The Influence of the Viewpoint in a Self-Avatar on Body Part and Self-Localization

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ABSTRACT

The goal of this study is to determine how a self-avatar in virtual reality, experienced from different viewpoints on the body (at eye- or chest-height), might influence body part localization, as well as self-localization within the body. Previous literature shows that people do not locate themselves in only one location, but rather primarily in the face and the upper torso. Therefore, we aimed to determine if manipulating the viewpoint to either the height of the eyes or to the height of the chest would influence self-location estimates towards these commonly identified locations of self. In a virtual reality (VR) headset, participants were asked to point at several of their body parts (body part localization) as well as "directly at you" (self-localization) with a virtual pointer. Both pointing tasks were performed before and after a self-avatar adaptation phase where participants explored a co-located, scaled, gender-matched, and animated self-avatar. We hypothesized that experiencing a self-avatar might reduce inaccuracies in body part localization, and that viewpoint would influence pointing responses for both body part and self-localization. Participants overall pointed relatively accurately to some of their body parts (shoulders, chin, and eyes), but very inaccurately to others, with large undershooting for the hips, knees, and feet, and large overshooting for the top of the head. Self-localization was spread across the body (as well as above the head) with the following distribution: the upper face (25%), the upper torso (25%), above the head (15%) and below the torso (12%). We only found an influence of viewpoint (eye- vs chest-height) during the self-avatar adaptation phase for body part localization and not for self-localization. The overall change in error distance for body part localization for the viewpoint at eye-height was small (M = −2.8 cm), while the overall change in error distance for the viewpoint at chest-height was significantly larger, and in the upwards direction relative to the body parts (M = 21.1 cm). In a post-questionnaire, there was no significant difference in embodiment scores between the viewpoint conditions. Most interestingly, having a self-avatar did not change the results on the self-localization pointing task, even with a novel viewpoint (chest-height). Possibly, body-based cues, or memory, ground the self when in VR. However, the present results caution the use of altered viewpoints in applications where veridical position sense of body parts is required.

CCS CONCEPTS

• **Computing methodologies → Perception**; **Virtual reality**; *Motion capture*; • **Applied computing → Psychology**.

KEYWORDS

body part localization, self-localization, pointing, self-avatar, viewpoint manipulation

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1 BACKGROUND AND INTRODUCTION

1.1 General Introduction

In this work we investigate where people locate their body parts as well as where they self-locate within their bodies, before and after a self-avatar adaptation phase experienced from different viewpoints in a VR headset. Our interest in this issue is motivated along the following lines.

Based on multiple studies, it is believed that people do not necessarily locate their body parts accurately. This can even be the case in healthy populations, when visual feedback is not available to guide responses. The literature also shows that people do not necessarily locate themselves in only one bodily location, but rather in multiple locations (mainly the face and torso). Furthermore, animated self-avatars are becoming increasingly common, both in applications and in research, while cues affording multisensory information processing related to bodily self-perception can vary substantially between current technological setups. It is therefore of relevance for both basic research and applications that provide users with animated self-avatars or visual perspectives from altered viewpoints to understand how these animated self-avatars and different viewpoints may influence both body part and self-localization.

The following subsections (1.2 - 1.5) discuss related work from a variety of research areas relevant for this topic, specifying the above general motivation for the present study. This work ranges from the neural and behavioral sciences to computer science and more applied research. This section ends with an overview of the hypotheses for our current experimental manipulations (subsection 1.6).

1.2 Body Part Localization

It is often assumed that humans perceive their body part locations in space and their relative positions to each other accurately [Van Beers et al. 1998; Soechting 1982]. While this seems intuitively correct, most individuals have to be taught to correctly draw human body proportions [Fairbanks and Fairbanks 2005], otherwise their drawings demonstrate several systematic distortions [Fuentes et al. 2013; Kahill 1984]. Using various methodologies relevant to the present study, systematic distortions in own body part localization have been discovered. For example, Hach and Schütz-Bosbach asked participants to point with their hand, with or without the help of a laser pointer, to several landmarks on their own physical body while their body except their face was hidden from view behind cardboard [Hach and Schütz-Bosbach 2010], and to body parts on one's own body imagined in front of oneself [Hach et al. 2011]. They found for self-directed pointing with one's own hand that shoulder, waist, and hip widths were overestimated by approximately 4 cm. Fuentes et al. [2013] performed a desktop body image task (BIT) where participants provided estimates of body part locations on a non-co-located body. On a computer screen, a head was seen as a mirror image of oneself and several body parts were to be located relative to this head. They found a large and systematic over-estimation of width relative to height. Linkenauger et al. [2015] asked participants to provide estimates of body lengths using one's hand size as a metric. They found systematic distortions, consistent with the sizes of the respective body parts' neural representations in somatosensory cortex, constituting what is often described as the perceptual homunculus. Recently, Van der Veer et al. [2019] investigated body part localization using VR setups and found that participants pointed relatively accurately to many of their body parts, but were particularly inaccurate for the body parts near the borders of their bodies (the feet, knees, and top of the head).

1.3 Self-localization within the Body

Most literature focusing on specifying self-location in the body has used an outlines of a human bodies, where the task did not involve pointing to oneself but rather localization on a depiction of a person. When participants were asked to indicate the "centre of the self" by placing markers on human silhouettes, Limanowski and Hecht [2011] found a dominant role for the brain (reported most) and the heart for self-location. They also found that most people seem to believe there is one single point inside the human body where their self is located. Using open questions and forced-choice self-localizing on a body silhouette Anglin [2014], on the contrary, found some participants reporting that the self is not centralized in a single location. Overall, she found participants locating the self and mind in the head and the soul in the chest. Starmans and Bloom asked people to judge when objects were closer to a depicted person [Starmans and Bloom 2012], as well as to erase as much as possible of a picture of a stick figure named Sally, while still leaving Sally in the picture [Starmans and Bloom 2011]. Based on their result, they argued that people locate the self mainly in the head and, more particularly, in or near the eyes.

Alsmith and Longo [2014] asked participants to point directly at themselves with a physical pointer, aiming to determine the bodily location, or set of locations, in which people think of themselves as located. They found that participants' judgments were not spread out homogeneously across the entire body, nor to be localized in any single point. Specifically, they observed pointing mainly to the upper face and to the upper torso. Van der Veer et al. [2018, 2019] extended the paradigm from Alsmith and Longo [2014] to VR setups and found pointing mostly to the (upper) face and, to a smaller extent, the (upper) torso. In addition, they found in a paper-and-pencil task of pointing to self on a picture of a body outline that people pointed primarily to the upper torso, followed by the upper face. Alsmith et al. [2017], using a more implicit method, recently found evidence for the use of a weighted combination of the head and the torso for self-location judgments. In their paradigm, self-location is implicated by the part(s) of the body used by participants to indicate the locations of external objects relative to themselves.

1.4 Self-avatars in VR

Animated self-avatars are becoming increasingly common both in applications and in neural and behavioural research. Specifically, a lot of research has focused on investigating body perception in VR [Slater and Sanchez-Vives 2016]; as well as bodily self-consciousness [Blanke et al. 2015] and body ownership [Ehrsson 2012]. In one of the best-known studies using VR, Lenggenhager et al. [2007] used a video see-through VR headset to study the phenomenology of out-of-body experiences and determined that people experienced a virtual body seen in front of them as being their own body and mislocalized themselves towards the virtual body. In addition, such related topics as the role of first-person (1PP) versus third-person perspective (3PP) [Petkova et al. 2011; Slater et al. 2010], the relative contribution of visuomotor and visuotactile information [Aspell et al. 2009; Kokkinara and Slater 2014] in full-body illusions, as well as body size experiences involving manipulations of the visual body [Van der Hoort et al. 2011; Piryankova et al. 2014], have all been investigated by using VR technology. It has specifically been demonstrated that a full-body illusion can be achieved more easily for a virtual body experienced from 1PP than from 3PP at a distance, both with [Petkova and Ehrsson 2008; Petkova et al. 2011] and without [Slater et al. 2010] the additional administration of synchronous visuotactile bodily information. Further, ownership over an avatar seen in a 3PP mirror-view has been shown to be promoted more strongly when it moved in sync with one's own body movements (visuomotor synchrony) compared to out of sync [González-Franco et al. 2010].

