment.

These two experiments will be shortly discussed below for the sake of completeness. However, as these experiments were dropped as inclusion criteria afterwards, the results will not be further discussed in the article.

*1) Rubber Hand Illusion:* The setup for the Rubber Hand Illusion-experiment is strongly based on the setup used by Botvinick & Cohen in the original experiment [7]. The rubber hand used in the original study was replaced by a poseable wooden hand (obtained from a local art store). The hand was wearing a white nitrile medical glove to obscure its wooden details. Participants wore an identical nitrile glove on their right hand. The wooden hand was clamped to a plate so that it could not rotate or move upon stimulation. The participant was seated at a table, with the wooden hand in front of them. It was placed on the left of a standing screen, while the participants placed their right hand on the right side of the screen so that their view on their own hand was obstructed. A black cloth was draped over the participant's shoulder and over the wrist of the wooden hand to hide the missing "arm" between shoulder and wooden hand. The participant's left hand was rested on the table.

Stimulations were presented to the participant's hand and the wooden hand in a synchronous and congruent way with a paintbrush. A pattern including stroking and tapping was used for the stimulation. Similar to mentioned above, participants wore headphones playing brown noise, so that they could not hear the sound of the brushes stroking either of the gloves. Participants were instructed to focus on the seen hand, and on the visual and tactile sensations. Also, they were asked to report any mismatch they may notice between the visual and tactile stimulations. Both instructions were repeated during the experiment. Stimulations lasted for about 5 minutes, after which the participants were asked to fill out the same 20-statement questionnaire as used during the actual experiment.

*2) Projected Hand Illusion:* The setup to test for the Projected Hand Illusion is the same setup as used during the actual experiment, and thus uses the Munin teleoperation system (see text above and Fig. 3). The only difference with the actual experiment is the task: participants were instructed to move around freely, exploring the dynamics and limits of the system and simultaneously trying to induce the PHI on themselves by touching the obstacles, while focusing solely on the image of the hand on the monitor and the visual and tactile sensations. This instruction was repeated throughout the experiment. Participants again wore the headphones playing brown noise, for consistency reasons. After about 5 minutes, the participants were again asked to fill out the 20-statement questionnaire.

## C. Task description

The task environment consisted of three obstacles, 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. 6.

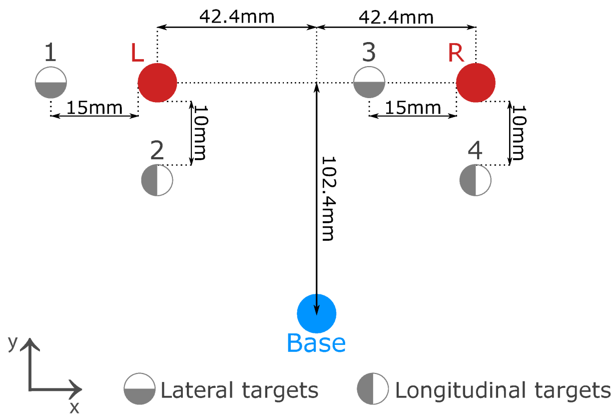


Fig. 6. Schematic lay-out of the 3 obstacles and the 4 targets, including dimensions and target numbering. The diameter of the obstacles is 6.5mm. Note: figure not on scale.

The targets were defined relative to the L and R obstacles. Each obstacle had two targets; a "lateral target" (located left of the obstacle) and a "longitudinal target" (located in front of the obstacle). 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. The distance between targets and obstacles can be seen in Fig. 6, as well as the numbering of the targets.

The schematic lay-out of the task environment was shown on-screen to the participants during the experiment. Targets were presented in a random order to the participant by changing its color from grey to green.

Before the actual task starts, the setup has to be calibrated. The participants were asked to touch all three obstacles from the front in succession, while the positions of each of the obstacles was registered. This was necessary as the length of the index finger of the participants varies, and thus the position of the obstacles relative to the manipulator also varies. For the same reason, the position of the slave manipulator relative to its obstacles was checked and adjusted to match the corresponding position of the master-setup. After calibration, the participants were instructed to move around and touch the obstacles freely. This was to get used to the system and specific condition, and to try and induce the Projected Hand Illusion. After about a minute, the calibration process was repeated to make sure the setup was properly calibrated, even after the participant has moved around for a while.

After this preparatory phase, the actual task can begin. The participants were asked to reach for the presented target, and to try to match the position of the center of the visible fingertip to the target's position as closely as possible. See Fig. 7 for the definition of the reference points of both fingertip and targets. The participants were instructed to always start a trial from contact with the front of the base. A target is then presented to them on-screen. The participants reach for the position of the presented target, using only the camera-feed and proprioceptive information to judge their position.

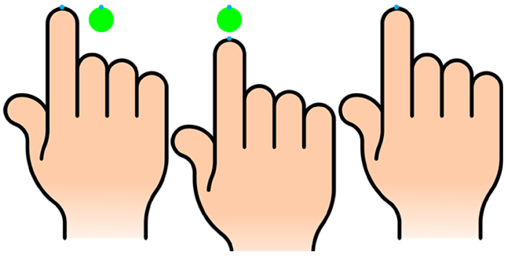

Fig. 7. Definition of reference points of both the fingertip and the targets. Left: longitudinal alignment; middle: lateral alignment; right: perfect alignment.

Participants were explicitly instructed not to look at the setup directly, and no participant actually did. Participants were also instructed not to touch any of the obstacles and were informed that they would receive a penalty if they did. In reality, no penalties were given; the instruction was given to ensure participants would perform the task as precisely as possible without "feeling" their way to the target and (recklessly) bumping into the obstacles – and possibly even damaging the setup. This approach proved successful, as no participant bumped into any of the obstacles, apart from one occasion where a participant slightly brushed against one. When the participants were satisfied with their position, they verbally indicated this, after which the position was registered by the experiment leader using the GUI. After a successful registration, the target on-screen colored blue. This is also an indication for the participant to move back to the base, and touch it from the front again, awaiting the next trial. The score – the distance between reach and the intended target's position – is shown to the participant, together with their current average score for the condition. Then, the next target is presented to them. This was repeated until the condition was complete. After completion, their total and average score for that condition is shown, and the participants fill out the 20-statement questionnaire shown on-screen.

### D. Experiment design

The experiment consists of multiple conditions. Each condition starts with a short training of three sets, in which the participants get increasingly less visual aid. This training phase is meant to get accustomed to the specific condition before the actual measurements start. In the first set of training, the participant can see their registered position relative to the intended target's position after a trial. On top of this, the participant first touches the L or R obstacle before moving to the target. In the second set of training, no touching is allowed, but the relative position of the reach is again shown after the trial. In both of these training sets, the score of each trial is also displayed after the trial. The third set of training is equal to the actual measurements; there is no visual or tactile aid, only the score after the trial.

The first condition is the Dedicated Training condition (or DT), in which participants can get accustomed to the system and the task, and train in order to reduce the impact of a possible training effect. Participants see the master setup and their own hand on-screen. In combination with moving their hand, this should induce the Projected Hand Illusion. This condition consists of 9 measurement sets on top of the 3 training sets.

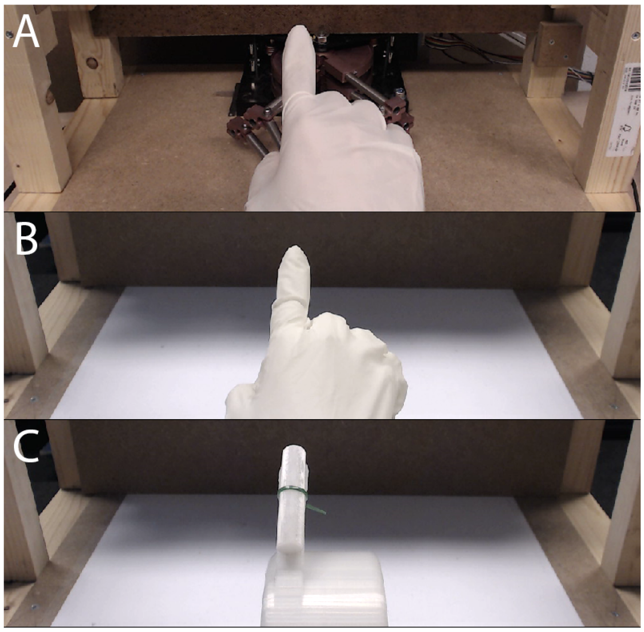


Fig. 8. Screenshots (cropped) showing what participants saw on the monitor during the experiment for the different conditions. A: DT condition, DC condition and CT condition (own hand, master side); B: PHI condition (fake hand, slave side); C: nPHI condition (fake finger, slave side).

After this, the participants are presented with the three actual measurement conditions in a randomized order: Direct Control (DC), Project Hand Illusion (PHI) or the no-Projected Hand Illusion (nPHI) conditions. Each of these conditions consists of 6 measurement sets, next to the 3 training sets mentioned before. In the DC condition, participants see their own hand moving on the screen, which should induce the Projected Hand Illusion. In the PHI and nPHI condition, the camera of the slave setup is active and provides the video-feed. In the PHI condition, participants thus see the attachment with the realistic looking 3D hand. In this condition, participants are expected to experience the Projected Hand Illusion (hence the name of the condition), as the fake hand looks similar to their own hand. In the nPHI condition, participants are expected not to experience the Projected Hand Illusion (again, hence the naming); they see the attachment with the non-realistic fake finger.

Lastly, the Control condition (CT) consists of 3 measurement sets and 3 training sets. It is designed to evaluate the impact of the learning effect on the measurement conditions post-experiment, by comparing the performance during this condition with that of the DT condition. Again, participants see their own hand on-screen, which should induce the Projected Hand Illusion.

Fig. 8 depicts what the participants saw on the monitor during the different conditions.

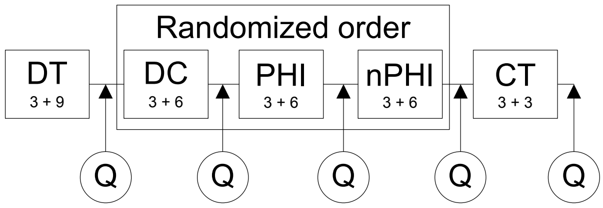


Fig. 9. Schematic overview of the order of conditions. The numbers below the abbreviated condition names indicate the training and measurement sets, respectively. The Q's represent the moments of filling out the questionnaire.

See Fig. 9 for a schematic overview of the order of the conditions, including the number of training sets and measurement sets (as indicated by the respective numbers below the abbreviated condition names) and the moment at which questionnaires were filled out (indicated by a circled Q).

### *E. Performance metrics*

To evaluate the performance of the participants, several metrics are used. The position in x- and y-direction of both the master and slave manipulator is recorded continuously at 1 kHZ and a resolution of 0.03 [mm] [49]. Furthermore, upon registering the location of the reach, the position at that time is explicitly recorded as well.

Task completion time is recorded from the start of the trial until the successful registration of the position, with a precision of 1 [ms].

Lastly, the subjective experience of the Body Illusion is assessed using a 20-statement questionnaire, adapted from Graham et al. [16] which is based on previous research [26]. The questionnaire uses a 7-point Likert scale, ranging from -3 ("strongly disagree") to 0 ("neutral") to +3 ("strongly agree"). Participants rated each statement according to the extent to which they agreed with the statement.

### *F. Data analysis*

The task completion time collected during the experiment needs to be corrected, to account for a slow start and a delayed registration of the reach.

As participants do not have a infinitely small reaction time, the starting time is corrected by looking at a position threshold. When the participant's position moves more than 5 [mm] from its initial position, the corrected time starts.

Similarly, the end time needs to be corrected too. As the position of the reach is registered by the experiment leader using the GUI after the participant gives a verbal indication, the timer is always stopped late. On top of this, the PC running the data acquisition and GUI occasionally shows lag and short freezes, also during registration of the reach. Therefore, the lag of the end time registration is inconsistent. This is corrected for after the experiment, by using thresholds for both position and speed. The thresholds are 0.25 [mm] away from the registered position, and a maximum absolute speed of 0.25 [mm/s]. The first time both position and speed adhere to these thresholds, is the corrected end time.

The analysis of the questionnaire was simplified to just one statement, as the question proved to be much more complex than initially thought. The statement chosen is commonly used and positively judged in past research [7], [12], [16] and was therefore deemed the most appropriate statement for assessing the induction of the Body Illusion. The analysis of the complete questionnaire is left to follow-up research.

Participants are grouped based on their response to this statement for conditions PHI and nPHI. If the score in the PHI condition is neutral or positive, and the score in the nPHI condition is lower than the score in the PHI condition, the participant is grouped in the Qualifying group (Q-group). In any other case, the participant is grouped in the non-Qualifying group (nQ-group).

