Where are you?
Self- and body part localization using virtual reality setups

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Tübingen, den 16. August 2019 Albert H. van der Veer

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Self- and body part localization using virtual reality setups

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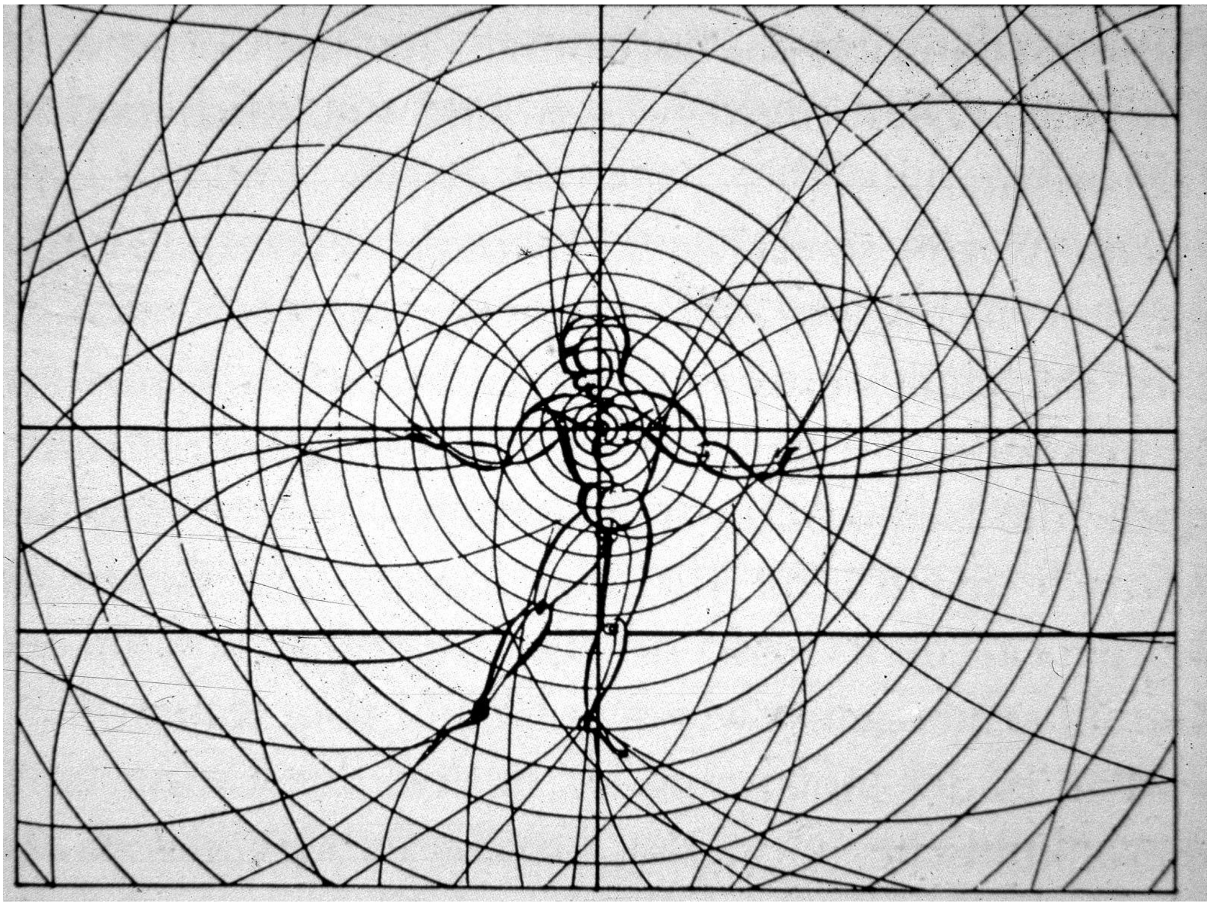

"Toute perception extérieure est immediatement synonyme d'une certaine perception de mon corps comme toute perception de mon corps s'explicite dans le langage de la perception extérieure. Si maintenant, comme nous l'avons vu, le corps n'est pas un objet transparent et ne nous est pas donné comme le cercle au géomètre par sa loi de constitution, s'il est une unité expressive qu'on ne peut apprendre à connaître qu'en l'assumant, cette structure va se communiquer au monde sensible. La théorie du schéma corporel est implicitement une théorie de la perception. Nous avons réappris à sentir notre corps, nous avons retrouvé sous le savoir objectif et distant du corps cet autre savoir que nous en avons parce qu'il est toujours avec nous et que nous sommes corps. Il va falloir de la même manière réveiller l'expérience du monde tel qu'il nous apparaît en tant que nous sommes au monde par notre corps, en tant que nous percevons le monde avec notre corps. Mais en reprenant ainsi contact avec le corps et avec le monde, c'est aussi nous-même que nous allons retrouver puisque, si l'on perçoit avec son corps, le corps est un moi naturel et comme le sujet de la perception."