VR technologies can vary significantly in terms of the visual and bodily cues available to users. Most prominently, VR headsets have been used in basic and clinical research. A study by Heydrich et al. [2013] directly compared headsets using video-generated versus computer-generated visual information and discussed the potential differences these technologies introduce to the study of bodily self-consciousness (concerning distance estimation, visual fidelity, latency, visual realism and the measure of self-location with respect to the environment). Some studies have also used large-screen immersive displays to study body and space perception [Mölbert et al. 2017; Piryankova et al. 2013]. One of the most relevant aspects mentioned by Heydrich et al. [2013], as well as by Piryankova et al. [2013], is the difference in distance estimations between different VR setups. It has typically been found that egocentric distance (the distance from oneself to another location) is underestimated in VR headsets [Loomis and Knapp 2003; Renner et al. 2013]. This factor may play a role in the present study, although egocentric distance has been found to be underestimated less in more modern (under 20%) as compared to older VR headsets (up to 60%) [Buck et al. 2018; Creem-Regehr et al. 2015; Kelly et al. 2017; Young et al. 2014]. Interestingly, avatars have been shown to improve spatial perception in VR headsets [Mohler et al. 2010; Ries et al. 2008], although the mechanism for e.g. the improvements found for distance estimates is not yet fully known. Suggested causes are familiar size cues, visuomotor adaptation, and increases in presence in the virtual space [Mohler et al. 2010; Ries et al. 2008]. Recent work has shown that self-avatars can improve the accuracy of reaching judgments in VR and that this effect increases with the visual fidelity of the avatar (up to approaching the level of real-world judgments), as well as after feedback during a calibration phase [Ebrahimi et al. 2018a,b]. Moreover, it was shown that people can also calibrate their action capacities according to altered (non-veridically scaled) avatars and that this calibration can persist even for actions performed in real-life, after the calibration in VR [Day et al. 2019]. We additionally hypothesize that a self-avatar allows people to better understand the boundaries of their body. The present study aims to test specifically the influence of a veridically scaled avatar on body part (and self-)localization by means of pointing to locations on one's own body before and after a self-avatar adaptation phase.

1.5 Potential Impact on VR Applications

The use of VR technology to provide self-avatars or altered viewpoints not only has implications for the study of human perception and bodily self-consciousness, but has also many use cases in industrial applications. Self-avatars are particularly useful in ergonomic applications, where the fit between humans, products, and procedures can be tested virtually before production [Colombo et al. 2013; Honglun et al. 2007]. There is also a large amount of recent work on collaborative work in virtual environments, showing (partial) self-avatars to be able to improve collaboration [Beck et al. 2013; Rabätje et al. 2017].

1.6 Hypotheses

For this study, each participant was provided with an individually scaled and gender-matched self-avatar, animated by the real-time tracked movements of the participant and seen from both 1PP (co-located) and a 3PP (visuomotor synchronous mirror-view), to provide rich visual and body-based cues about the participant's body. This multisensory feedback was provided to test whether (a form of memory based on) visual and kinesthetic information from this avatar phase would change self- and body part localization in a post-avatar compared to in a pre-avatar pointing task. People seem to self-locate mainly in the (upper) face and the (upper) torso [Alsmith et al. 2017; Alsmith and Longo 2014; Van der Veer et al. 2018, 2019]. The viewpoint from the body during the self-avatar adaptation phase was therefore manipulated to either (normal) eye-height or chest-height, to investigate whether this would change self- and body part localization. Our hypotheses are the following.

(1) Body part localization post-avatar from eye-height will be more accurate compared to pre-avatar. The multisensory feedback about the participant's body will improve body part localization accuracy. (2)(a) Body parts will be indicated as higher post-avatar from chest-height compared to pre-avatar. (2)(b) In terms of the difference between post-avatar and pre-avatar body part localizations, there will be a relative shift upwards for chest-height compared to eye-height. (2)(a) and (b) are expected to result from the viewpoint having been lower than normal (seeing 'from the chest') and thereby body part locations having been experienced as higher. (3) In terms of the difference between post-avatar and pre-avatar self-localizations, there will be a relative shift downwards, towards the upper torso, for chest-height compared to eye-height. Specific self-localization in the body is expected to be influenced by the viewpoint in the body, i.e. self-location will be shifted towards the experienced viewpoint, which might be expected based on a suggested connection between 1PP and self-location [Ehrsson 2007; Guterstam et al. 2015; Ionta et al. 2011; Pfeiffer et al. 2013]. (3*) An alternative hypothesis is a relative shift upward for self-localization for chest-height compared to eye-height, to occur in case self-location is influenced by the body parts being perceived as higher, rather than by the viewpoint being lowered.

2 METHODS

2.1 Participants

Twenty-five healthy volunteers (thirteen female; age: M = 27.2, SD = 5.5, range: 18-44 years; twenty-four right-handed), naive to the purpose of the experiment and with normal or corrected-to-normal vision including stereo depth vision participated in the approximately 1 hour study. Two participants (one male and one female, both from the viewpoint at chest-height group) were excluded for failure to perform the task as intended: one hardly moved during the avatar adaptation phase and ignored the 1PP, the other verbally indicated difficulties with interpreting the direction of the pointer and pointed very erratically. The participants were recruited from the local university community. All participants gave written informed consent. Procedures were in accordance with the principles of the Declaration of Helsinki. Participants were randomly assigned to one of two viewpoint condition groups. Of the twenty-three participants included in the analysis, twelve were from the eye-height group and eleven from the chest-height group. Experiments were conducted in the participant's most fluent language (German or English). There were seventeen German and six English speakers.

2.2 Experimental Setup

During the experiment the participant stood in a fixed location in a 12 × 15 m hall, donned the HTC Vive headset and either held a Microsoft Xbox controller or two Vive hand-held controllers (see Figure 1, right image). Tracking was done with the Lighthouse infra-red tracking system of the HTC Vive. The experiment was run using a Dell Precision T3600 computer with an Intel Xeon E5-1620 central processor running at 3.60 GHz and an NVIDIA GeForce GTX 1080 graphics card. The HTC Vive headset was used for stimulus presentation. This VR headset has a resolution of 1080 × 1200 pixels per eye and a refreshment rate of 90 Hz, while affording a maximum field of view (FOV) of about 110° (horizontal). The pointing task was designed in Unity 5.3.2p1, the avatar adaptation phase in Unity 5.5.0f3.

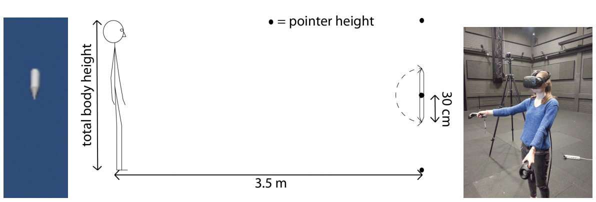

Figure 1: Left: A Close-up View of a Pointer Stimulus. Center: A Schematic Depiction of the Setup during the Pointing Task. The dotted line indicates the range of possible pointer rotations. The pointer starting direction was either straight up or down. Three pointer heights were spread out across the complete height of the participant's body: at 0, 0.5, and 1 x total body height; the viewing distance was 3.5 meters. Right: A Participant in the Experimental Setup during the Self-avatar Adaptation Phase.

2.3 Procedure

Participants read an information sheet and signed an informed consent form. This was followed by filling out the Edinburgh Handedness Inventory (revised) [Oldfield 1971], an interpupillary distance (IPD) measure and a test for binocular stereo vision (Stereo fly test, Stereo Optical Co., Inc., Chicago, IL). The experimenter measured the height of the participant's *top of the head* (cranial vertex), *eyes* (pupils), (tip of the) nose, *chin* (gnathion), *shoulders* (acromion), elbows (the most laterally protruding part of the bone), *hips* (where the circumference is largest), *knees* (top of the knee cap), and *feet* (above the talus). Additionally, arm span was measured on the participants back, with the hands completely spread out in a T-pose.