A one-way analysis of variance is calculated over the complete data per group, over all three conditions for each metric and each target separately. A p-value $< 0.05$ is considered significant ($\alpha = 0.05$). If the result of the ANOVA indicates a significant difference (i.e. if $p < 0.05$), a post-hoc paired t-test is performed over conditions PHI and nPHI, as these conditions are of the most concern to this study. Again, a p-value $< 0.05$ is considered significant ($\alpha = 0.05$).

## III. Results

Using the method explained in Section II, participants are grouped in two groups; the qualifying group (Q-group) and the non-qualifying group (nQ-group). That is, participants that experienced the Projected Hand Illusion in the PHI condition (indicated by a response of 0 or higher to statement 4 of the questionnaire) and rated their experience of the Body Illusion lower in the nPHI condition, are deemed qualified and are thus grouped in the Q-group. All other participants are grouped in the nQ-group.

This resulted in 5 participants being grouped in the Q-group, while the other 11 participants are grouped in the nQ-group.

See Table I for the participants' responses in conditions PHI and nPHI, and the group they are grouped in.

Table II shows how many participants judged statement 4 of the questionnaire to be 0 (neutral) or higher (positive) for each condition, including the conditions initially meant as inclusion criteria (indicated by the *-suffix).

TABLE II
BI's Induced per Condition

| Condition | n | % |
|---|---|---|
| RHI* | 12 | 75.00 |
| PHI* | 13 | 81.25 |
| DT | 13 | 81.25 |
| DC | 13 | 81.25 |
| PHI | 12 | 75.00 |
| nPHI | 13 | 81.25 |
| CT | 13 | 81.25 |

*: inclusion criteria

TABLE I
QUESTIONNAIRE RESPONSES AND PARTICIPANT GROUPING

| Participant | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| PHI | 3 | -1 | -2 | 3 | -2 | -2 | 1 | 0 | 0 | 1 | 3 | 2 | 0 | 0 | 1 | 2 |
| nPHI | 3 | 2 | 2 | 2 | -1 | -3 | 1 | 1 | 1 | 1 | 2 | 1 | -1 | 0 | 2 | 0 |
| Group | nQ | nQ | nQ | Q | nQ | nQ | nQ | nQ | nQ | nQ | Q | Q | Q | nQ | nQ | Q |

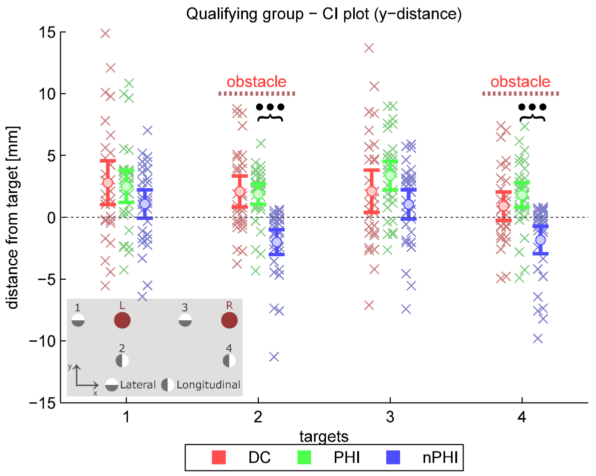


Fig. 10. Distance in y-direction between reach and intended target, for the Q-group (n=5). Each cross represents the result of one trial, while the circles show the mean of all trials and the error bars indicate the 95% confidence intervals. Significance is denoted by "•", "••" and "• • •", representing $p \leq 0.05$, $p \leq 0.01$ and $p \leq 0.001$, respectively.

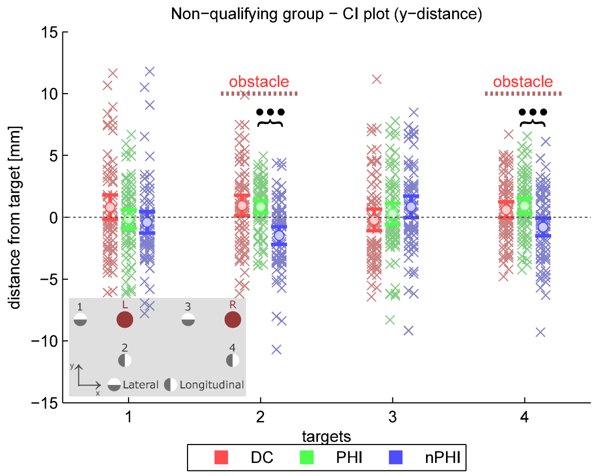


Fig. 11. Distance in y-direction between reach and intended target, for the nQ-group (n=11). Each cross represents the result of one trial, while the circles show the mean of all trials and the error bars indicate the 95% confidence intervals. Significance is denoted by "•", "••" and "• • •", representing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

Fig. 10 shows the deviation between the position of reach 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 (15) 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 ($F(2, 84) = 19.36$, $p < 0.001$) and target 4 ($F(2, 84) = 11.61$, $p < 0.001$). Subsequently, dependent t-tests were performed over conditions PHI and nPHI for target 2 and target 4.

This resulted in finding the following significant differences between conditions PHI and nPHI for the Q-group:

- **Target 2:** $\mathrm{M_{PHI}} = 1.91$ [mm], $\mathrm{SE_{PHI}} = 1.04$ [mm], $\mathrm{M_{nPHI}} = -2.10$ [mm], $\mathrm{SE_{nPHI}} = 1.25$ [mm], $t(28) = 5.47$, $p < 0.001$
- **Target 4:** $\mathrm{M_{PHI}} = 1.82$ [mm], $\mathrm{SE_{PHI}} = 1.27$ [mm], $\mathrm{M_{nPHI}} = -1.89$ [mm], $\mathrm{SE_{nPHI}} = 1.41$ [mm], $t(28) = 4.33$, $p < 0.001$

Similarly, Fig. 11 depicts the deviation between the position of reach and intended target in y-direction (longitudinal direction from the participant's point of view), 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.

An ANOVA over all three conditions for each target separately (again, a Bonferroni correction was applied, such that $\alpha = 0.0125$) 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 were again performed to assess whether the data of conditions PHI and nPHI show significant differences.

The results for the nQ-group are as follows:

- **Target 2:** $\mathrm{M_{PHI}} = 0.85$ [mm], $\mathrm{SE_{PHI}} = 0.62$ [mm], $\mathrm{M_{nPHI}} = -1.48$ [mm], $\mathrm{SE_{nPHI}} = 0.89$ [mm], $t(65) = 6.75$, $p < 0.001$
- **Target 4:** $\mathrm{M_{PHI}} = 0.93$ [mm], $\mathrm{SE_{PHI}} = 0.76$ [mm], $\mathrm{M_{nPHI}} = -0.79$ [mm], $\mathrm{SE_{nPHI}} = 0.89$ [mm], $t(65) = 4.63$, $p < 0.001$

The data of the other metrics (absolute distance, distance in x-direction and time) were subjected to the same analysis: first performing an ANOVA over the three conditions for each target (alpha level corrected to 0.0125 after applying Bonfer-

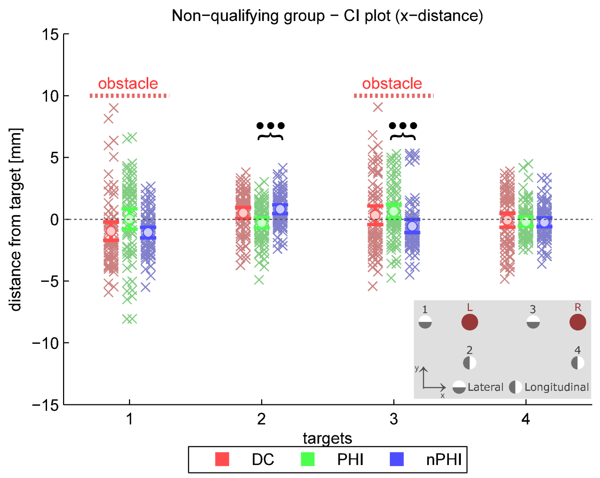


Fig. 12. Distance in x-direction between reach and intended target, for the nQ-group (n=11). Each cross represents the result of one trial, while the circles show the mean of all trials and the error bars indicate the 95% confidence intervals. Significance is denoted by "•", "••" and "• • •", representing $p \leq 0.05$, $p \leq 0.01$ and $p \leq 0.001$, respectively.

roni correction) assess whether a post-hoc test is needed, and subsequently performing a dependent t-test over conditions PHI and nPHI when needed. This resulted in the following significant findings.

Distance in x-direction, nQ-group:

- **Target 2:** $F(2, 195) = 7.72, p < 0.001$
- **Target 2:** $M_{PHI} = -0.29$ [mm], $SE_{PHI} = 0.51$ [mm], $M_{nPHI} = 0.82$ [mm], $SE_{nPHI} = 0.45$ [mm], $t(65) = -4.91$, $p < 0.001$
- **Target 3:** $F(2, 195) = 3.79, p < 0.05$
- **Target 3:** $M_{PHI} = 0.64$ [mm], $SE_{PHI} = 0.70$ [mm], $M_{nPHI} = -0.56$ [mm], $SE_{nPHI} = 0.66$ [mm], $t(65) = 4.37$, $p < 0.001$

Thus, the nQ-group shows a significant difference between the position of reach and intended target in x-direction (lateral direction from the participant's point of view) for longitudinal target 2 and lateral target 3. These results are also shown in Fig. 12. The positive direction is defined as being directed to the right from the participant's point of view.

The Q-group however, does not show any difference in distance between reach and target in x-direction for any of the targets.

The presented results indicate that there is indeed a difference between conditions PHI and nPHI measured by distance between position of reach and position of intended target, in y-direction (in both groups of participants for longitudinal targets 2 and 4) and in x-direction (in the nQ-group for longitudinal target 2 and lateral target 3).

## IV. Discussion

Discussing the meaning of the performance-related results would make no sense if it is not clear what may have influenced the results in the first place. Thus, the possible explanations for the results need to be identified first, together with the most likely explanation.

Therefore, first the results of the questionnaire are discussed. With the information from the questionnaire responses in mind, the most likely explanation for the found differences in performance (distance in y-direction and x-direction) between conditions PHI and nPHI can be discussed. Although the most likely, this explanation is not necessarily true. So, next all other possible explanations are presented and shortly discussed as well. After this, the performance-related results can be interpreted with due diligence. This is followed by some recommendations regarding the current study, and ideas for future work. Finally, this discussion is concluded with a short summary.

### A. *Questionnaire*

Looking at the results of the questionnaire, it is quite notable that only 5 participants are grouped in the Q-group. However, it is even more striking that all participants in the Q-group, except for one (participant 16), 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.

Even more so, looking at Table I it becomes obvious that 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 participants experienced the BI only in the nPHI condition (the opposite of what was designed to happen).

From Table II it can be seen that in all conditions, about 80% of participants is found to experience a Body Illusion, which is in accordance with literature [7], [52]. This suggests that statement 4 is capable of assessing the presence of the BI.

### B. *Most likely explanation*

It is remarkable to note that in *all* conditions about 80% of participants experienced a Body Illusion; even in the nPHI condition. On top of this, the BI is even slightly more prevalent in the nPHI condition than in the PHI condition: 81% versus 75%, respectively.

Combined with the fact that 13 out of 16 participants (81%) did not report an actual difference in presence of the BI between conditions PHI and nPHI, this suggests that there is no notable difference between the conditions in the ability to induce the Projected Hand Illusion; the physical setups of the two conditions are most likely too similar.

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 Fig. 8 for a visual comparison of the conditions as seen by the participants, and Fig. 5 for a side-by-side comparison of the attachments used in the two conditions.

If this is indeed the case, the independent variable (i.e. the presence of the BI) was not varied between conditions PHI and nPHI.

This also explains why there is no difference in performance between the Q-group and the nQ-group; the Body Illusion was equally prevalent in both conditions, so there are no differences between conditions or the groups based on the presence of the BI – the only differences between the conditions are in the physical setups used.

Therefore, the results suggest that the differences in performance are caused by differences in hardware, rather than by the experience of the BI.

### C. *Possible explanations*

The discussed most likely explanation that not the presence of a BI, but rather the differences in hardware used in conditions PHI and nPHI cause the differences found, is not necessarily true.

Combined with the experimental nature of this research, it is essential to identify all other possible explanations. Basically, there are two possible scenarios:

1. The Body Illusion does not influence teleoperation
2. The Body Illusion does influence teleoperation

For both scenarios, a specific question can be asked. In case of scenario 1, the question would be: what caused the found differences if the Body Illusion has no influence on teleoperation? For scenario 2, the question would rather be: why was no correlation found between the found differences and the experience of the Body Illusion?