Maurice Merleau-Ponty, Phenomenologie de la perception (1945)

"Every external perception is immediately synonymous with a certain perception of my body, just as every perception of my body is made explicit in the language of external perception. If, then, as we have seen to be the case, the body is not a transparent object, and is not presented to us in virtue of the law of its constitution, as the circle is to the geometer, if it is an expressive unity which we can learn to know only by actively taking it up, this structure will be passed onto the sensible world. The theory of the body schema is, implicitly, a theory of perception. We have relearned to feel our body; we have found underneath the objective and detached knowledge of the body that other knowledge which we have of it in virtue of its always being with us and of the fact that we are our body. In the same way we shall need to reawaken our experience of the world as it appears to us in so far as we are in the world through our body, and in so far as we perceive the world with our body. But by thus remaking contact with the body and with the world, we shall also rediscover ourself, since, perceiving as we do with our body, the body is a natural self and, as it were, the subject of perception."

Maurice Merleau-Ponty, Phenomenology of perception
(2002; translation by Colin Smith, 1958)

Front cover. Egozentrische Raumlineatur [ink on paper], Oskar Schlemmer (1924).
Back cover. Figur und Raumlineatur [ink on paper], Oskar Schlemmer (1924).

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Abstract

This thesis investigates where it is that people locate themselves in their bodies, as well as how accurately people can indicate the locations of several of their body parts. It is not well known, whether there is/are one or more region(s) of their bodies people associate themselves with most. To answer this question, three experimental studies were performed using several virtual reality (VR) setups where participants pointed directly at themselves with a virtual pointing stick. In the first two studies, participants were also asked, outside of VR, to indicate their self-location on pictures of simple body outlines. In the last two studies, participants were additionally asked, in VR, to point to several of their body parts. Based on body part locations as pointed out by the participants in VR, the indicated self-locations could subsequently be interpreted in terms of regions of the participants' *perceived* bodies, besides in terms of regions of their physical bodies (i.e. based on body part locations measured on their bodies).

In studies of self-location in the body, self-localization has mostly been performed using outlines of bodies not co-located with the participants' own bodies. Results from these studies have mainly shown self-localization in the (upper) face region, sometimes combined with in the upper torso region. Studies of self-location in the body using both explicit and implicit behavioral measures, have mainly shown self-localization in both the upper face *and* the upper torso regions. Across these previous studies findings show a mixed picture, which has motivated this further study of self-location.

For this thesis, a self-directed, first-person perspective (1PP) pointing paradigm was developed, which was implemented in several VR setups across the different experiments. This paradigm was used for self-localization, as well as for body part localization. The participant was instructed to rotate a pointer with a controller for each trial such that it was pointing "directly at you", or at one of several of his body parts. The VR setups were used in the present experiments, mainly because they provide strong experimental control and the possibility of manipulating sensory cues in ways not otherwise possible (the viewpoint in study three). Further, they make comparisons possibly between results from in- and outside of VR (all studies), as well as between different VR setups (study two).

In addition to the VR tasks, a not self-directed, third-person perspective (3PP) body template self-localization pointing task was used, outside of VR. There the participant was instructed to point "directly at you" with a pen on an A4 print of an outline of a body, under the assumption that this was a picture of himself.

In the first study participants performed the VR self-localization task using the Oculus Rift DK2 and the template self-localization task. VR self-localization showed a very strong preference for the upper face. This was not in line with previous behavioral studies, showing self-localization mainly in both the upper face *and* the upper torso. Template self-localization was mostly in the upper torso, followed by in the (upper) face. This was not in line with previous studies using body outlines, showing self-localization mostly in the (upper) face. The present template results are more in line with the previous behavioral findings (from studies

outside of VR), whereas the present VR behavioral findings are more in line with the previous body outline findings. It was concluded that wearing a VR headset might make people more head-focused.

To investigate whether the VR findings from study one were specifically due to the use of a headset (blocking visual access to the body), or more generally to VR, in study two the VR pointing paradigm was implemented in both the Oculus Rift and a large-screen immersive display (LSID), where no headset is worn. Further, VR body part localization was added to the VR self-localization. Both in specific clinical, as well as in healthy populations, systematic distortions in the perception and representations of one's own body have been found. This has provided additional motivation for the inclusion of body part localization in studies two and three for this thesis.