During the measurement of these heights, the participant was instructed explicitly where the respective body parts are located on the body and which names they would hear for them over the loudspeakers during the experiment (these names are in *italics* in the list above; note that nose and elbows were not used as pointing targets). In an additional round of instruction, they were briefly tapped on the locations where they were to point, while again the names of the locations were mentioned.

2.3.1 Pre-test Pointing Task. Participants were instructed that they would be asked to do a pointing task wearing a VR headset. The pointing targets were: top of the head, eyes, chin, shoulders, hips, knees, feet, and self. There were six repetitions per target. Specifically they were asked to: "[...] adjust the direction in which the stick is pointing, so that it is pointing directly at you or at your mentioned body part.", (or in German: "[...] die Richtung des Zeigestocks so zu verändern, dass dieser direkt auf Sie oder Ihr erwähntes Körperteil zeigt."). For the pointing task, the participant used a joystick on the left-hand side of a controller to rotate the pointer upwards or downwards through their sagittal plane (both directions were permitted at all times; the rotation speed of the pointer was relative to the pressure applied). The Xbox controller was used as opposed to the hand-held controllers of the HTC Vive, to prevent participants from potentially relating the pointer motion too directly to their hand movements. They confirmed their preferred position by pressing a button on the right-hand side of the controller. Participants were asked to respond as accurately and quickly as possible, and to stand still throughout the experiment. After completing the pre-test (this pointing task, as performed before the subsequent self-avatar adaptation phase) the participants took off the VR headset and had a short break.

2.3.2 Self-avatar Adaptation Phase. After the pointing task, a five-minute adaptation phase began, in which the participants saw a self-avatar, real-time animated (using inverse kinematics) by their tracked movements (tracking of the two Vive controllers and the headset), where their viewpoint was either at eye- or at chest-height (= at the height of their nipples). During this phase the joystick was replaced by the two Vive controllers for movement tracking. Participants could see the avatar both co-located with their physical body and in a mirror. They were instructed to freely move and explore the body. Directly before the adaptation phase, the participants were specifically instructed to "[...] look at the body freely and move freely. We recommend moving your hands and arms, and looking all around, both in the mirror and down towards your feet. Please keep your feet planted on the floor, do not step out of position and do not twist your torso (far) to look behind you.", (or in German: "[...] sich diesen Körper frei anschauen und frei bewegen. Wir empfehlen Ihre Hände und Arme zu bewegen, und überall herumzuschauen, sowohl in den Spiegel als auch runter auf Ihre Füße. Bleiben Sie aber bitte mit den Füßen immer fest stehen, treten Sie nicht aus der Position heraus und drehen Sie sich nicht (weit) herum um nach Hinten zu schauen."). The experimenter also showed example movements for the participants to make. Between the adaptation phase and the post-test (the pointing task, as performed after this self-avatar adaptation phase), participants stayed in the VR headset and were asked to close their eyes shortly until the post-test run was started.

2.3.3 Post-test Pointing Task. Following the adaptation phase, the two controllers were again replaced by the Xbox controller and participants were asked to do exactly the same pointing task as described in section 2.3.1. Note, that during the post-test (just as in the pre-test), there was no avatar.

2.3.4 Conscious Full-body Self-perception Questionnaire. Following the post-test, the participants filled out the Conscious full-body self-perception questionnaire from Dobricki and De la Rosa [2013] on a laptop. Twenty Questions about the embodiment of the self-avatar were answered on a visual-analogue scale.

2.4 Stimuli

2.4.1 Stimuli for VR pointing tasks. The virtual environment consisted of empty space with a blue background. In each trial, the participant saw a round pointing stick with a blunt backside and a pointy front side (see Figure 1, left image). The backside of the pointer was fixed to a (non-visible) vertical plane orthogonal to the participant's viewing direction at 3.5 m distance from the participant. The pointer had a virtual length of 30 cm and a diameter of 4 cm, was light-grey in color and had a fixed lighting source straight above, providing some shadow at the underside of the pointer. The starting direction of the pointer was pointing either straight up or straight down, at one of the three fixed backside heights: 0, 0.5, and 1 × total body height. These different pointer starting directions and heights were included to make the task more diverse and to prevent biasing participants' responses (see Figure 1, center image). Every combination of pointer starting direction and height was combined with every target once. The number of trials was 3 (pointer heights) × 2 (pointer starting angles) × 2 (pre-test and post-test) × 8 (targets) = 96 trials in total per participant.

2.4.2 Stimuli for Self-avatar Adaptation Phase. A gender-matched, rigged SMPL avatar [Loper et al. 2015] was scaled through the skeletal-rigging to the measured arm span and total body height of each individual participant (see Figure 2). The same female and male avatar textures were used for all participants (gender-matched, but not otherwise matched in appearance). The textures were created by a 3D graphical artist.

The only experimental manipulation that was made to the avatar was the location of the viewpoint (see Figure 3). For this eye-height and chest-height were chosen, because in previous research people reported self-locations most often in the upper face and upper torso. The difference between these two viewpoints consisted of 21% of total body height (M = 35.7 cm) for the females and 20% (M = 34.6 cm) for the males.

The 4-meter high ruler (with height labels every 10 cm) placed behind the avatar was intended to further assist the participant with the scale of the space. In particular participants could see that the height of the avatar was always the height of themselves in

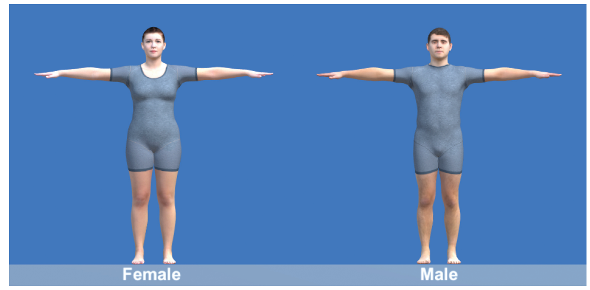

Figure 2: The Female and Male SMPL Avatars used in the Experiment.

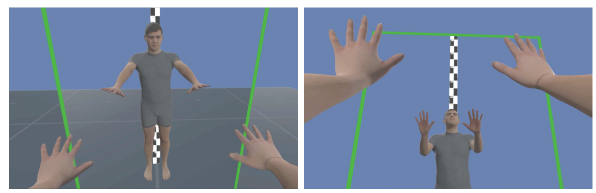

Figure 3: Image of the Avatar Adaptation Phase from the Viewpoint at: Left: Eye-height, and Right: Chest-height.

centimeters. The ground plane was the same size as the floor in the tracking hall the participant was standing on, 12 x 12 m. Due to the participant's location, the distance to the far end of the plane was approximately 7.5 m.

2.5 Design & Analysis

The primary measure recorded during the experiment was the angle of the pointer with the virtual plane to which its backside was fixed (with a range from 0° for completely down and 180° for completely up), when the participant indicated that the pointer was pointing "directly at you" or at a particular body part. Using the individualized height of the pointer, this angle was recomputed into the height where the virtual extension of the pointer would intersect with the participant's body.

2.5.1 Body Part Localization Analysis. For pointing at body parts the pointing heights on the body were compared to the heights of the respective target body parts, as measured on the physical body, and the difference was taken as the measure error distance, in signed number of cm (with negative values being down and positive values up, relative to the physical height of the respective body part). To analyze whether the different viewpoints during the avatar adaptation phase affected where participants located their body parts, the difference in error distance (which equals the difference in pointing height) was computed (post-test − pre-test) for each trial (matched individually by the levels of the variables participant number, pointer height, and pointer angle, in order not to use average values and thereby lose data-points), for both viewpoints. The error distances were analyzed using an ANOVA, with one between-subjects factor viewpoint (2 levels: eye-height and chest-height) and one within-subject factor target body part (7 levels: feet, knees, hips, shoulders, chin, eyes, top of the head).