There can be several explanations for either scenario. These are summed up per scenario below:

1. The Body Illusion does not influence teleoperation:
   1.1. Other factors caused the found differences
2. The Body Illusion does influence teleoperation:
   2.1. Assessment and/or grouping method are incorrect
   2.2. Inducing the Body Illusion did not succeed as expected*
   2.3. The Body Illusion influences an unmeasured metric*

*: implies that other factors caused the found differences

The mentioned explanations can in turn be caused by different underlying factors. These are all schematically depicted in Fig. 13 and will each be elaborated below.

### D. *Scenario 1*

*The Body Illusion does not influence teleoperation.*

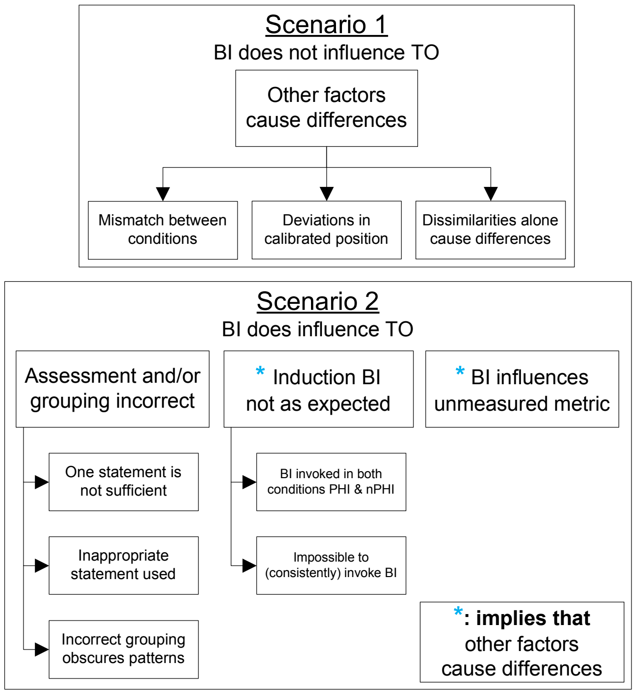


Fig. 13. Diagrams depicting the two possible scenarios, their corresponding explanations and the potential contributing factors.

If this scenario is true, then none of the found differences can be attributed to the experience of a Body Illusion. Instead, these deviations are caused solely by other factors. Possible influences are worked out in more detail below.

*1) Mismatch between conditions causes bias:* A mismatch between the setups of the two conditions could induce a bias in spatial estimations.

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. Even though great care was taken to make sure the end-position of the fingertip is equal in both conditions, it is not completely excluded that there are differences.

Also, as the attachments of conditions PHI and nPHI show quite some geometrical differences, visual references provided by the attachments are different. This difference can easily influence the estimations of the participants as well. On top of this, 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.

Furthermore, as the human hand and the used attachments are asymmetrical, the left and right side of the hand or attachment provide different visual cues in the x-direction.

On top of this, target 3 is closer to the center of the setup than target 1 (see Fig. 6). Therefore, the position of target 3 may be easier to estimate as it is viewed at a smaller angle than target 1. Because of this, the visual reference of targets 1 and 3 are different, and can thus influence spatial estimations.

Another cause could be the glove that the participants wear and is wrapped around the PHI-attachment, but not around the nPHI-attachment. The glove did not fit the fake hand tightly around the tip of the index finger in order to create a “buffer” to try and account for differently-sized index fingers. However, the glove creates a “softer” (loosely determined) visual reference, whereas the finger-like boom has a sharp, hard (strictly determined) edge to use as visual reference. On top of this, the slacking part of the glove can slightly change shape and size during the experiment due to pressing against the base obstacle before each trial.

Finally, if the obstacle plate has been mounted slightly skewed, this could influence the results. Even though great care was taken to prevent this kind of error (for example by careful calibration per subject before each condition), a skewed obstacle plate could certainly be a cause, as it also influences visual references.

To reduce the impact of the mentioned problems caused by the hardware of the setups, the experiment included a training before each condition’s measurements by design. Participants are expected to get accustomed to, and compensate for, minor differences in the setups during this training phase. The results from pilot experiments and from comparing the Dedicated Training (DT) and Control (CT) conditions, showed a solid decline in learning effect. However, it is stil possible that the training was not long enough to completely compensate for this bias.

*2) Deviations in calibrated position:* During the experiment, it was noticed that the participant’s finger would occasionally slide down the slope slightly, affecting the position of the fingertip in the y-direction. Although the participants were explicitly instructed to take special care in avoiding this, it actually happened to the majority of participants. As there was no good way of detecting and correcting this deviation – or better yet, counteracting it – this could have easily and significantly affected the measurements.

Also, it might be possible that participants were less likely to slide back when they could focus on a realistically looking hand, than they would when viewing the finger-like boom. This could thus cause a difference between the two conditions.

Furthermore, the variation in finger length across the participants may have influenced the measurements. Calibration was performed before the start of each condition to account for this, but it is possible that somewhere in the calibration process, a bias is present towards one of the conditions.

*3) Dissimilarities between attachments alone cause different behavior:* Despite having different hand sizes, most of the participants reported not recognizing when the fake hand was displayed or when their own hand was displayed. (See Fig. 8 for a visual comparison between the three conditions.) It is therefore possible that the visual similarities between the fake hand (PHI condition) and the own hand (DC condition) alone cause participants to behave quite similarly in both conditions (as can be seen from Fig. 10 and Fig. 11 in particular).

Conversely, participants could have behaved differently solely due to the dissimilarities between the finger-like boom (nPHI condition) and the own/fake hand.

One could also argue that this is caused by the Body Illusion. However, previous research found that proprioceptive drift can occur by just looking at a realistic hand next to one’s own, unseen hand, without necessarily inducing a Body Illusion [33]. Something similar might apply here: not a Body Illusion, but proprioceptive drift may cause changes to the participant’s behavior. Or perhaps another, similar mechanism which is not necessarily tied to a BI.

For instance, it could be due to an effect known as the “body size effect”, introduced by Van der Hoort et al. [47]. This effect dictates that the size of the body sensed as one’s own body affects the sense of scale and thus also the sense of distance; the bigger the perceived body, the smaller the sizes and distances estimated. The finger-like boom used in the nPHI-setup is slightly thicker than the finger of the fake hand used in the PHI-setup. Therefore, in condition nPHI the body size effect could cause participants to underestimate the distance between the perceived fingertip and the obstacle. This may have resulted in more “cautious” movements, and a bias in the negative y-direction. Thus, participants would keep more distance to the obstacle in the nPHI condition than in the PHI condition. Although it certainly is no proof for this theory, the predicted bias in positive and negative y-direction (for the PHI and nPHI condition respectively) corresponds with the found results, as is visible from both Fig. 10 and Fig. 11.

### *E. Scenario 2*

*The Body Illusion does influence teleoperation.*

If this is true, the found differences can either be dependent solely on the presence of the Body Illusion, solely on other factors, or on a combination of both. These different possibilities, together with their potential causes, are elaborated in the following.

*1) Assessment and/or grouping method are not correct:* If the assessment and/or grouping method are not correct, it would be impossible to reliably assess the successful induction of the Body Illusion, or it could obscure patterns otherwise visible, respectively.

Although the results suggest that the assessment method is capable of successfully assessing the BI (see Section III), it is not certain. There are two reasons why the assessment method might not be correct.

a) One statement may provide too little information and certainty about the induction of a Body Illusion. Even though the statement is almost identical to a commonly used statement in literature (for example, [7], [23], [12], [16]) which was consistently positively responded to by people experiencing a Body Illusion, using just this single statement to assess the presence of the Body Illusion has not been validated.

b) The statement might be inappropriate for the specific setup used in the current research. It has been used in previous research into the Projected Hand Illusion [16] successfully during a passive experiment, in which the participant's hand was brushed with a paintbrush. However, the current research utilizes an active experiment in which participants actively move their right lower arm to induce the Projected Hand Illusion, for which no validation was found in literature.

Also, the method of grouping participants may be incorrect, which can be caused by an incorrect assessment method or wrong grouping criteria. Incorrect grouping can conceal possible effects or patterns in the data which could otherwise become clear.

However, different ways of grouping were tried out during analysis, which all resulted in approximately the same findings as currently presented.

*2) Inducing the Body Illusion did not succeed as expected:* Even though the results from the questionnaire show that the induction of the Body Illusion was successful, it is still possible that the assessment method used is incorrect (see text above). Therefore, it may still be possible that the BI did not succeed as expected – or succeed at all – and thus its influence cannot be (properly) assessed. Two possibilities are identified and discussed below.

As mentioned earlier, it is possible that the BI was successfully invoked in both the PHI and nPHI conditions. If this is the case, it is impossible to assess the influence of the BI as both conditions are influenced.

It could also be impossible to consistently invoke a PHI using the current setup, if at all. It has been shown that a Body Illusion can be induced by active movement in a virtual environment [35] and in a real environment, either through physical coupling of real and fake hand [12], or using a master-slave system [18], [3]. Furthermore, the Projected Hand Illusion can be induced in a real environment through a camera-monitor setup passively, by brushing the participant's hand with a paintbrush [16] or by moving one's finger, or actively by letting the particpant move their finger [45]. However – to the best of the author's knowledge – it has not been proven yet that the Projected Hand Illusion can be actively invoked in a real environment by moving *the lower arm* (where generally movement of the hand and fingers is reported in literature to induce a RHI or PHI), seen through a camera-monitor setup.

Furthermore, there are limitations to the setup used, such as the lag of the camera-monitor setup (which was more than 50-100 [ms], commonly reported in literature as the maximum allowable amount of lag which allows for a proper feeling of presence and a proper induction of a BI; e.g., [28] and [3], respectively) and the lack of a first-person perspective due to the unnatural viewpoint on the monitor [13], which can inhibit the successful induction of the Projected Hand Illusion.

If it is indeed true that the BI was either invoked in both conditions, or in none, the measurements must have been influenced by other factors (described in Section IV-D above).

*3) Body Illusion influences an unmeasured metric:* If the current findings are the result of other factors alone, but a Body Illusion does influence teleoperation, it is possible that the influences of the BI is not measured.

For example, task load could be influenced by the experience of a Body Illusion.

In this case, the currently found differences are solely caused by other factors, as is explained in more detail in a previous section.

### *F. Performance-related results*

Now that all possible explanations for the performance-related results are discussed, it is time to discuss the results themselves in more detail, and compare them to the prior expectations.

It was anticipated that when comparing conditions PHI and nPHI, differences in position between reach and target in the y-direction would be more likely to occur than in the x-direction, as perception of depth is more difficult than discriminating positions horizontally [6], [10].

Indeed, for longitudinal targets 2 and 4, the PHI and nPHI conditions were found to differ in the y-direction: the average difference in position between reach and target in y-direction is positive (away from the participant) in the PHI condition, while it is negative (towards the participant) in the nPHI condition.

However, PHI and nPHI also differ in the x-direction: comparing condition PHI and nPHI, the average difference in position between reach and target in x-direction is in opposite directions for both longitudinal target 2 and lateral target 3.

These findings will be discussed in more detail in the subsections below.

Furthermore, it was expected that participants would benefit more from a possible advantage due to a Body Illusion when reaching for the lateral targets; reaching for these targets is hard, since these targets have almost no visual reference to aid the participants in their task. This benefit was, however, not found. It is possible that the task in itself becomes so difficult without visual references that – even when using one's own hand – the deviations from the intended target's position and the spread of the results become significantly larger. A larger spread in results makes finding significant changes increasingly difficult.

*1) Distance in y-direction:* From Fig. 10 and Fig. 11 it is clear that there is a significant difference in distance between reach and target in the y-direction, for longitudinal targets 2 and 4. During the PHI condition (designed for subjects to experience the Projected Hand Illusion), the average position of the reaches is further away from the front of the setup, and thus closer to the obstacle, than during the nPHI condition (designed for subjects to *not* experience the Projected Hand Illusion).

There is no significant difference between the results of the PHI condition and those of the DC condition, while the results of the PHI condition and the nPHI condition do show a significant difference. This suggests that participants behave more as if seeing their own hand on the monitor during the PHI condition than during the nPHI condition.

Important to note is that compared to the PHI condition, in the nPHI condition the average deviation from the intended target's position is in the opposite direction: closer to the participant and thus further away from the obstacle. This suggests that participants proceed with more caution and maintain a larger "safety zone", and thus tend to stay further away from the obstacle.

As a final note, even though this difference in results is quite notable, it does not necessarily mean that the situation during the PHI condition is preferable over the situation during the nPHI condition. On the contrary, if safety during teleoperation is a critical factor, these results would suggest choosing the more "safe behavior" corresponding with the nPHI condition.