In study two, VR self-localization in terms of the physical body was mostly to all regions of the body from the upper torso upwards, as well as above the head. Further, participants were able to point reasonably accurately to most of their body parts in the LSID, but much less so in the VR headset. Inaccuracies were particularly large for the body parts near the borders of the body. After rescaling the self-localization pointing to the perceived body, it was mainly to the (upper followed by lower) face, followed by the (upper followed by lower) torso. This looked much more like the results from the previous behavioral studies than it did in terms of the physical body, while the differences between the VR setups had disappeared. The template task largely replicated study one, with pointing being to the upper torso most, followed by the regions of the face. It was concluded that people mostly localize themselves in the (upper) face and the (upper) torso. Moreover, that, for the interpretation of where people locate themselves, when using VR setups, it is important to take into account the occurring inaccuracies in body part localization.

In study three, an individually scaled and gender-matched self-avatar, animated by the tracked movements of the participant and seen from 1PP (co-located) and a 3PP (mirror-view), was implemented in the HTC Vive to provide rich feedback about the participant's body in a VR headset. Two groups of participants performed the VR self- and body part localization tasks, before and after an avatar adaptation phase where the self-avatar was experienced from either (normal) eye-height, or from chest-height.

The self-avatar as such did not reduce inaccuracies in body part localization. Changing the viewpoint did alter body part localization, though. Pointing to body parts was overall shifted upwards (more for the lower body parts) from the pre- to the post-test for the chest-height group, but not for the eye-height group. The self-avatar as such, nor changing the viewpoint, changed self-location, though. No evidence was found for experienced self-location being manipulated towards the viewpoint location. A non-significant trend towards higher self-location was present for the chest-height group on the contrary, which might be due to body parts being perceived higher than normal. It was concluded that experienced body part locations might be more plastic (influenced by viewpoint) than experienced self-location.

The differences between the self-localization results from the VR and the template tasks are debated and might be due to the 3PP pointing in the template task resembling pointing to someone else or even an external object, rather than to oneself.

Taken together, this thesis suggests a differential involvement of multi-sensory information processing in our experienced specific self-location and our ability to locate our body parts. Self-localization seems to be less flexible, possibly because it is strongly grounded in the 'bodily senses', while body part localization appears more adaptable to the manipulation of sensory stimuli, at least in the visual modality.

Keywords

Bodily self; bodily self-consciousness; body part locations; body template; first-person perspective; large-screen immersive display; multisensory cues; perspective; pointing; self; self-avatar; self-consciousness; self-location; third-person perspective; viewpoint; virtual reality; VR headset.

Abbreviations

1PP	: first-person perspective
3PP	: third-person perspective
AIC	: anterior insular cortex
AN	: anorexia nervosa
BIT	: body image task
BPQ	: Body Perception Questionnaire
CFBSPQ	: Conscious Full-body Self-perception Questionnaire
HMD	: head-mounted display
fMRI	: functional magnetic resonance imaging
IPD	: inter-pupillary distance.
LSID	: large-screen immersive display.
MPI	: Max Planck Institute
MPS	: minimal phenomenal selfhood
OBE	: out-of-body experience
(RM-)ANOVA	: (repeated measures) analysis of variance
SCR	: skin-conductance response
TPJ	: temporo-parietal junction
VAS	: visual analogue scale
VR	: virtual reality

1. General introduction

This thesis investigates where it is that people locate themselves in their bodies. Typically, when someone is asked where he[1] is, he identifies the location of his body as where he is located. Assuming asking where someone is, is indeed posing a question after the location in space of the material object constituting him, this answer is a perfectly correct one. However, as human bodies are extended in space, the answer may possibly be further specified. By asking a more specific question, possibly a more specific answer will be provided. Is/are there one or more specific region(s) of their bodies people consider themselves to be most? Or—in slightly different words—is/are there one or more region(s) of their bodies people associate themselves with specifically? The answer to this question is not currently known. Therefore, it is this question after (a) more specific self-location(s) in the human body that is investigated in this thesis, by means of different behavioral tasks in a series of related experiments using virtual reality (VR) setups. Furthermore, it is investigated how accurately people can locate several of their body parts, when using VR setups. This provides the additional possibility to examine indicated self-locations not only in terms of the physical body, but also in terms of what I call the perceived body (the perceived body will be introduced further in section 9).