2.5.2 Self-localization Analysis. For self-pointing, using the participant's individual body height measurements, the pointing height on the body was classified as a score for one of seven regions of the body (in the figures the responses are shown in terms of percentages of trials per body region). As in earlier studies [Alsmith and Longo 2014; Van der Veer et al. 2018, 2019] each response was coded as falling into a bodily region, depending on where it would intersect the body: below the torso (= below the hips), lower torso (= between the hips and the elbows), upper torso (= between the elbows and the shoulders), neck (= between the shoulders and the chin), lower face (= between the chin and the nose), upper face (= between the nose and the top of the head (= total body height)), and above the head (= above total body height; this region was added, because we found a substantial amount of pointing here). These regions were chosen according to visually salient boundaries to facilitate coding, which correspond roughly to nameable body parts; head and torso are both split into two roughly equal regions, with another region between them, the neck, bounded by chin and shoulders. To analyze whether the different viewpoints during the avatar adaptation phase affected where participants located themselves, the difference between the percentages of pointing for each body region was computed (post-test − pre-test) for both viewpoints. The responses were analyzed using an ANOVA, with one between-subject factor viewpoint (2 levels) and one within-subject factor body region (7 levels).

2.5.3 Conscious Full-body Self-perception Questionnaire . As suggested by Dobricki and De la Rosa [2013] based on their analyses, the questions of their Conscious full-body self-perception questionnaire were assigned to one of three components, forming its subscales self-identification, spatial presence, and agency. An ANOVA was run with viewpoint as between-subjects factor, questionnaire component as within-subjects factor and the questionnaire score (% of maximum possible score) per component as the measure. Furthermore, two-sided Welch t-tests for all combinations of the three sub-scales were computed. We were also interested in whether or not the scores on this questionnaire correlated with any changes in self- or body part localization. Therefore, also two-tailed Pearson correlations were computed between the overall score on the questionnaire and the change (post-test − pre-test) in normalized pointing height on the body for self, separately for the eye-height and the chest-height groups; as well as between the overall score on the questionnaire and the change (post-test − pre-test) in error distance across all body parts, for the eye-height and the chest-height groups separately.

3 RESULTS

In a total of eight trials, the pointing height values for trials in which the pointer was not moved (the pointing angles were straight down or up) were replaced by the mean pointing height of the individual participant for the specific body part on the pre- or the post-test in order to get meaningful results (six trials for one participant, two trials for another participant).

3.1 VR Pointing Task

3.1.1 Body Part Localization Results.

Error Distance for Pre-test Trials. As expected, and suggesting that the randomly assigned groups did not perform the body part localization task differently prior to the avatar phase, there was no significant main effect of viewpoint ($F(1, 21) = 1.11$, $p = .304$, $\eta^2 = .02$), nor a significant interaction between viewpoint and body part ($F(2.07, 43.5) = 1.81$, $p = .175$, $\eta^2 = .05$), in terms of the error distance for pointing at body parts (pointed height − physical height) on the pre-test. Therefore, we further analyzed the pre-test error distances collapsed over the two groups. The error distance per target body part can be seen in Figure 4. A significant effect of body part was found in terms of error distance: ($F(2.26, 49.72) = 20.64$, $p < .001$, $\eta^2 = .25$). Holm-Bonferroni corrected two-sided paired t-tests showed strong significant differences in error distances for most of the pairs of body parts ($p < .001$); less strongly significant differences only for the pairs chin-eyes and shoulders-eyes ($p < .01$), and knees-hips and knees-chin ($p < .05$); and no significant differences only for the pairs hips-chin and chin-shoulders.

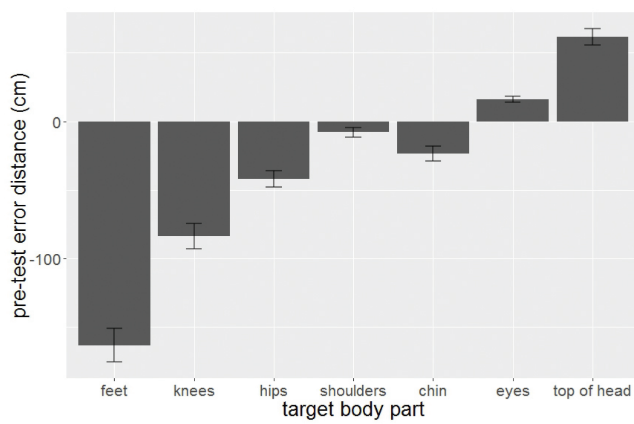

Figure 4: Pre-test (before the Avatar Adaptation Phase) pointing for body Part localization. Mean error distances between pointed at and physical body part location, per target body part, for pre-test trials (N = 23; error bars: ± 1 SE). Data was collapsed over viewpoint groups. The error distances are directional, with negative being down and positive being up relative to the physical location of the participant's target body part.

Difference in Error Distance between Pre-test and Post-test Trials. The differences in the error distance between pre-test and post-test trials per target body part can be seen in Figure 5. For this difference measure there was a significant main effect of viewpoint ($F(1, 21) = 5.73$, $p = .026$, $\eta^2 = .073$; eye-height: M = −2.8, SD = 74.0 cm; chest-height: M = 21.1, SD 88.3 cm). There were no significant effects for target body part ($F(2.42, 50.78) = 1.10$, $p = .37$, $\eta^2 = .036$) or the interaction between viewpoint and target ($F(2.42, 50.78) = 1.96$, $p = .076$, $\eta^2 = .063$).

3.1.2 Self-localization Pointing Results.

Self-localization Regions for Pre-test Trials. Before the self-avatar adaptation phase, there was no significant difference between the

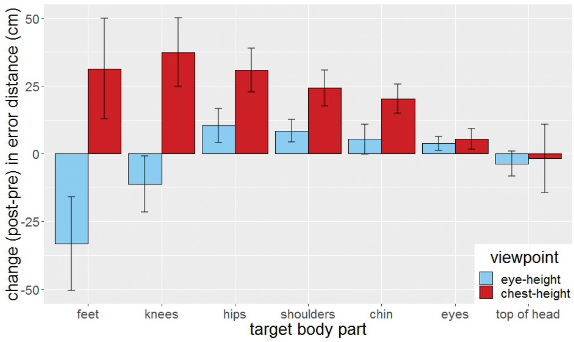

Figure 5: Shift in Pointing for Body Part localization between Pre-test and Post-test in Terms of Mean Error Distance between Pointed at and Physical body Part Location, per Target Body Part (N = 23; error bars: ± 1 SE). The shifts are directional, with negative being down and positive being up relative to the pre-test body part localization.

two viewpoint groups in terms of the regions they pointed to in the self-localization task (viewpoint x body region interaction: $F(3.86, 81.0) = .44, p = .77, \eta^2 = .02$). The percentages of trials pointed at the different regions for self-localization in the pre-test self-localization task can be seen in Figure 6, collapsed over viewpoint. Pre-test self-localization was mostly in the following regions: the upper face (25%) and the upper torso (25%), and, to a lesser extent, above the head (15%) and below the torso (12%). A significant effect of body region was found in terms of percentage of pointed trials ($F(3.91, 85.94) = 3.69, p = .0084, \eta^2 = .14$).

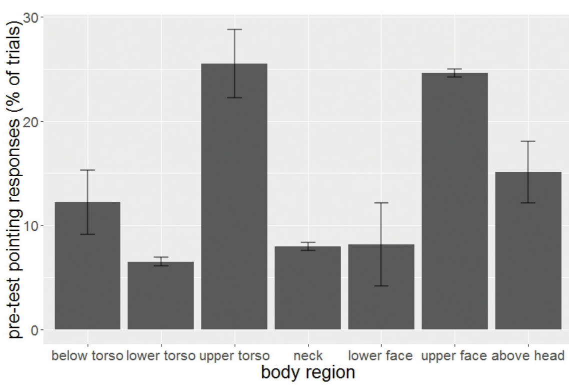

Figure 6: Pre-test (Before the Avatar Adaptation Phase) Self-localization in terms of Percentages of Trials Pointed at the Different Body Regions (N = 23; error bars: ± 1 SE). Data was collapsed over viewpoint groups, as they showed no significant differences.

When performing Holm-Bonferroni corrected two-sided paired t-tests for each pair of body regions (21 pairs) no significant differences in the percentage of trials per region were found, except for the upper torso as compared to the lower torso ($p < .05$).

Difference in Self-localization Regions between Pre-test and Post-test Trials. The differences between the post-test compared to the pre-test in the percentages of trials pointed at the different regions for self can be seen in Figure 7. No significant effect of body region ($F(4.74, 99.54) = 1.08, p = .38, \eta^2 = .049$), nor a significant interaction between viewpoint and body region ($F(4.74, 99.54) = 1.73, p = .12, \eta^2 = .076$) were present in terms of this post-test – pre-test difference measure.