*2) Distance in x-direction:* From Fig. 12 it can be seen that there is a significant difference in the deviation in x-direction for longitudinal target 2 and lateral target 3 for the nQ-group. What is remarkable about this finding, is the fact that although targets 1 and 3 are designed to be equivalent to each other, and the pair of targets 2 and 4 as well, a significant difference is only found for target 2 (and not also target 4) and target 3 (and not also target 1). Apparently, the mentioned pairs of targets are not completely equivalent. There are several factors that may have contributed to this.

For example, the fact that target 3 is located closer to the center of the setup laterally than target 1, causes different visual references (and the view shows less angular distortion) which may make it easier to estimate the lateral position (x-direction). This explains why a significant difference is only found for target 3, and not also for target 1.

Similarly, target 2 and target 4 are possibly not equivalent due to two factors, both of which were discussed in more detail earlier.

First, it could be that the obstacle plate was mounted slightly skewed (in the horizontal plane), which could significantly influence the estimations in the x-direction.

Second, the attachments are non-symmetrical in the x-direction. Therefore, visual references differ between the left and right side of the attachments, and thus also between reaching for target 2 (left side of the setup) and target 4 (right side).

These factors could both influence the estimations in x-direction for target 2 in a different way than for target 4, explaining why a significant difference was found only for target 2.

The actual differences between conditions PHI and nPHI can be explained by physical differences between the setups of both conditions that influence the estimation of the participants and possibly also the measurement itself, as was discussed in a previous section.

Finally, it is notable that these differences in estimation in x-direction are only found in the nQ-group and not in the Q-group. It is possible that there are not enough participants in the Q-group to find the same significant differences as for the nQ-group (5 versus 11, respectively).

### *G. Recommendations*

From the above, it becomes clear that there are quite some factors that possibly influenced the experiment in unwanted ways; e.g., bias due to physical differences between setups and hardware used, the Body Illusion that was induced successfully in all conditions and a possibly incorrect assessment and/or grouping method. On top of these already discussed issues, there are other possible flaws in the experiment, like bias in the participants due to prior knowledge regarding either Body Illusions or the purpose of the study.

Furthermore, apart from improving upon these specific issues, there are some recommendations that can significantly benefit this and similar studies.

These recommendations will be discussed below.

First of all, to minimize bias caused by the hardware, special care should be taken to make sure that the end-point of each attachment is as equal as possible in each condition, further fortified by a methodical and more robust method of calibrating the position of the participant's finger and the attachment's end-point. Fixating the index finger to prevent longitudinal movements helps counteracting unwanted shifts during measurements. Moreover, using a specialized system to track the exact position of the participant's fingertip and the attachment's end-point would provide even more robustness to the setup. Next to this, increasing the size of the acrylic plate that holds the obstacles could take away most of the unwanted visual references. Furthermore, as the current setup was made from wood by hand, the measurements would also benefit from a more precisely-built setup (for instance, one made out of machine-cut aluminum bars).

Also, instead of trying to eliminate all sources of the physical setup that can create a bias, it is also possible to reduce the amount of bias by proper training prior to the measurements. As stated before, the training was added to let participants get accustomed to the setup and task, as well as for this specific reason. However, as the training may be too short to significantly reduce bias, increasing the length of the training could be beneficial.

Problems with the unwanted successful induction of the Body Illusion in the nPHI condition can be diminished by increasing the amount and level of visual differences between the PHI- and nPHI-setups.

One way to achieve this is by changing the nPHI-attachment to just the finger-like boom, without the mouse-like part, as it is possible that the mouse-like part looks too much like the back of a hand.

Next, the influence of a possibly incorrect assessment and/or grouping method can also be diminished in different ways.

For instance, employing a more objective (and preferably on-line) method to assess the successful induction of the BI. For instance, proprioceptive drift is commonly used in literature to assess the presence of a BI (e.g., [7], [38]). Even though there is proof that proprioceptive drift is not strictly related to the presence of a BI [33] – one of the reasons it was not employed in the current study – it might still prove effective and worthwhile in assessing the BI.

Of course, a complete and thorough analysis of the current questionnaire can also yield a more representative and reliable insight into the successful induction of the BI among the participants. This can shed a new light on the current results, possibly combined with a different way of grouping the participants (e.g., grouping participants based on specific components which the questionnaire can identify).

As mentioned above, there are other ways to potentially improve the (outcome of) the current study and its reliability, aimed at issues not mentioned in this discussion.

First, considering the fact that not everyone is susceptible to experiencing Body Illusions (about 80% of people is [7], a proper pre-selection of participants based on their ability to experience a Body Illusion could strongly affect the outcome of this study (or actually any BI-related experiment).

Similarly, ensuring that the Projected Hand Illusion can be induced in the PHI condition and cannot be induced in the nPHI setup would also have a beneficial effect on the outcome of this study.

Combining these recommendations may even be better: pre-selecting participants that are able to experience the PHI in the PHI condition, combined with not being able to feel the PHI in the nPHI condition.

Next, incorporating the ability to accurately track and display finger movements could enhance the potential to induce the Projected Hand Illusion.

Also, having more participants could have quite some influence on the findings, especially in the Q-group. With just 5 participants in this group, it is difficult to be certain about the found results and conclusions.

Participants might also be biased by knowing about (the working of) Body Illusions or understanding the purpose of the study. The briefing and instructions state that the purpose of the study is to investigate the possible effects of Body Illusion on teleoperation. Clearly, the participants could not know in what way the BI may influence teleoperation, but it is still possible that they are biased due to specific prior knowledge about the subject.

The recommendations mentioned above can all individually improve the current study. However, there are two recommendations to not only improve the current study in multiple ways, but that would also benefit similar studies and studies into Body Illusions in general.

*1) Execution of experiments in Virtual Reality:* Executing this experiment, and similar experiments, in a virtual environment has numerous advantages regarding the physical setup and all issues that may arise from differences in hardware and setups used.

For instance, the hand-shaped attachments can be adjusted to each specific participant, providing participants with visuals more closely matching their own physique. Next to the aesthetics, the variation in finger length between participants, and thus each individual end-position, can also be taken into account, making measurements more reliable.

Also, the view-point of the participants on the attachments or their own hand would be much closer to natural, as head-mounted displays enable three-dimensional video and viewpoints based on the position, orientation and movements of the head by employing head-tracking. This added level of visual fidelity enhances the feeling of presence [39], and should make it easier to induce the BI [13].

Furthermore, the finger-like boom used in the nPHI-setup could be experimented with more easily to make it more different to the PHI-attachment, and find a way to hinder inducing a BI in the nPHI condition.

On top of this, it is easier, faster and cheaper to set up different kinds of experiments, test setups and specific conditions (such as introducing delays in controls and/or visuals, or other kinds of visual degradation).

And, of course, after a promising experiment in virtual reality, the transfer to a real-world experiment could be considered for verification.

In short: a virtual environment to carry out this type of experiments offers more flexibility (regarding possibilities) and robustness (regarding the execution), whilst reducing time and costs.

*2) More fundamental research:* The field of research of Body Illusions is still rather young. Therefore, much is not yet clear or even unknown, preventing the development of a proper paradigm or framework on which to build experiments.

For example, more complete information about the different ways to induce Body Illusions, including their effectiveness and (objective) methods to assess their presence, or more clarity about constraints regarding the amount and nature of visual similarities or tolerated amount and type of incongruence could all greatly benefit future research.

Furthermore, there are various settings in which Body Illusions may be induced: directly in the physical world, or through the use of cameras and monitors, and even completely in virtual reality. Apart from information and constraints applicable to all three settings, each of these settings probably has specific properties and requires their own set of limitations to adhere to.

For instance, to the best of the author's knowledge it is not yet clear how many people are able to experience a BI in these settings, apart from in the physical world [7], [52].

Also, it is not clear how much one's viewpoint may deviate from a natural viewpoint when using a camera-monitor setup, or how much of one's body has to be visible on-screen or in the virtual reality to be able to induce a Body Illusion through e.g., visuomotor congruence.

Finally, there seems to be no consensus regarding the exact building blocks or components of a Body Illusion, how the presence (and possibly strength) of a Body Illusion can be best measured or even the correct terminology to use when discussing the topic. This all hampers (practical) research and the sharing of knowledge.

Therefore, more fundamental research is strongly recommended to advance developments in the field of practical applications of Body Illusions.

### *H. Summary*

To summarize this discussion, it is difficult to interpret the results due to the experimental nature of the current research; there are numerous factors that may have influenced the results. Nonetheless, the results do suggest that the used assessment method is capable of assessing the presence of the Body Illusion. Furthermore, according to this assessment method, it is possible to induce the Projected Hand Illusion during teleoperation. However, the presented results also show that the Projected Hand Illusion was successfully induced in both the PHI *and* the nPHI condition – the latter of which was unwanted. In other words, the independent variable was actually not successfully varied between conditions. Thus, the presence of the Body Illusion cannot explain the found differences between the two conditions. Therefore, the differences must have been caused by other factors, most likely by differences in the hardware of the setups.

## V. CONCLUSIONS

This research investigated the influence of applying Body Illusions on the performance during teleoperation by presenting participants a reaching task under three different conditions: the Direct Control (DC), the Projected Hand Illusion (PHI) and the no-Projected Hand Illusion (nPHI) conditions. The PHI condition was designed to induce the Projected Hand Illusion, while the nPHI was designed not to. The participants were grouped in two different groups, based on their responses to a single statement regarding conditions PHI and nPHI; the qualifying group (n=5) and the non-qualifying group (n=11). Performance during each trial was measured by distance between the position of the reach and the intended target's position (absolute distance as well as both x- and y-direction separately) and time-to-completion.

The following was found from the results:

- Body Illusions were successfully induced in both conditions PHI (75%, 12 participants) and nPHI (81%, 12 participants), as well as all other conditions (75%-81%)
- There are differences in performance (deviation from target in both y-direction and x-direction) between conditions PHI and nPHI, namely:
  - **Longitudinal targets 2 and 4**
    y: +1.5mm and -2mm, respectively PHI and nPHI
  - **Longitudinal target 2**
    x: -0.5mm and +0.5mm, respectively PHI and nPHI
  - **Lateral target 3**
    x: +0.5mm and -0.5mm, respectively PHI and nPHI

This suggests that, in the y-direction, there was an increased perception of risk in the nPHI condition. The results in the x-direction suggest a difference in visual perception between both longitudinal targets and both lateral targets.

Possible explanations for the presented results therefore are a difference in visual perception between the two conditions or the influence of the Body Illusion (BI).

However, the Body Illusion was found to be successfully induced in both conditions. Therefore, according to the metric used to assess the presence of the Body Illusion, the BI cannot have caused the found differences.

It is however also possible that the used assessment method is incorrect. In that case, the presence of the BI could be (one of) the cause(s) for the results.

This research is – to the best of the author's knowledge – the first to explore the practical application of Body Illusions during teleoperation, and to find evidence that it is indeed possible to induce a Body Illusion during teleoperation. However, as the induction proved successful in both measurement conditions, no conclusions can be drawn regarding the effect of a Body Illusion on teleoperation.

The presented results yield an interesting finding: successful induction of a Body Illusion is possible during teleoperation. Therefore, this exploratory study gives rise to further research in this field and serves as a starting point for future studies.

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# Appendix A

# Experiment Documents

This appendix contains the documents created for the experiment to inform participants and receive their written informed consent, and the questionnaires used to assess the Body Illusion during the experiment.

## A-1 Task Instructions

The *Task Instructions*-document informs participants about the complete procedure of the experiment. This includes the (general) objective of the experiment, the description of the Rubber Hand Illusion and Project Hand Illusion experiments (initially meant as inclusion criteria), information about the experiment setup, the actual task description and general notes regarding safety amongst others.

The original document is inserted into the report, starting from the next page.

## Teleoperation performance with and without Projected Hand Illusion
### Task instructions

Welcome to this experiment! Thank you for participating. Please read the following instructions carefully before the experiment.

**Objective**
The aim of this experiment is researching to what extent the Project Hand Illusion can be used to benefit telemanipulation.

**Notes prior to the experiment**
Before the actual experiment starts, the experiment leader will check whether you are suited during two short experiments, which are both assessed by a questionnaire. This will take about 15 minutes.

**First short experiment**
In the first short experiment, you are seated at a table, with a wooden screen in front of you. You are asked to put on a nitrile glove on your right hand, and place it on the right side of the screen so that you can't see it. In front of you, on the left side of the screen, there is a fake hand. The experiment leader will put a cloth over your shoulder and the fake hand. After everything is set up, the experiment leader will use a paintbrush to stroke your hand and fingers, together with the fake hand and fingers. Your task is to focus solely on the sensation of the stroking on your hand and on the seen stroking on the fake hand. The experiment will take about 10 minutes. After this, you are asked to fill out a questionnaire.