In the sections following this general introduction, first some background will be provided on the position of the topic of self-location within the cognitive science and neuroscience literature on the bodily self (section 2). This will be followed by some background on where the topic of the bodily self fits in the philosophical literature on (self-)consciousness (section 3). These positioning efforts will not be comprehensive, as the relevant literature in both fields is much too extensive for providing such here. They are mainly there to show the most important connections of the current work with the existing literature on the bodily self. After having provided this wider framework, a section (4) will follow discussing previous work that has experimentally studied self-location, focusing on tasks probing the specific part(s) of the body people locate themselves in. This will be followed by a discussion of the motivations for performing the current series of experiments using various VR setups (section 5). Then the first-person perspective (1PP) pointing paradigm will be introduced which was used in the current experiments for both self- and body part localization using VR setups, as well as the third-person perspective (3PP) pointing to self on a body template task which was performed outside of VR (section 6). Then an overview of the first of the three current experimental studies will be provided (section 7). In this study, participants were asked to point directly to themselves with a virtual pointer while wearing a VR headset, as well as to point directly to themselves outside of VR on an outline of a human body under the assumption it was depicting them. As a VR pointing to body parts task was included in the second study of this thesis, section 8 will then discuss several tasks testing how accurately people can indicate the locations of their body parts. In the second study (introduced in section 9), participants were

[1] In cases without a specified referent, male pronouns are to be read as referring to all sexes or genders.

asked to point directly to themselves with a virtual pointer, as well as to several of their body parts, in two different VR setups, i.e. a VR headset and a large-screen immersive display (LSID). As a self-avatar was implemented in study three, section 10 will introduce the use of VR self-avatars in relevant research and applications. In the third study (introduced in section 11), participants pointed directly to themselves and to their body parts with a virtual pointer while wearing a VR headset, before and after having had a self-avatar adaptation phase, experienced from two different viewpoints on the body, i.e. at eye- and at chest-height. How the experiments for this thesis were performed and why they were designed as they were, will be explained in the three specific introductory sections (7, 9 and 11). Section 12 contains the general conclusions and an overall discussion of the thesis as a whole. Then the three original research papers will follow, with only formatting changes and incidental corrections in language relative to the published article versions: article 1: Van der Veer, Alsmith, Longo, Wong & Mohler (2018); article 2: Van der Veer, Longo, Alsmith, Wong, & Mohler (2019); and arrticle 3: Van der Veer, Alsmith et al. (2019).

2. Self-location and the bodily self in the cognitive and neurosciences

This section will briefly provide some background on the topic of self-location from the cognitive science and neuroscience literature on the bodily self. The next section will then provide a wider framework to this topic by discussing the bodily self from the philosophical literature on (self-)consciousness. Specific experimental studies on (global) self-localization and self-localization within one's body will then be discussed in section 4. section 8 is where previous experimental work on body part localization will be presented, which becomes relevant from the second study on.

As Blanke (2012) states, "Human adults experience a 'real me' that 'resides' in 'my' body and is the subject (or 'I') of experience and thought." In this statement he connects the experienced me, with my body, as well as with the experiencing I, and thereby self-consciousness with the body and consciousness per se. What I would like to take from this, is that there thus seems to be a link between my experience of what I typically refer to with the terms 'I', 'me', 'myself', or 'my self'[2] and my body. This and similar ideas have, particularly in the last two decades, led to a blooming field of experimental work into the so-called bodily self and bodily self-consciousness.

Bodily self-consciousness is typically defined as the non-conceptual and pre-reflective representation of body-related information (Lenggenhager, Tadi, Metzinger & Blanke, 2007). Often, three components of bodily self-consciousness are discerned: self-identification or body ownership, self-location, and first-person perspective (1PP). Body ownership concerns the conscious experience of identifying with or owning a body; self-location the experience of where 'I' am in space, or, more bodily, of being a body with a given location within the environment; and 1PP the experience of the position from where 'I' perceive the world, or, again more bodily, of taking a first-person, body-centered, outlook on an environment (Blanke, 2012). For a good recent overview of the scientific work on the functional, computational and neural aspects of bodily self-consciousness, see Blanke, Slater & Serino (2015).

In clinical cases of patients reporting different types of autoscopic experiences (mainly linked to lesions centered on the temporo-parietal junction (TPJ)), different aspects of bodily self-consciousness (body ownership, self-location and 1PP) can come apart (Blanke, 2008; Blanke & Metzinger, 2009). In autoscopic hallucination you see your body in extracorporeal space (as a double), from the usual 1PP anchored to your physical body and without disembodying your physical body (i.e. your experienced self-location is in your physical body). In heautoscopic hallucination you see your body alternatingly from the usual 1PP in your physical body (like in autoscopy) and from an extracorporeal perspective. Self-location is often experienced as ambiguous, or as alternating between the physical body and the double.