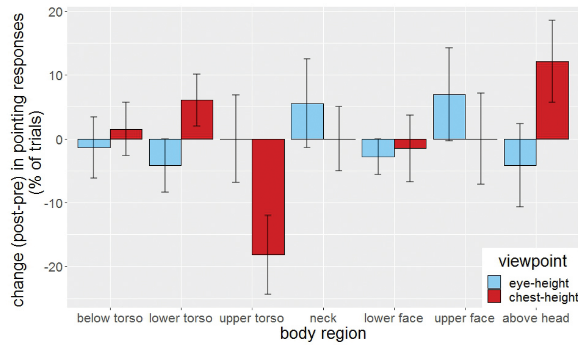

Figure 7: Shift in Pointing for Self-localization between Pre-test and Post-test in Terms of Percentages of Trials Pointed at the Different Body Regions (N = 23; error bars: ± 1 SE). The changes are directional, with negative being less and positive being more pointing to the participant's physical body regions.

3.2 Conscious Full-body Self-perception Questionnaire

The scores for the three components of the Conscious full-body self-perception questionnaire [Dobricki and De la Rosa 2013] can be seen by viewpoint in Figure 8. In the ANOVA, there was a significant main effect of embodiment sub-scale ($F(2, 42) = 29.97, p = < .001, \eta^2 = .23$), but not of viewpoint, nor a significant interaction between sub-scale and viewpoint, on the percentage of the maximum score attained. The two-sided Welch t-tests showed significant differences for all combinations of the questionnaire sub-scales: self-identification and spatial presence, self-identification and agency, and spatial presence and agency (all $p < .001$).

No significant effects were found for the two-tailed Pearson correlations between the score on the complete questionnaire and the change (post-test – pre-test) in normalized pointing height on the body for self, separately for the eye-height and the chest-height groups; nor between the score on the complete questionnaire and the change (post-test – pre-test) in error distance across all body parts, for the eye-height and the chest-height groups separately. Only the correlation between the questionnaire score and the change in pointing height for self for the chest-height group was close to significant ($r(9) = .59, p = .054$).

4 SUMMARY & DISCUSSION

The results from the current study support the previous findings that humans do not perceive the locations of their body parts accurately [Van Beers et al. 1998; Linkenauger et al. 2015; Soechting 1982; Tamè et al. 2017], at least not for all body parts. This finding

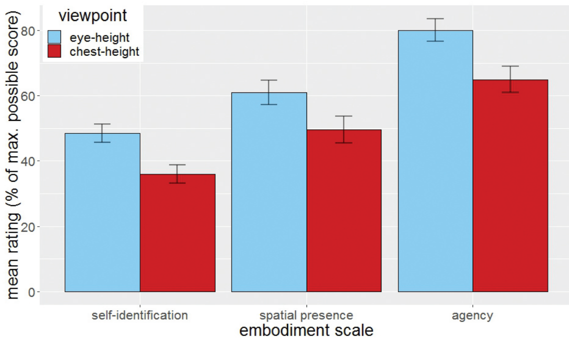

Figure 8: Mean Percentage of the Maximum Score for the Three Components of the Conscious Full-body Self-perception Questionnaire per Viewpoint (N = 23; error bars: ± 1 SE).

is consistent with the growing body of work showing (systematic) distortions in position sense in healthy populations [Fuentes et al. 2013; Hach and Schütz-Bosbach 2010; Linkenauger et al. 2015; Longo and Haggard 2012]. Further, we found that when asked to point directly at themselves in a VR headset, people point mostly to the upper torso and the upper face, with some pointing to all regions of the body, as well as above the head. This is largely consistent with Alsmith and Longo [2014], who reported self-location pointing to both the upper torso and the upper face in a physical setup. The present results are only partially consistent with previous VR findings, where Van der Veer and colleagues found pointing predominantly to the upper face [Van der Veer et al. 2018], and to the (upper) face and to a lesser extent to the (upper) torso [Van der Veer et al. 2019]. See section 5 for additional discussion of these different findings. Moreover, we found in the present study that the viewpoint in the self-avatar adaptation phase did influence body part localization in the virtual pointing task, but not self-localization.

4.1 Body Part Localization

The distortions found in this research in body part localization could be due to real distortions as reported in studies conducted outside of VR in healthy populations (e.g. Linkenauger et al. [2015]; Tamè et al. [2017]). However, the distortions in body part localization might also be exaggerated due to the VR experience of not having visual access to one's body; or to not having a sufficiently good sense of one's body's boundaries in the virtual environment. Participants pointed relatively accurately to locations near their eyes, but when the body parts were closer to the boundaries of their bodies (i.e. their feet and top of the head) large inaccuracies occurred. What might have contributed to these large inaccuracies closer to the body boundaries is that people may simply be less aware of the borders of their bodies than of more centrally located parts of their bodies.

When considering the differences in body part localization between the pre- and the post-test, an effect was found of the viewpoint during the self-avatar adaptation phase on the error distances. For viewpoint at eye-height, there was no significant change in the error distances for body part localization. In other words, the self-avatar as such did not reduce inaccuracies in body part localization, as the pointing between the post- and the pre-test was not different for the eye-height group. So, hypothesis (1) was not confirmed. Therefore, we also find no support for our additional hypothesis that a self-avatars might improve egocentric distance estimation in VR [Mohler et al. 2010; Ries et al. 2008] by improving people's sense of the boundaries of their body in space (see the end of section 1.4). Instead, as the avatar was scaled to the user's dimensions, our results suggest that adaptation to a self-avatar from a normal eye-height viewpoint may rather reinforce the distortions in body part localization found in healthy populations. Further research is needed to better understand the distortions in body part localization, with and without a self-avatar, under normal viewpoint conditions.

Changing the viewpoint did alter body part localization, though. Body part localization was overall shifted upwards (more for the lower body parts) from the pre- to the post-test for the chest-height group, resulting in a significant effect of viewpoint on (post-test – pre-test) body part localization. Therefore, hypotheses (2)(a) and (b) were confirmed. A possible reason for the shift upwards of the estimated locations of all body parts below the eyes for the chest-height viewpoint could be to compensate for the experienced lower viewpoint. The reason for a larger shift upwards in the localization of the lower body parts could be the experience of the lower body as being much closer to your eyes than normally, when looking down at the co-located avatar from 1PP. In contrast, in the mirror one could see that the upper body of the self-avatar was above the viewpoint. This however did not seem to influence the estimates of the higher body parts as strongly, suggesting that the physical body part locations (and not the altered viewpoint, or the mirror information) were used for pointing to the upper body parts. Another potential cause of the pointing to the eyes and the top of the head not being shifted upwards could be a tight coupling of the origin of the first-person perspective (egocenter) to body based cues. This may have resulted in participants not having experienced the viewpoint as altered at all, but rather the avatar and the other visual information as shifted around their fixed eye-height/egocenter in space. This is consistent with the work of Leyrer et al. [2015b], where body-based, rather than visual, cues were found to be used for determining one's eye-height in VR headsets.

4.2 Self-localization within the Body

There was no difference in self-localization pointing performance between viewpoints in the self-avatar adaptation phase. As such, none of the two alternative hypotheses (3) was supported. Based on indications of a tight link between 1PP and self-location [Ionta et al. 2011; Pfeiffer et al. 2013], a difference might have been expected. However manipulating perspective in terms of the origin of the visual field may not be enough to manipulate experienced self-location. The current findings seem to argue that self-localization in the body is not very malleable, compared to body part localization. This could be due to self-localization within the body while in VR being performed relative to the physical experiences, or perhaps memories, of one's own body, rather than visual feedback (from the self-avatar).

A general question of relevance for the self-localization measure used in this study is, in which space the participants experienced themselves to be, the virtual space as provided to them visually in the VR headset, the physical laboratory space, or perhaps even some combination of both? There were visual cues which may have led to immersion and presence in the virtual space. However, the normal body-based cues from proprioception, interoception, somatosensation, and the vestibular sense, were still present, which may have reinforced to the participants that they were in a physically existing laboratory room. An open question is thus still, whether participants were pointing to themselves and their body parts in the virtual or in the physical space, or a combination thereof. This suggests the relevance of an additional presence scale in future work.