Important to note:

- Make sure you are seated in a comfortable way
- Make sure that you cannot see your right hand or arm in any way
- Keep your right hand and arm as still as possible (you can move your left arm and hand)
- Focus only on the seen stroking on the fake hand and the felt stroking on your real hand
- If you notice a mismatch between the stroking (either spatially and/or temporally), please let the experiment leader know
- During the experiment, the experiment leader will ask you some questions about the experiment; also, feel free to share whatever you are experiencing

**Second short experiment**
The second experiment is equal to the preparatory phase of a condition of the actual experiment, which will take about 5 minutes. After this, you are again asked to fill out a questionnaire. For the instructions on this preparatory phase (and the rest of the experiment), please continue reading.

## Experiment setup and procedure

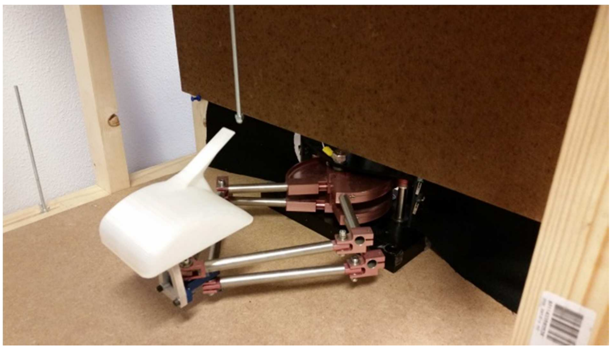

**Figure 1 - The Munin teleoperation system (master-side; actual machine is covered by the backplate)**

In this experiment, your task is to move your finger to the position of a target as accurately as possible. Based on your distance to the target, you are given a score in millimeters. Your goal during the experiment is thus to **minimize** this score!

During the experiment you hold a mouse-like actuator with your right hand, with your index finger resting on the elevated support (see Figure 1). There is an emergency button on the left of the setup, which you can use to shut down the machine in case something goes wrong. A small curtain is mounted across the setup, above the mouse; slip your hand underneath it when you grab the mouse. Three physical obstacles are mounted in front of the mouse. The front obstacle is called the base, the two obstacles in the back are simply referred to as left (or L) and right (R). The (virtual) targets are positioned around these two obstacles. For more detailed information, see *Detailed task description* below. Due to noises which may distract you, you are asked to wear a pair of headphones, playing brown noise.

On the screen in front of you, you will see a live video-feed of either your hand or the teleoperated manipulator together with an information panel and a schematic view of the left and right obstacles and their surrounding targets. Basic instructions (such as the next target) and your score will be displayed on screen. See Figure 2.

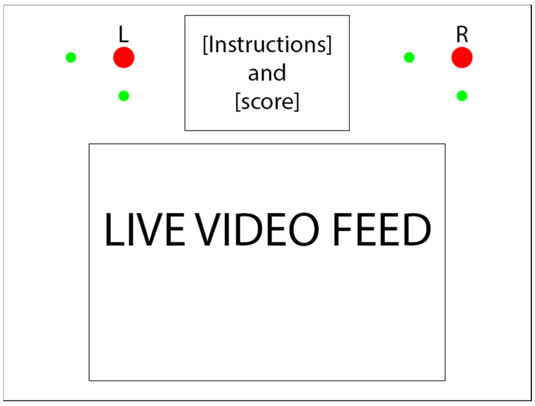


**Figure 2 - Schematic view of display**

Important to note:

- You are **not** allowed to see the setup or your own hand directly, so do not look over, under, or past the curtain in any way. If you do, it will disqualify your input to the experiment, rendering your and my time and effort **useless**
- Make sure you are seated directly in front of the screen and that you sit **comfortably**, as it is important that you remain seated this way to keep the same viewpoint
- Make sure your hand goes underneath the curtain
- Just before measuring, the Munin has to calibrate. During this, you are requested to **take your hands off the Munin** (this will also be displayed on the screen)

The experiment consists of one test condition, three measurement conditions and one (shorter) control condition. Each condition starts with three training sets, followed by a number of measurement sets (3, 6 or 9 sets, depending on the condition). More information about this can be found in the *Detailed task description* below. All conditions are followed by questionnaires. Each condition will take about 15-20 minutes. The complete experiment will take about **90 minutes** to complete.

**Note:** If you would like to take a break, let the experiment leader know. Between blocks the experiment can be paused. Also, note that you can opt out of the experiment at any time before or during the experiment.

**Detailed procedure**

As mentioned earlier, the Munin calibrates itself before each condition. After this, you can grab the mouse (make sure your hand goes underneath the curtain). Next, the setup and software need to be calibrated as well. For this, you are asked to lightly touch the base obstacle from the front, while trying to keep your hand as straight as possible. The experiment leader will then calibrate the setup. After this, you are requested to move to the obstacles in the back, and touch those as well, while the experiment leader checks if everything is ok.

After calibration, you are asked to play with the setup and move around for a couple of minutes. This is to allow you to induce the Projected Hand Illusion on yourself before we start measuring. During this period, try moving around at a normal pace and try touching each of the obstacles every now and then. You can also try brushing against the obstacles. Try to focus only on what you feel on your hand and on what you see happening on-screen. (This is equal to the second short experiment mentioned before.)

After this, the condition starts.

As stated before, each condition starts with three training sets, followed by a number of measurement sets. In all cases, after a complete set your total and average score during that set will be displayed.

During the first set of training, you first **touch the obstacles** before moving to the target. After each trial, the registered position of your fingertip will be shown on the schematic top-view, together with your score (last and average score, in mm's) on the information panel.
During the second set, you are **not** allowed to touch the obstacles anymore, but instead, you need to move to the target directly. However, you will still get to see the registered position and your score after each trial.
In the third set you will **not** see the registered position after a trial anymore, but only your score. This phase is the same as the actual measurements.

After the training sets, the actual measurements begin.

**Detailed task description**

In Figure 3 the schematic top-view of the experiment lay-out is depicted. As mentioned earlier, there are three obstacles; one at the front (the base, displayed in blue) and two at the back (L and R, displayed in red). Two (virtual) targets (green) are defined around both targets. The distance between the targets and the obstacles are defined as depicted in Figure 4.

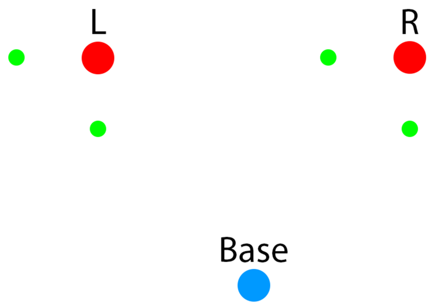


**Figure 3 - Experiment lay-out showing position of obstacles and targets (schematic top-view)**

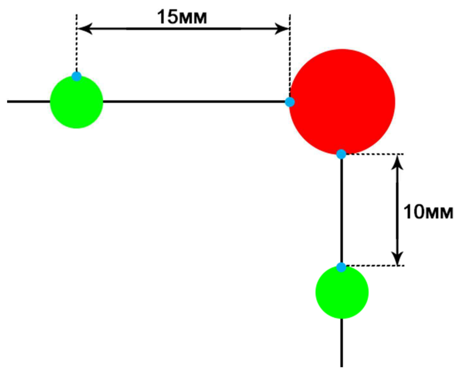


**Figure 4 - Position of targets around the obstacles (schematic top-view)**

Your task is to match the position of the targets as closely as possible with your fingertip, by aligning the center of your fingertip with the center of the furthest edge of the target. See Figure 5.

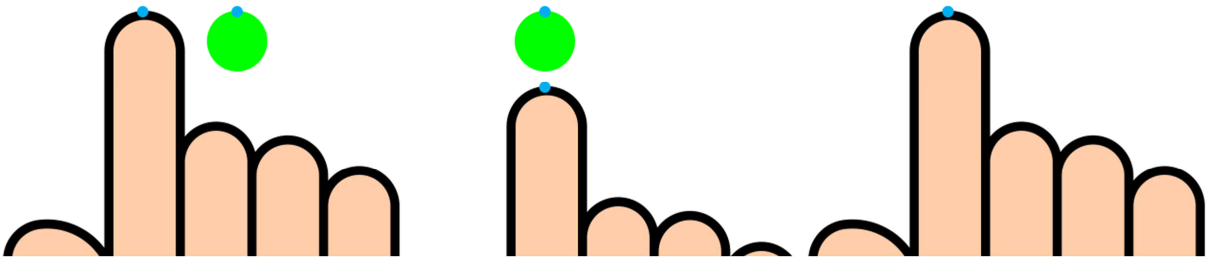

**Figure 5 – Alignment of the center of the fingertip with the center of the furthest edge of the target. The blue dots represent the reference points.**
**(Left: longitudinal alignment. Middle: lateral alignment. Right: both longitudinal and lateral alignment.)**

You start each trial at the base, with the tip of your finger pressing softly against the base obstacle from the front. You can rest your arm on the table at this point.

The next target will become **green**. When the target is presented to you, move your hand towards the target to position the center of your fingertip at the center of the furthest edge of the target as closely as possible (see Figure 5). Important to note is that you are **not** allowed to touch any obstacle other than the base (unless you're in the first phase of training). If you do, you will receive a fixed penalty of **+100mm** to your score! Also, remember that the task is about **accuracy**, not speed.

If you are satisfied with the position of your fingertip, keep your hand and finger still and say "ok", "yes", or something similar to notify the experiment leader. Shortly after, the target will become **blue** to indicate a successful registration of your position. Do **not** move until it does!

After the target turns blue, move back to the base and touch the front again, gently pushing against it. You can rest your arm on the table again. Your score and average score will be displayed in the information panel for a short while. After this, the following target will be presented and you continue in the same way until all sets are complete.

After all sets are complete, you are asked to fill out a questionnaire.

**Important notes**

- You may quit and opt out of the experiment at any time, before or during the experiment.
- During the experiment you are allowed to take a break between blocks – **not** between trials.
- If anything goes wrong (with the Munin) and you do not feel safe, you can press the **red emergency button**. This will deactivate the machine immediately. The experiment leader will also keep a close eye on you and the system at all times.
- During the experiment, keep your hand and finger on the mouse-attachment at all times and **try not to move** your hand or finger! Apart from possibly disrupting the (outcome of the) experiment, you can get your fingers stuck in the moving mechanisms of the Munin.
- If you are **allergic** to nitrile (material of the glove), let the experiment leader know!
- To prevent any unwanted audio cues, you are asked to wear a pair of headphones (playing brown noise).
- As the experiment will take a while, it is very important that you are sitting comfortably.
- Unless otherwise stated, do **not** touch the obstacles during the trials! If you do, you will receive a fixed penalty of **+100mm** to your score!
- Do **not** look at either of the setups directly! You are only allowed to look at the computer screen in front of you. Failure to comply with this restriction will **disqualify** your entry to the experiment!

If you agree to all of the above, you are asked to read and sign the informed consent form (right before the experiment).

If you have any questions, feel free to ask me before the experiment. However, I may choose not to answer specific questions before the end of the experiment if it may influence the experiment. Of course, if you want to take a break or have a question about how your data is stored or anything like that, I **will** answer you!

For questions after the experiment, please contact me through email (l.v.wajon@student.tudelft.nl).

Good luck and enjoy the experience!

## A-2 Informed Consent Form

Topic of research: Teleoperation performance with and without Projected Hand Illusion

I, the undersigned, confirm that I read and understood the written experiment instructions for the "Teleoperation performance with and without Projected Hand Illusion" experiment. I understand that, after successfully passing the first two experiments (approximately 15 minutes), my task is to execute a manual control task for approximately 75 minutes. If I do not pass the two tests, I will not continue with the experiment. I was able to ask questions, and I am satisfied with the answers to my questions about the experiment protocol.

I, the undersigned, am aware that my anonymized measured data (e.g. positions and forces of hand) and anonymized participant data (e.g. age, gender, handedness) can be seen by a select group of researchers and may be used for publication purposes of this study.

I, the undersigned, am aware that my participation in this study is voluntary and that I can stop with the experiment at any given time. If I feel any discomfort during the study I will inform the experiment leader about this. I am aware that I can ask questions anytime during this experiment and therefore I am always able to ask for breaks during the experiment.

I, the undersigned, declare to have read and understood the information about the project, the use of data and to consent in the experiment.