4.3 Conscious Full-body Self-Perception Questionnaire

The Conscious Full-body Self-Perception Questionnaire was included mainly as a control. If the scores on the (subscales of the) questionnaire would be low, this in itself would shed doubt on whether participants would have related information about the avatar to themselves at all, which would in turn shed doubt on the avatar adaptation phase as a means of providing rich multisensory information about their bodies to the participants. Fortunately, the scores on the (subscales of the) questionnaire were not particularly low.

The questionnaire was further included to check for differences between the viewpoint groups during the avatar phase. No differences were found between the scores on the full questionnaire or on any of its subscales, self-identification, spatial presence, and agency. The presence of such differences would not have been surprising, considering the unnatural manipulation of the viewpoint to chest-height. Not finding these differences is again fortunate, as they might have indicated that the manipulation of the viewpoint would also have manipulated the extent to which the participants had related the viewpoint to themselves.

The significant differences found between the different subscales follow a common pattern (increasingly higher scores from self-identification, to spatial presence, to agency) and are not of central interest here.

Not finding any significant correlations between the score on the full questionnaire and the change in the self- or body part localization between the pre- and the post-test, for either viewpoint group, forms an indication that the questionnaire score (i.e. conscious bodily self-perception, made up by its three subcomponents) probably has no strong relation with the effects of the avatar or the viewpoint on the self- or body part localization measures (in as far as these effects are present)."

4.4 Impact on VR Applications

What is the significance of these findings for related VR applications involving animated self-avatars or altered viewpoints? Our findings suggest that a self-avatar experienced from a viewpoint matched to the eye-height of the user does not alter body part localization (which is known not to be very accurate in various cases). However, when altering the viewpoint, body part localization can change. Our results show that when the viewpoint in a VR application is moved down on the body of a self-avatar (e.g. to look at something from a different angle, or possibly when only a partial avatar is used), that this might not affect where in that avatar the user experiences himself to be, but may move the experienced locations of body parts (particularly the lower ones) upwards. So, for self-localization in an avatar a manipulation in viewpoint of this kind may not be very disruptive, but for experienced body part locations it can be, which is important to realize for applications where users need to be able to operate effectively and precisely within a virtual environment (at a later point in time, when the avatar is not present). The present results caution the use of altered viewpoints in applications where veridical position sense of body parts is desired (i.e., any application that demands reliable precision of spatial estimates or actions). On the other hand, they suggest the possibility of giving people illusory body part locations and possibly illusory spatial perceptions and action capabilities. Regarding self-localization, the present results support the idea that body-based cues, or memory, are likely to ground the sense of self when in VR [Leyrer et al. 2011, 2015a,b].

5 LIMITATIONS AND FUTURE OUTLOOK

One limitation of the current study is that there were no body part or self-localization data from a study outside of VR with a fully analogous design for comparison.

In addition, the present VR pointing paradigm varied in two distinct ways from Van der Veer et al. [2018]. A farther distance for the pointing stimuli (3.5 instead of 1.3 m) was used and the heights of the pointer stimulus spanned the whole body as opposed to just the upper body. These design decisions, which were intended to allow the participant to point to all parts of the body in a less biased way, might have in fact introduced other unintentional errors or noise in our data. Specifically, choosing to put the pointer stimuli at 3.5 instead of 1.3 m might have caused distance underestimation of the pointer stimuli, since they were outside of stereo cues available in the VR headset. Having added lower pointer heights might have effectively biased pointing towards lower regions of the body, where people may actually not so much experience themselves to be located. Van der Veer et al. [2019] used the same pointer distance as in the present study, as well as pointer heights across the complete extent of body. The results from that study are similar to the present findings, with self-localization spread out more across the body, but still with pointing mostly to the face, followed by–to a much lesser extent–the torso. While more spread-out or bimodal (face and torso) findings may more aptly represent individuals' self-localization within their bodies, more work is needed to fully rule out potential confounding task-effects. Further research is therefore needed to investigate pointing to self and body parts outside of VR with the present paradigm, as well as the errors in the present measure that may be introduced by the distance (both actual and perceived) and the heights of the pointer stimuli.

When—as in pointing tasks—spatial actions are performed to indicate spatial locations, a mismatch between the target and the indicated location can result from several causes. Not only can the target location be mis-judged, but also the indicated location may be mis-judged. Here, this means that the error distances for the body parts may not only reflect participants' inaccuracies in locating these body parts, but also their inaccuracies in interpreting where the pointer, the efFector of their behavior, precisely points to under different angles. In the present study, with the external pointer, this interpretation issue may indeed play a role. In previous work [Felician et al. 2003; Hach and Schütz-Bosbach 2010; Longo and Haggard 2010; Paillard 1999; Sirigu et al. 1991; Tamè et al. 2017], typically the part of the body acted with is also the part of the body doing the pointing, i.e. the actuator is the same as the efFector, making the task execution particularly embodied. In the present study however, the actuator (the hand using the joystick) and the efFector (the pointer) are not the same, making the task execution less embodied in a sense. The task here is not to indicate the location of a body part with and, thereby also relative to, another body part, but relative to an external, visual object, i.e. the pointer. This makes the present task in a sense a purer, or more allocentric, measure of body part localization ability. Although our task involves the difficulty of interpreting where on the body the pointer under specific angles points to, we believe it is of additional value to also investigate how well people are able to locate body parts when the effector is an external object, perceived visually. To investigate further to what extent inaccuracies in body part localization may have resulted from specific task characteristics, we suggest follow-up studies using (also) substantially different tasks for indicating bodily locations.

Another limitation of the present study is that only investigated two viewpoints were investigated. We specifically chose chest-height, because it is a novel viewpoint that places the camera in the second-most indicated area for self-localization (i.e. the upper torso). However, a viewpoint at chest-height is not as relevant to applications, where an over-the-shoulder, top-down, or from-behind viewpoint might be more relevant. Further research is necessary to determine what happens to body part and self-localization when these viewpoints are provided instead. Upon request, the software for replicating and modifying this experiment will gladly be made available (upon signing the SMPL license agreement [Loper et al. 2015] for the used avatars).

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REFERENCES

Adrian J. T. Alsmith, Elisa R. Ferrè, and Matthew R. Longo. 2017. Dissociating contributions of head and torso to spatial reference frames: The misalignment paradigm. *Conscious. Cogn.* 53 (2017), 105–114. https://doi.org/10.1016/j.concog.2017.06.005

Adrian J. T. Alsmith and Matthew R. Longo. 2014. Where exactly am I? Self-location judgements distribute between head and torso. *Conscious. Cogn.* 24 (2014), 70–74. https://doi.org/10.1016/j.concog.2013.12.005

Stephanie M. Anglin. 2014. I think, therefore I am? Examining conceptions of the self, soul, and mind. *Conscious. Cogn.* 29 (2014), 105–116. https://doi.org/10.1016/j.concog.2014.08.014

Jane E. Aspell, Bigna Lenggenhager, and Olaf Blanke. 2009. Keeping in touch with one's self: Multisensory mechanisms of self-consciousness. *PLOS One* 4, 8, Article e6488 (2009), 10 pages. https://doi.org/10.1371/journal.pone.0006488

Stephan Beck, Andre Kunert, Alexander Kulik, and Bernd Froehlich. 2013. Immersive group-to-group telepresence. *IEEE Transactions on Visualization and Computer Graphics* 19, 4 (2013), 616–625. https://doi.org/10.1109/TVCG.2013.33

Robert J. Van Beers, Anne C. Sittig, and Jan J. Denier van der Gon. 1998. The precision of proprioceptive position sense. *Exp. Brain Res.* 122, 4 (1998), 367–377. https://doi.org/10.1007/s002210050525

Olaf Blanke, Mel Slater, and Andrea Serino. 2015. Behavioral, neural, and computational principles of bodily self-consciousness. *Neuron* 88, 1 (2015), 145–166. https://doi.org/10.1016/j.neuron.2015.09.02

Lauren E. Buck, Mary K. Young, and Bobby Bodenheimer. 2018. A comparison of distance estimation in HMD-based virtual environments with different HMD-based conditions. *ACM Transactions on Applied Perception (TAP)* 15, 3, Article 21 (2018), 15 pages. https://doi.org/10.1145/3196885

Giorgio Colombo, Daniele Regazzoni, and Caterina Rizzi. 2013. Markerless motion capture integrated with human modeling for virtual ergonomics. In *Digital human modeling and applications in health, safety, ergonomics, and risk management. Human body modeling and ergonomics*, Vincent G. Duffy (Ed.). Springer Berlin Heidelberg, Germany, 314–323. https://doi.org/10.1007/978-3-642-39182-8_37

Sarah H. Creem-Regehr, Jeanine K. Stefanucci, William B. Thompson, Nathan Nash, and Michael McCardell. 2015. Egocentric distance perception in the Oculus Rift (DK2). In *Proceedings of the ACM SIGGRAPH Symposium on Applied Perception*. ACM, New York, NY, 47–50. https://doi.org/10.1145/2804408.2804422

Brian Day, Elham Ebrahimi, Leah S. Hartman, Christopher C. Pagano, Andrew C. Robb, and Sabarish V. Babu. 2019. Examining the effects of altered avatars on perception-action in virtual reality. *J. Exp. Psychol. Appl.* 25, 1 (2019), 1–24. https://doi.org/10.1037/xap0000192

Martin Dobricki and Stephan De la Rosa. 2013. The structure of conscious bodily self-perception during full-body illusions. *PLOS One* 8, 12, Article e83840 (2013), 9 pages. https://doi.org/10.1371/journal.pone.0083840

Elham Ebrahimi, Leah S. Hartman, Andrew Robb, Christopher C. Pagano, and Sabarish V. Babu. 2018a. Investigating the effects of anthropomorphic fidelity of self-avatars on near field depth perception in immersive virtual environments. In *2018 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*. IEEE, New York, NY, 1–8. https://doi.org/10.1109/VR.2018.8446539

Elham Ebrahimi, Andrew Robb, Leah S. Hartman, Christopher C. Pagano, and Sabarish V. Babu. 2018b. Effects of anthropomorphic fidelity of self-avatars on reach boundary estimation in immersive virtual environments. In *Proceedings of the 15th ACM Symposium on Applied Perception*. ACM, New York, NY, Article 4, 8 pages. https://doi.org/10.1145/3225153.3225170

H. Henrik Ehrsson. 2007. The experimental induction of out-of-body experiences. *Science* 317, 5841 (2007), 1048–1048. https://doi.org/10.1126/science.1142175

H. Henrik Ehrsson. 2012. *The new handbook of multisensory processes*. MIT Press, Cambridge, MA, Chapter The concept of body ownership and its relation to multisensory integration, 775–792.

Avard T. Fairbanks and Eugene F. Fairbanks. 2005. *Human proportions for artists*. Fairbanks Art and Books, Bellingham, WA.

Olivier Felician, Mathieu Ceccaldi, Mira Didic, Catherine Thinus-Blanc, and Michel Poncet. 2003. Pointing to body parts: A double dissociation study. *Neuropsychologia* 41, 10 (2003), 1307–1316. https://doi.org/10.1016/S0028-3932(03)00046-0

Christina T. Fuentes, Matthew R. Longo, and Patrick Haggard. 2013. Body image distortions in healthy adults. *Acta Psychol. (Amst.)* 144, 2 (2013), 344–351. https://doi.org/10.1016/j.actpsy.2013.06.012

Mar González-Franco, Daniel Pérez-Marcos, Berhard Spanlang, and Mel Slater. 2010. The contribution of real-time mirror reflections of motor actions on virtual body ownership in an immersive virtual environment. In *2010 IEEE Virtual Reality Conference (VR)*. IEEE, New York, NY, 111–114. https://doi.org/10.1109/VR.2010.5444805

Arvid Guterstam, Malin Björnsdotter, Giovanni Gentile, and H Henrik Ehrsson. 2015. Posterior cingulate cortex integrates the senses of self-location and body ownership. *Curr. Biol.* 25, 11 (2015), 1416–1425. https://doi.org/10.1016/j.cub.2015.03.059

Sylvia Hach, Masami Ishihara, Peter E. Keller, and Simone Schütz-Bosbach. 2011. Hard and fast rules about the body: Contributions of the action stream to judging body space. *Exp. Brain Res.* 212, 4 (2011), 563–574. https://doi.org/10.1007/s00221-011-2765-1

Sylvia Hach and Simone Schütz-Bosbach. 2010. Sinistrals' upper hand: Evidence for handedness differences in the representation of body space. *Brain Cogn.* 72, 3 (2010), 408–418. https://doi.org/10.1016/j.bandc.2009.12.001

Lukas Heydrich, Trevor Dodds, Jane Aspell, Bruno Herbelin, Heinrich Buelthoff, Betty Mohler, and Olaf Blanke. 2013. Visual capture and the experience of having two bodies–evidence from two different virtual reality techniques. *Front. Psychol.* 4, Article 946 (2013), 15 pages. https://doi.org/10.3389/fpsyg.2013.00946

Hou Honglun, Sun Shouqian, and Pan Yunhe. 2007. Research on virtual human in ergonomic simulation. *Comput. Ind. Eng.* 53, 2 (2007), 350–356. https://doi.org/10.1016/j.cie.2007.06.027

Björn Van der Hoort, Arvid Guterstam, and H. Henrik Ehrsson. 2011. Being Barbie: The size of one's own body determines the perceived size of the world. *PLOS One* 6, 5, Article e20195 (2011), 10 pages. https://doi.org/10.1371/journal.pone.0020195

Silvio Ionta, Lukas Heydrich, Bigna Lenggenhager, Michael Mouthon, Eleonora Fornari, Dominique Chapuis, Roger Gassert, and Olaf Blanke. 2011. Multisensory mechanisms in temporo-parietal cortex support self-location and first-person perspective. *Neuron* 70, 2 (2011), 363–74. https://doi.org/10.1016/j.neuron.2011.03.009

Sophia Kahill. 1984. Human figure drawing in adults: An update of the empirical evidence, 1967–1982. *Canadian Psychology/Psychologie Canadienne* 25, 4 (1984), 269–292. https://doi.org/10.1037/h0080846

Jonathan W. Kelly, Lucia A. Cherep, and Zachary D. Siegel. 2017. Perceived space in the HTC Vive. *ACM Transactions on Applied Perception (TAP)* 15, 1, Article 2 (2017), 16 pages. https://doi.org/10.1145/3106155

Elena Kokkinara and Mel Slater. 2014. Measuring the effects through time of the influence of visuomotor and visuotactile synchronous stimulation on a virtual body ownership illusion. *Perception* 43, 1 (2014), 43–58. https://doi.org/10.1068/p7545

Bigna Lenggenhager, Tej Tadi, Thomas Metzinger, and Olaf Blanke. 2007. Video ergo sum: Manipulating bodily self-consciousness. *Science* 317, 5841 (2007), 1096–1099. https://doi.org/10.1126/science.1143439

Markus Leyrer, Sally A. Linkenauger, Heinrich H. Bülthoff, Uwe Kloos, and Betty Mohler. 2011. The influence of eye height and avatars on egocentric distance estimates in immersive virtual environments. In *Proceedings of the ACM SIGGRAPH Symposium on Applied Perception in Graphics and Visualization*. ACM, New York, NY,, 67–74. https://doi.org/10.1145/2077451.2077464

Markus Leyrer, Sally A. Linkenauger, Heinrich H. Bülthoff, and Betty J. Mohler. 2015a. Eye height manipulations: A possible solution to reduce underestimation of egocentric distances in head-mounted displays. *ACM Transactions on Applied Perception (TAP)* 12, 1, Article 1 (2015), 23 pages. https://doi.org/10.1145/2699254

Markus Leyrer, Sally A. Linkenauger, Heinrich H. Bülthoff, and Betty J. Mohler. 2015b. The importance of postural cues for determining eye height in immersive virtual reality. *PLOS One* 10, 5, Article e0127000 (2015), 23 pages. https://doi.org/10.1371/journal.pone.0127000