Name: ____________________

Location: ____________________

Date: ____________________

Signature: ____________________

## A-3 Questionnaire

The questionnaire used to assess the presence of the Projected Hand Illusion throughout the experiment is taken from Graham et al. (Graham, Martin-Iverson, Holmes, & Waters, 2014). It is based on the questionnaire by Longo et al. (Longo, Schüür, Kammers, Tsakiris, & Haggard, 2008), which is intended for the assessment of the Rubber Hand Illusion. The questionnaire consists of 20 statements, which are rated on a 7-point Likert scale, ranging from -3 (*strongly disagree*) to 0 (*neutral*) to +3 (*strongly agree*).

Two different versions of the questionnaire were used during the experiment. Since the questionnaire is specific to the Projected Hand Illusion, the statements were adjusted to refer to a “wooden hand” instead of “the image (of the hand)” in the assessment of the Rubber Hand Illusion (which in this experiment actually used a wooden hand).

Table A-1 contains the questionnaire for assessing the Rubber Hand Illusion. This questionnaire was used only in the RHI-condition.

The questionnaire used to assess the Projected Hand Illusion in all other conditions is presented in Table A-2.

**Table A-1:** Questionnaire used for assessing the RHI

| | **It seemed like...** | **-3** | **-2** | **-1** | **0** | **+1** | **+2** | **+3** |
|---|---|---|---|---|---|---|---|---|
| 1 | ...I was looking directly at my own hand, rather than at an wooden hand. | | | | | | | |
| 2 | ...the wooden hand began to resemble my real hand. | | | | | | | |
| 3 | ...the wooden hand belonged to me. | | | | | | | |
| 4 | ...the wooden hand was my hand. | | | | | | | |
| 5 | ...the wooden hand was part of my body. | | | | | | | |
| 6 | ...my hand was in the location where the wooden hand was. | | | | | | | |
| 7 | ...the wooden hand was in the location where my hand was. | | | | | | | |
| 8 | ...the touch I felt was caused by the paintbrush touching the wooden hand. | | | | | | | |
| 9 | ...I could have moved the wooden hand. | | | | | | | |
| 10 | ...I was in control of the wooden hand. | | | | | | | |
| 11 | ...I was unable to move my hand. | | | | | | | |
| 12 | ...I couldn't have moved my hand if I had wanted. | | | | | | | |
| 13 | ...I couldn't really tell where my hand was. | | | | | | | |
| 14 | ...my hand had disappeared. | | | | | | | |
| 15 | ...my hand was out of my control. | | | | | | | |
| 16 | ...my hand was moving towards the wooden hand. | | | | | | | |
| 17 | ...the wooden hand was moving towards my hand. | | | | | | | |
| 18 | I had the sensation of pins and needles in my hand. | | | | | | | |
| 19 | I had the sensation that my hand was numb. | | | | | | | |
| 20 | ...the experience of my hand was less vivid than normal. | | | | | | | |

**Table A-2:** Questionnaire Used for Assessing the PHI

| | **It seemed like...** | **-3** | **-2** | **-1** | **0** | **+1** | **+2** | **+3** |
|---|---|---|---|---|---|---|---|---|
| 1 | ...I was looking directly at my own hand, rather than at an image. | | | | | | | |
| 2 | ...the image began to resemble my real hand. | | | | | | | |
| 3 | ...the image of the hand belonged to me. | | | | | | | |
| 4 | ...the image was my hand. | | | | | | | |
| 5 | ...the image was part of my body. | | | | | | | |
| 6 | ...my hand was in the location where the image was. | | | | | | | |
| 7 | ...the image was in the location where my hand was. | | | | | | | |
| 8 | ...the touch I felt was caused by the obstacles and curtain touching the image. | | | | | | | |
| 9 | ...I could have moved the image of the hand. | | | | | | | |
| 10 | ...I was in control of the image. | | | | | | | |
| 11 | ...I was unable to move my hand. | | | | | | | |
| 12 | ...I couldn't have moved my hand if I had wanted. | | | | | | | |
| 13 | ...I couldn't really tell where my hand was. | | | | | | | |
| 14 | ...my hand had disappeared. | | | | | | | |
| 15 | ...my hand was out of my control. | | | | | | | |
| 16 | ...my hand was moving towards the image. | | | | | | | |
| 17 | ...the image was moving towards my hand. | | | | | | | |
| 18 | I had the sensation of pins and needles in my hand. | | | | | | | |
| 19 | I had the sensation that my hand was numb. | | | | | | | |
| 20 | ...the experience of my hand was less vivid than normal. | | | | | | | |

# Appendix B

# Results

As not all results are relevant or valuable enough to include in the paper, this appendix presents all of the results obtained during the experiment.

The appendix is divided into six sections. Section B-1 first presents the results of statement 4 of the questionnaire, which was used to assess the presence of the Body Illusion. Section B-2 presents all results of the absolute distance between reach and the intended target's position. The results of the two components of the absolute distance, being distance in the x-direction and distance in the y-direction, are presented separately in Sections B-3 and B-4, respectively. The results of the time-to-completion are presented in Section B-5. Finally, the superposed trajectories of the reaches of all participants are presented in Section B-6.

## B-1 Questionnaire results

Table B-1 shows the response to statement 4 of the questionnaire of each participant per condition. The groups participants are grouped in based on their response in conditions PHI and nPHI are also denoted.

Note that the first three participants were excluded from the experiment due to a change in setup after the third participant. Their data is therefore displayed in italics in the table.

**Table B-1:** Questionnaire Results per Condition and Resulting Grouping per Participant

| **Participant** | *1* | *2* | *3* | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **RHI*** | *1* | *1* | *3* | 2 | 1 | 3 | 3 | 1 | -2 | -3 | 1 | 1 | 0 | 1 | -2 | 2 | 2 | -3 | 0 |
| **PHI*** | *3* | *3* | *1* | 3 | -2 | 3 | 3 | -1 | 3 | -1 | 0 | 1 | 1 | 2 | 2 | 1 | 1 | 1 | 1 |
| **DT** | *3* | *3* | *1* | 3 | 2 | 2 | 3 | -1 | -1 | -1 | 0 | 0 | 1 | 2 | 1 | 0 | 1 | 1 | 1 |
| **DC** | *1* | *3* | *1* | 3 | 2 | 3 | 3 | 1 | 1 | -2 | 0 | 1 | 1 | -1 | -1 | 1 | 1 | 1 | 3 |
| **PHI** | *1* | *2* | *2* | 3 | -1 | -2 | 3 | -2 | -2 | 1 | 0 | 0 | 1 | 3 | 2 | 0 | 0 | 1 | 2 |
| **nPHI** | *-2* | *3* | *-2* | 3 | 2 | 2 | 2 | -1 | -3 | 1 | 1 | 1 | 1 | 2 | 1 | -1 | 0 | 2 | 0 |
| **CT** | *2* | *3* | *2* | 3 | -1 | 2 | 3 | -2 | 1 | -2 | 1 | 2 | 2 | 2 | 1 | 2 | 1 | 1 | 2 |
| **Group** | *Q* | *nQ* | *Q* | nQ | nQ | nQ | Q | nQ | nQ | nQ | nQ | nQ | nQ | Q | Q | Q | nQ | nQ | Q |

*: inclusion criteria

## B-2 Absolute distance

The results for the absolute distance between reach and intended target's position are presented in the following. The results do not show significant differences in both groups, according to a one-way analysis of variance (ANOVA) with $\alpha = 0.05$. No ANOVA was calculated over the results of all participants, but the figure is provided for completeness.

Nevertheless, these results may provide more useful insights into the results presented in the paper.

In the figures, 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.

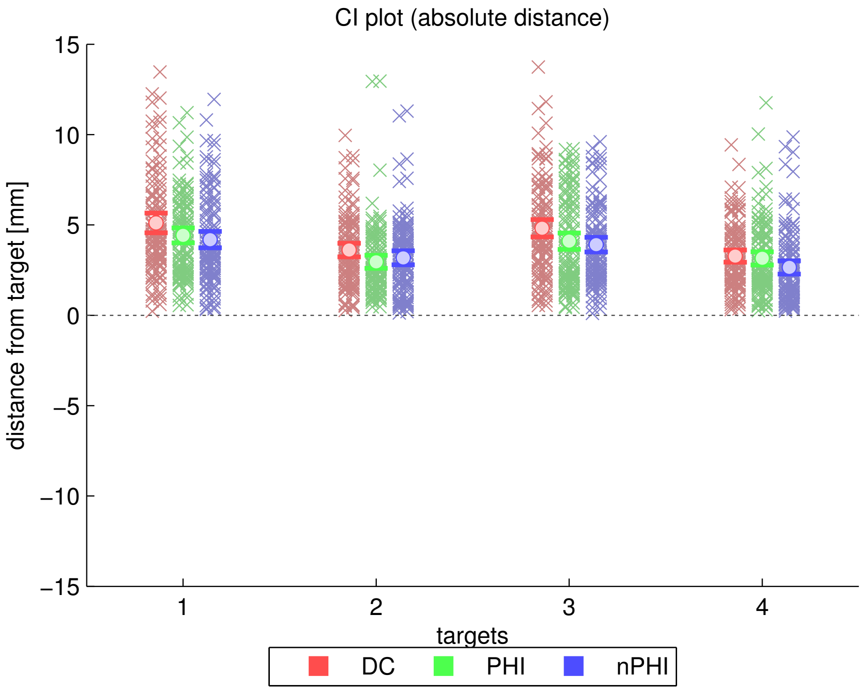


**Figure B-1:** Absolute distance between reach and intended target, for all participants (n=16).

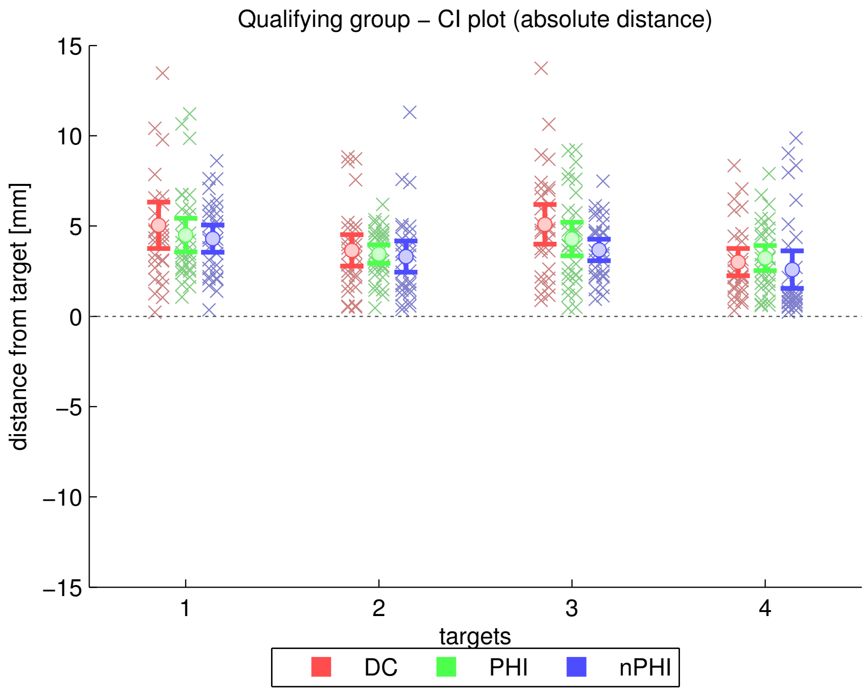


**Figure B-2:** Absolute distance between reach and intended target, for the Q-group (n=5).

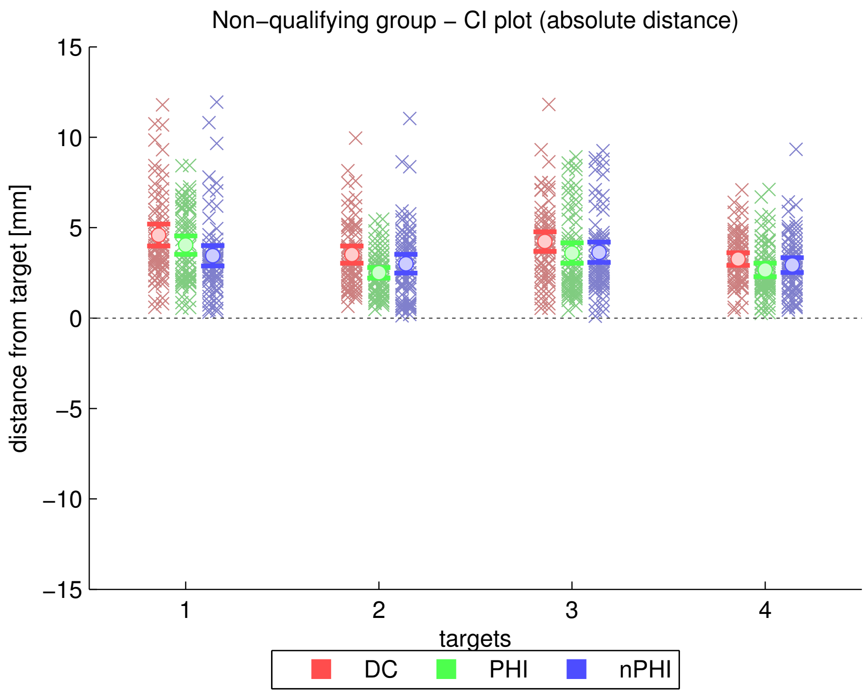


**Figure B-3:** Absolute distance between reach and intended target, for the nQ-group (n=11).

## B-3 Distance in x-direction

This section presents the results in the x-distance to the target. As also stated in the paper, a significant difference was found for the nQ-group, in longitudinal target 2 and lateral target 3. As with the absolute distance, no ANOVA was calculated over the results of all participants.

In the figures, 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.

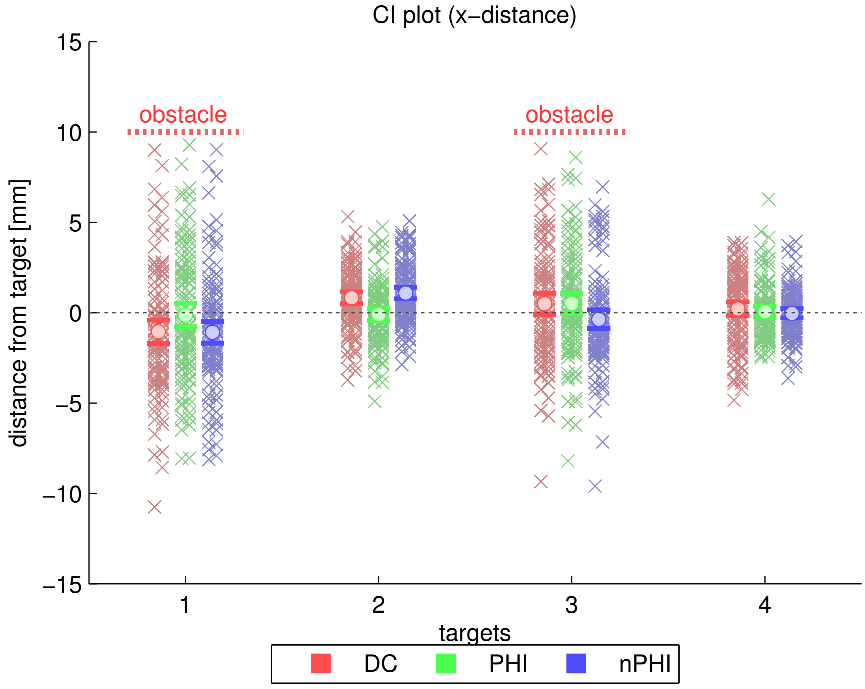


**Figure B-4:** Distance in x-direction between reach and intended target, for all participants (n=16).

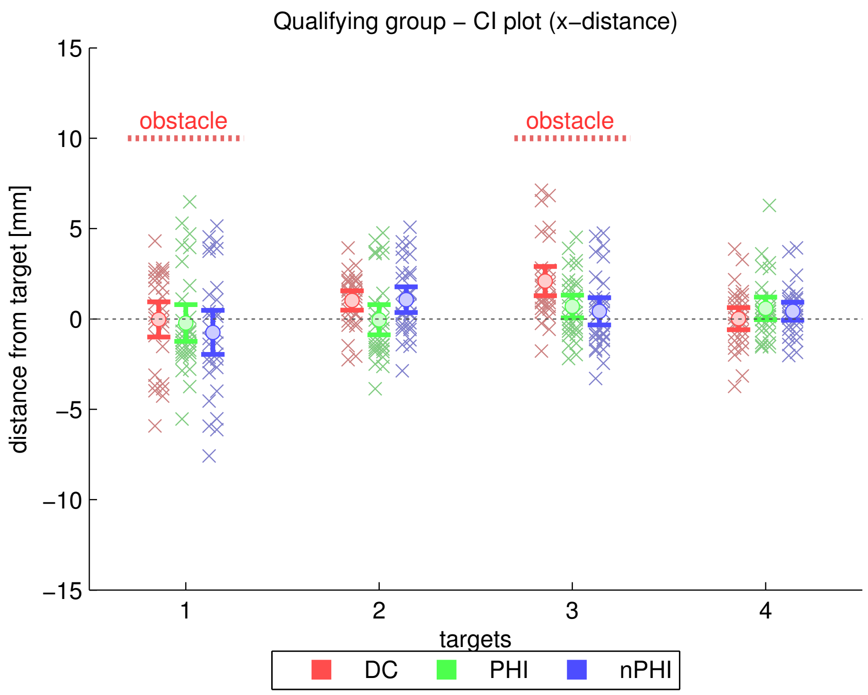


**Figure B-5:** Distance in x-direction between reach and intended target, for the Q-group (n=5).

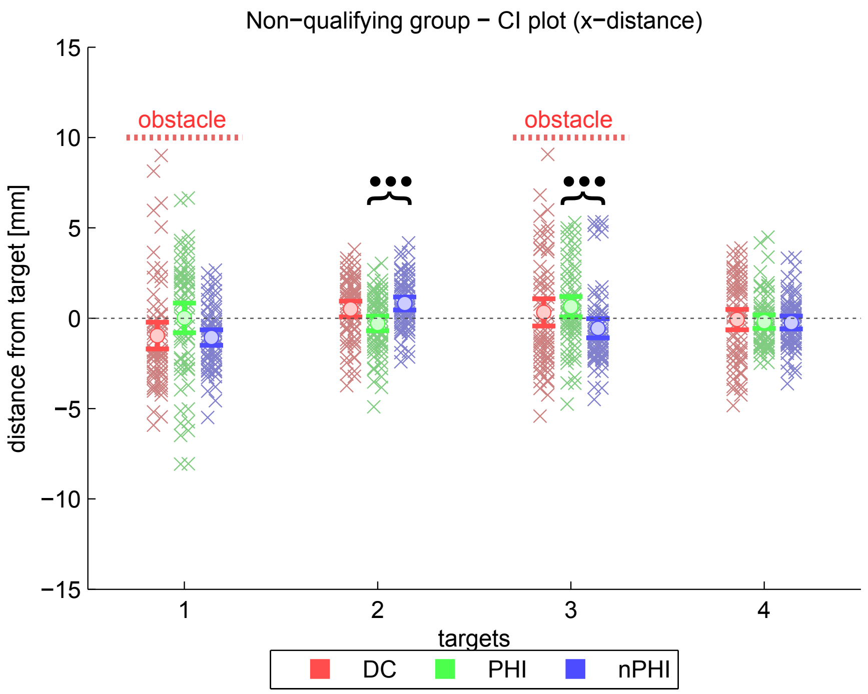


**Figure B-6:** Distance in x-direction between reach and intended target, for the nQ-group (n=11).

## B-4 Distance in y-direction

The results in the distance to target in y-direction are presented in this section. A significant difference was found in longitudinal targets 2 and 4, for both the Q-group and the nQ-group. An ANOVA was only calculated over the groups, and not over the results of all participants together.

In the figures, 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.

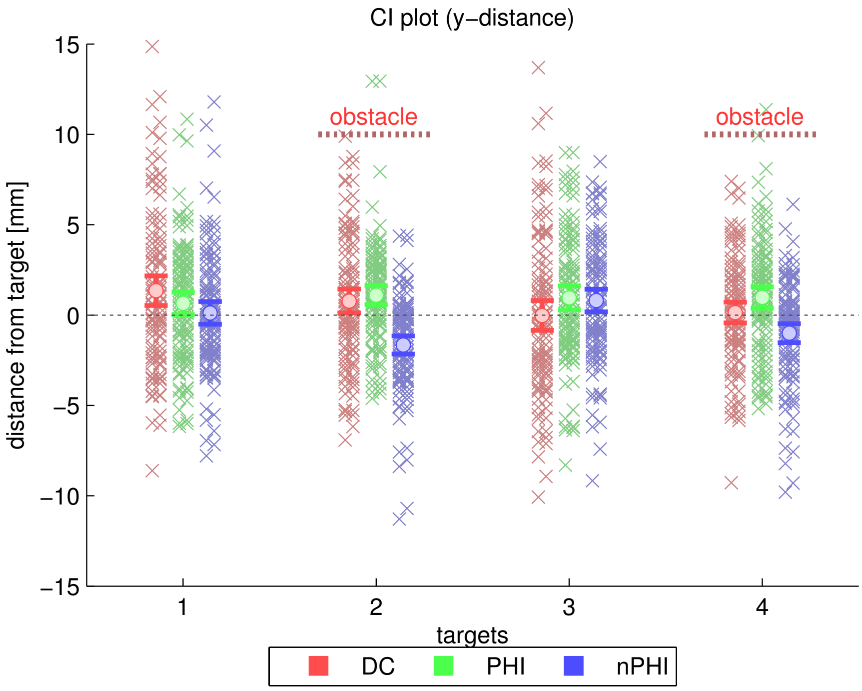


**Figure B-7:** Distance in y-direction between reach and intended target, for all participants (n=16).

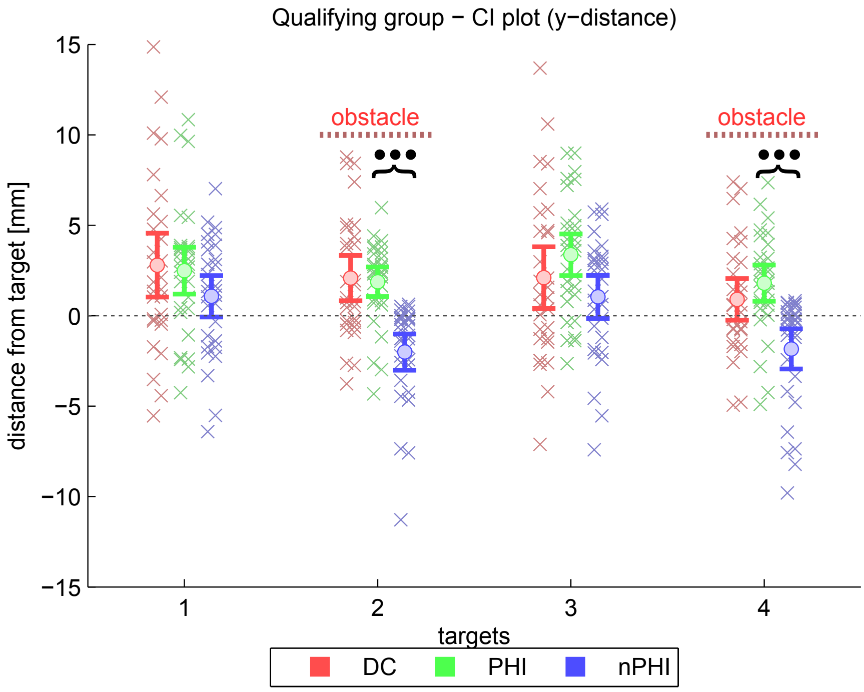


**Figure B-8:** Distance in y-direction between reach and intended target, for the Q-group (n=5).

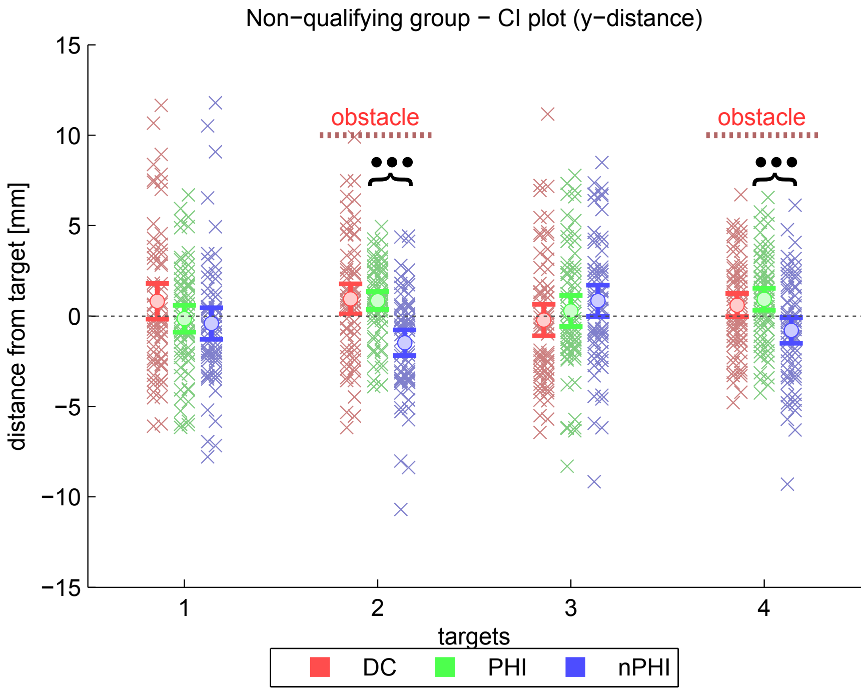


**Figure B-9:** Distance in y-direction between reach and intended target, for the nQ-group (n=11).

## B-5 Time

The results for the time-to-completion are presented next. These results do not show significant differences in either group, according to a one-way analysis of variance (ANOVA) with $\alpha = 0.05$. Again, no ANOVA was calculated over the results of all participants, but the figure is provided for completeness and consistency.