Jakub Limanowski and Heiko Hecht. 2011. Where do we stand on locating the self? *Psychology* 2, 4 (2011), 312–317. https://doi.org/10.4236/psych.2011.24049

Sally A. Linkenauger, Hong Yu Wong, Michael Geuss, Jeanine K. Stefanucci, Kathleen C. McCulloch, Heinrich H. Bülthoff, Betty J. Mohler, and Dennis R. Proffitt. 2015. The perceptual homunculus: The perception of the relative proportions of the human body. *J. Exp. Psychol. Gen.* 144, 1 (2015), 103–113. https://doi.org/10.1037/xge0000028

Matthew R. Longo and Patrick Haggard. 2010. An implicit body representation underlying human position sense. *Proc. Natl. Acad. Sci. U.S.A.* 107, 26 (2010), 11727–11732. https://doi.org/10.1073/pnas.1003483107

Matthew R. Longo and Patrick Haggard. 2012. Implicit body representations and the conscious body image. *Acta Psychol. (Amst.)* 141, 2 (2012), 164–168. https://doi.org/10.1016/j.actpsy.2012.07.015

Jack M. Loomis and Joshua M. Knapp. 2003. Visual perception of egocentric distance in real and virtual environments. *Virtual and adaptive environments* 11 (2003), 21–46. https://doi.org/10.1080/17470218.2016.1143956

Matthew Loper, Naureen Mahmood, Javier Romero, Gerard Pons-Moll, and Michael J. Black. 2015. SMPL: A skinned multi-person linear model. *ACM Trans. Graphics* 34, 6, Article 248 (2015), 16 pages. https://doi.org/10.1145/2816795.2818013

Betty J. Mohler, Sarah H. Creem-Regehr, William B. Thompson, and Heinrich H. Bülthoff. 2010. The effect of viewing a self-avatar on distance judgments in an HMD-based virtual environment. *Presence* 19, 3 (2010), 230–242. https://doi.org/10.1162/pres.19.3.230

Simone C. Mölbert, Anne Thaler, Stephan Streuber, Michael J. Black, Hans-Otto Karnath, Stephan Zipfel, Betty Mohler, and Katrin E. Giel. 2017. Investigating body image disturbance in anorexia nervosa using novel biometric figure rating scales: A pilot study. *Eur. Eat. Disord. Rev.* 25, 6 (2017), 607–612. https://doi.org/10.1002/erv.2559

Richard C. Oldfield. 1971. The assessment and analysis of handedness: The Edinburgh inventory. *Neuropsychologia* 9, 1 (1971), 97–113. https://doi.org/10.1016/0028-3932(71)90067-4

Jacques Paillard. 1999. Body Schema and body image-a double dissociation. In *Motor control, today and tomorrow*, G.N. Gantchev, S. Mori, and J. Massion (Eds.). Academic Publishing House "Prof. M. Drinov", Sofia, Bulgaria, 197–214.

Valeria I Petkova and H Henrik Ehrsson. 2008. If I were you: perceptual illusion of body swapping. *PloS One* 3, 12, Article e3832 (2008), 9 pages. https://doi.org/10.1371/journal.pone.0003832

Valeria I Petkova, Mehrnoush Khoshnevis, and H Henrik Ehrsson. 2011. The perspective matters! Multisensory integration in ego-centric reference frames determines full-body ownership. *Front. Psychol.* 2, Article 35 (2011), 7 pages. https://doi.org/10.3389/fpsyg.2011.00035

Christian Pfeiffer, Christophe Lopez, Valentin Schmutz, Julio Angel Duenas, Roberto Martuzzi, and Olaf Blanke. 2013. Multisensory origin of the subjective first-person perspective: Visual, tactile, and vestibular mechanisms. *PLOS One* 8, 4, Article e61751 (2013), 15 pages. https://doi.org/10.1371/journal.pone.0061751

Ivelina V. Piryankova, Stephan De la Rosa, Uwe Kloos, Heinrich H. Bülthoff, and Betty J. Mohler. 2013. Egocentric distance perception in large screen immersive displays. *Displays* 34, 2 (2013), 153–164. https://doi.org/10.1016/j.displa.2013.01.001

Ivelina V. Piryankova, Hong Yu Wong, Sally A. Linkenauger, Catherine Stinson, Matthew R. Longo, Heinrich H. Bülthoff, and Betty J. Mohler. 2014. Owning an overweight or underweight body: Distinguishing the physical, experienced and virtual body. *PLOS One* 9, 8, Article e103428 (2014), 13 pages. https://doi.org/10.1371/journal.pone.0103428

Ralf Rabätje, Stephan Menzel, and Mathias Wochnig. 2017. *Challenges of collaborative applications using VR-HMDs (white paper)*. Technical Report. vr-on GmbH, München, Germany.

Rebekka S. Renner, Boris M. Velichkovsky, and Jens R. Helmert. 2013. The perception of egocentric distances in virtual environments-a review. *ACM Comput. Surv.* 46, 2 (2013), 23. https://doi.org/10.1145/2543581.2543590

Brian Ries, Victoria Interrante, Michael Kaeding, and Lee Anderson. 2008. The Effect of self-embodiment on distance perception in immersive virtual environments. In *Proceedings of the 2008 ACM Symposium on Virtual Reality Software and Technology*. ACM, New York, NY, 167–170. https://doi.org/10.1145/1450579.1450614

Angela Sirigu, Jordan Grafman, Karen Bressler, and Trey Sunderland. 1991. Multiple representations contribute to body knowledge prcessing: Evidence from a case of autotopagnosia. *Brain* 114, 1 (1991), 629–642. https://doi.org/10.1093/brain/114.1.629 arXiv:http://oup.prod.sis.lan/brain/article-pdf/114/1/629/756611/114-1-629.pdf

Mel Slater and Maria V. Sanchez-Vives. 2016. Enhancing our lives with immersive virtual reality. *Front. Robot. and AI* 3, Article 74 (2016), 47 pages. https://doi.org/10.3389/frobt.2016.00074

Mel Slater, Bernhard Spanlang, Maria V. Sanchez-Vives, and Olaf Blanke. 2010. First person experience of body transfer in virtual reality. *PLOS One* 5, 5, Article e10564 (2010), 9 pages. https://doi.org/10.1371/journal.pone.0010564

John F. Soechting. 1982. Does position sense at the elbow reflect a sense of elbow joint angle or one of limb orientation? *Brain Res.* 248, 2 (1982), 392–395. https://doi.org/10.1016/0006-8993(82)90601-1

Christina Starmans and Paul Bloom. 2011. What do you think you are? *Ann. N. Y. Acad. Sci.* 1234, 1 (2011), 44–47. https://doi.org/10.1111/j.1749-6632.2011.06144.x

Christina Starmans and Paul Bloom. 2012. Windows to the soul: Children and adults see the eyes as the location of the self. *Cognition* 123, 2 (2012), 313–318. https://doi.org/10.1016/j.cognition.2012.02.002

Luigi Tamè, Nicola Bumpus, Sally A. Linkenauger, and Matthew R. Longo. 2017. Distorted body representations are robust to differences in experimental instructions. *Atten. Percept. Psychophys.* 79, 4 (2017), 1204–1216. https://doi.org/10.3758/s13414-017-1301-1

Albert H. Van der Veer, Adrian J. T. Alsmith, Matthew R. Longo, Hong Yu Wong, and Betty J. Mohler. 2018. Where am I in virtual reality? *PLOS One* 13, 10, Article e0204358 (2018), 10 pages. https://doi.org/10.1371/journal.pone.0204358

Albert H. Van der Veer, Matthew R. Longo, Adrian J. T. Alsmith, Hong Yu Wong, and Betty J. Mohler. 2019. Self and body part localization in virtual reality: Comparing a headset and a large-screen immersive display. *Front. Robot. AI* 6, Article 33 (2019), 16 pages. https://doi.org/10.1016/10.3389/frobt.2019.00033

Mary K. Young, Graham B. Gaylor, Scott M. Andrus, and Bobby Bodenheimer. 2014. A comparison of two cost-differentiated virtual reality systems for perception and action tasks. In *Proceedings of the ACM Symposium on Applied Perception*. ACM, New York, NY, 83–90. https://doi.org/10.1145/2628257.2628261