Furthermore, these results might provide more insight into the subject.

In the figures, 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.

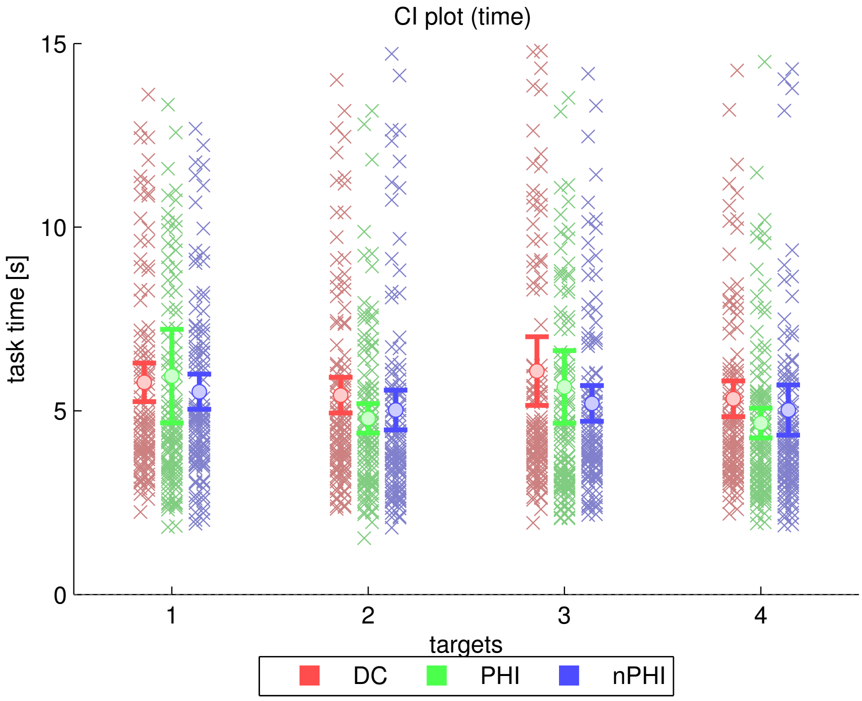


**Figure B-10:** Time-to-completion per trial, for all participants (n=16).

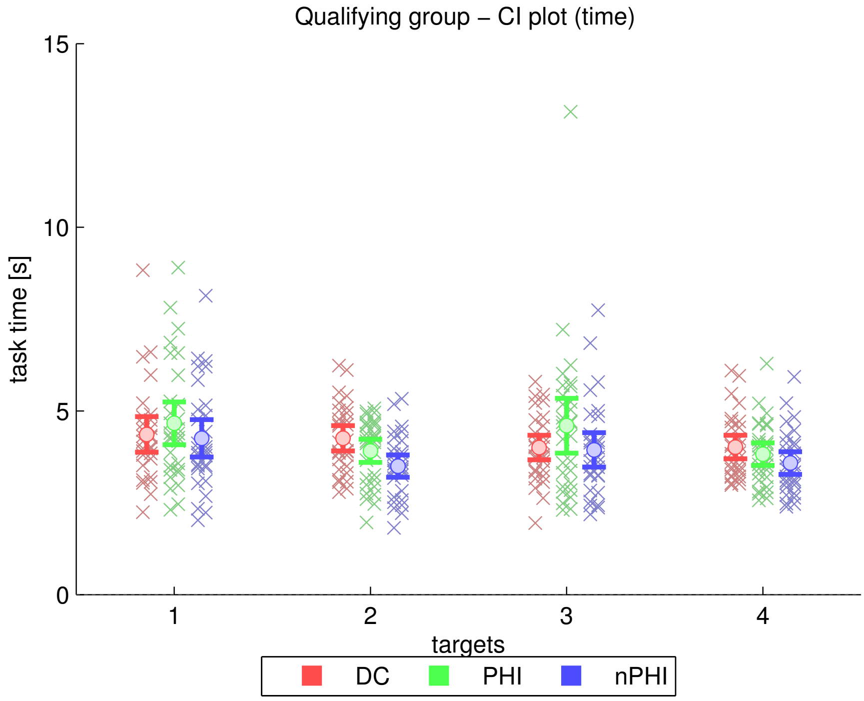


**Figure B-11:** Time-to-completion per trial, for the Q-group (n=5).

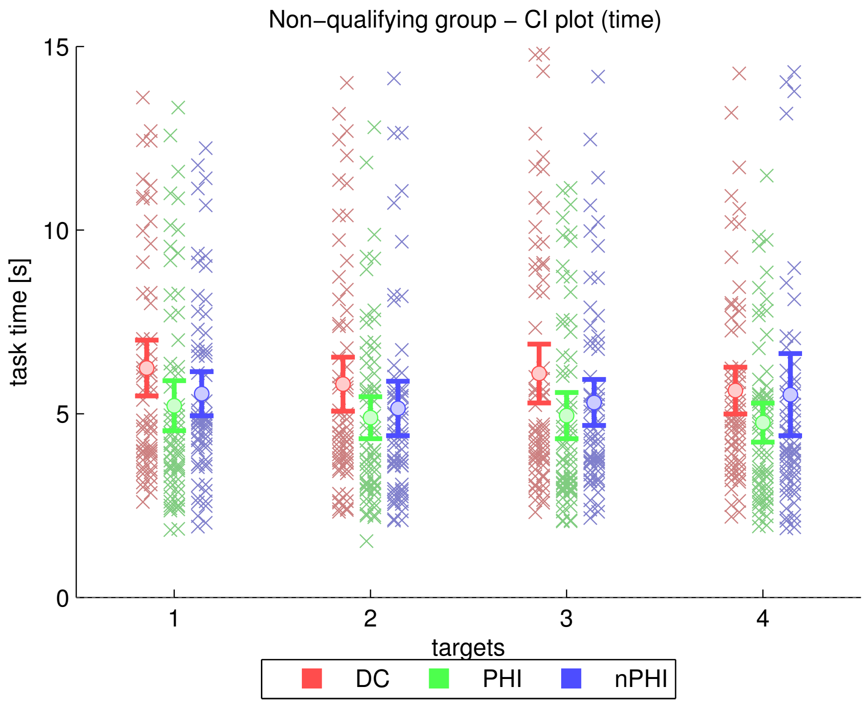


**Figure B-12:** Time-to-completion per trial, for the nQ-group (n=11).

## B-6 Trajectories

The trajectories of the reaches of all participants are superposed. The resulting figures give an idea of the movements made during the task, and might provide insight into the behavior of the participants in conditions DC, PHI and nPHI.

The results are shown below.

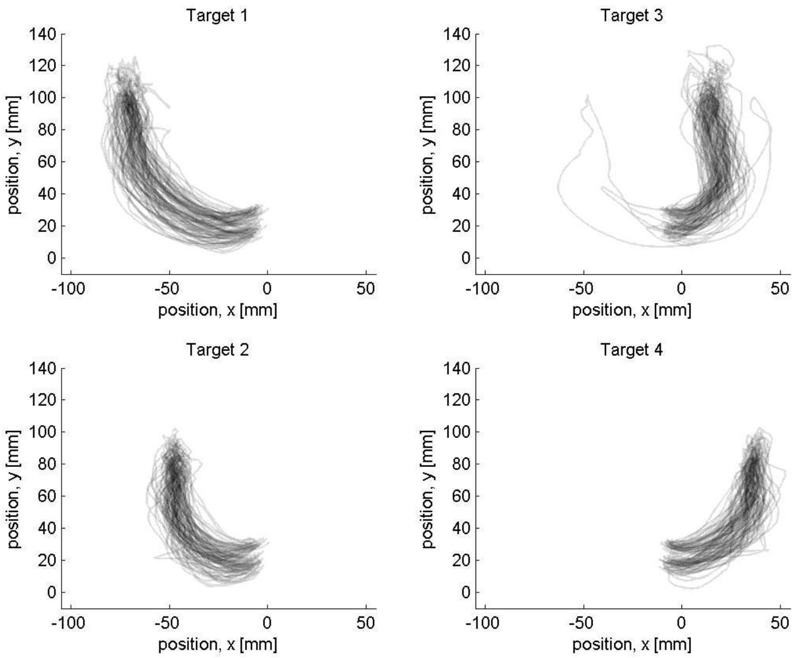


**Figure B-13:** Trajectories of all reaches superposed, for all participants (n=16), condition DC.

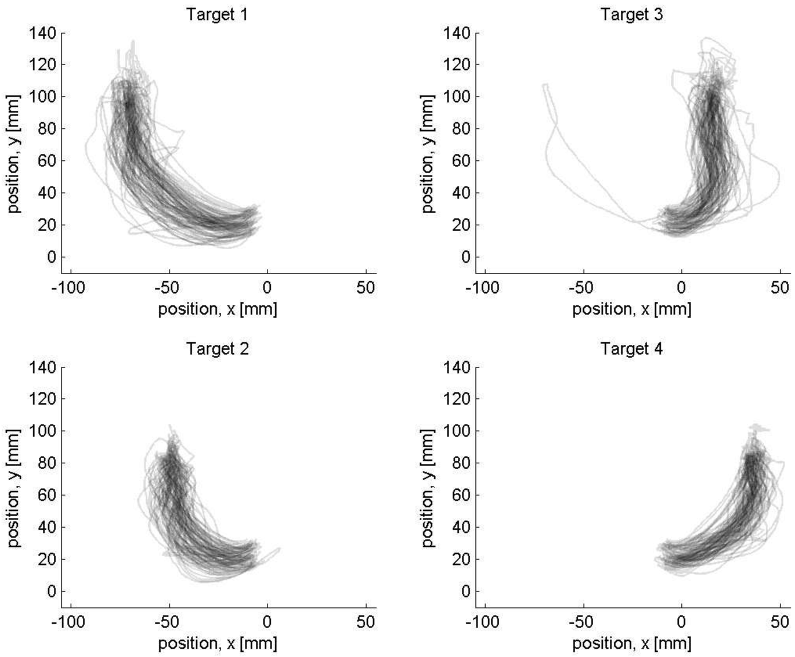


**Figure B-14:** Trajectories of all reaches superposed, for all participants (n=16), condition PHI.

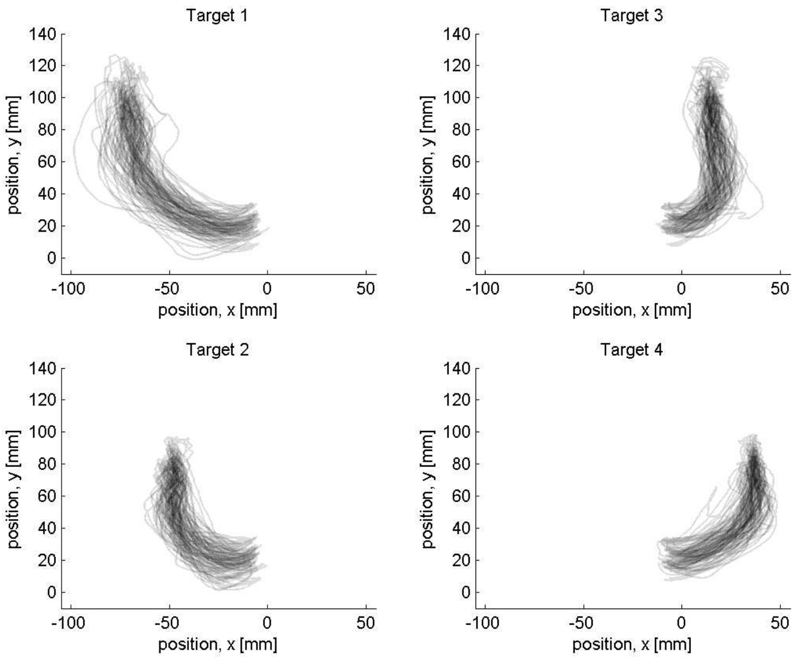


**Figure B-15:** Trajectories of all reaches superposed, for all participants (n=16), condition nPHI.

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