[2] I will use these terms interchangeably in the context of self-location, as the versions of different person and number will be. In this context, I consider the main differences between them of mere syntactical nature.

In heautoscopy, experiences of bi-location can occur, such that self-location and the origin of the 1PP are simultaneously experienced in different positions. Body ownership can be experienced over the double, your physical body, both (simultaneously or alternatingly), or be unclear. Heautoscopy forms an intermediate between autoscopy and out-of-body experience (OBE). In an OBE you experience yourself as located outside of your body (disembodiment), while you typically see your body and the world from an extracorporeal perspective above yourself (a form of autoscopy). In an OBE, body ownership, self-location, and 1PP are all abnormal, but typically do not come apart; ownership is over the virtual body, from where you see your body and wherein you experience yourself to be located. There are some reports of OBEs, induced by electrically stimulating the TPJ in patients, with disembodiment but not autoscopy, indicating that self-location and 1PP can also come apart there and may have (partially) different neural underpinnings (De Ridder, Van Laere, Dupont, Menovsky & Van de Heyning, 2007). In autoscopy body ownership, self-location, and the origin of the 1PP (but not the perspective on your body) are as normal; in heautoscopy they can all three be abnormal *and* need not be spatially consistent; in a typical OBE they are all three abnormal, while being spatially consistent with each other. For a discussion of disturbances of bodily awareness with a focus on disturbances of body part awareness and localization, see section 8.1.

Experimental work on bodily self-consciousness has been strongly promoted by advances in VR and related technologies, making it possible to provide ambiguous multisensory cues concerning body ownership, self-location, and 1PP in healthy participants (Blanke, 2012). Some of these experimental findings will be discussed in section 4.1 on global self-localization. Overall, and largely in line with patient studies, experimental studies have provided more extensive back-up for the functional and neuro-anatomical dissociation of ownership from self-location and 1PP, than of self-location and 1PP (Blanke, 2012; Serino et al., 2013).
Regarding 1PP, a further fruitful differentiation can be made into egocenter, origin, and egomotion (Alsmith, 2014). Egocenter is then the center of an egocentric frame of reference, centered on the body and used to locate external objects relative to you. This apparently simple phenomenon may in fact be quite complex. Neurophysiological and neuropsychological research on spatial representation suggests independent motivations for the head (e.g., Avillac, Denève, Olivier, Pouget & Duhamel, 2005; Grubb & Reed, 2002) and the torso (e.g., Karnath, Schenkel & Fischer, 1991) grounding the relevant frame of reference. Origin can be understood as the origin of a sensory field, from where you experience the world; which I will call viewpoint. Egomotion concerns the flow of your sensory experience, such that you can see where you are headed when moving.

The aspect of the bodily self of specific interest in this thesis is that of self-location. In the context of the bodily self, self-location is typically described in *global* terms, as the location where 'I' am in space, of being a body with a given location within the environment (Blanke, 2012), or as the experience of occupying a determinate location that may or may not be coinciding with one's own body (Lenggenhager et al., 2009). The question under investigation in this thesis is rather where it is that people locate themselves *specifically* within their bodies, or, slightly different, the part(s) of their bodies people associate themselves with the most. This question is still about self-localization in space and in bodily terms[3], but forms a specified version of the more global examples of self-location just given. The main interest here is to find out whether people locate themselves equally spread out over their bodies, or rather in one or more specific regions of their bodies, and if the latter, which one(s). section 4 will discuss some well-known examples of studies of self-location of the typical, global kind, followed by summaries of the rarer type of self-localization studies trying to specify self-location(s) within the body.

[3] This also means that the location(s) under investigation here are not of an immaterial self or a self separate from the body (not withstanding possibilities like selves extending into peripersonal space, tools, or towards or into other bodies of different kinds).

Where are you?

3. The bodily self and (self-)consciousness in philosophy

The present section forms somewhat of a side tour. It widens the framework of this thesis by providing some further background on the bodily self from the philosophical literature on the self, self-consciousness, and consciousness per se. It thereby aims to clarify the relation of the current experimental studies with this body of philosophical work, without aiming for comprehensiveness or strongly defending a position within the philosophical debates.

As Gallagher and Zahavi (2008) state, there is no scientific or philosophical consensus concerning what it means to be a self, or even whether selves exist. The spectrum of opinions can be sketched as lying between the position that the sense of self is an integral part of consciousness, as e.g. Damasio (1999) argues, and positions rejecting the existence of a self, as e.g. defended by Metzinger (2003) and common in Buddhism[4]. Gallagher and Zahavi further indicate that the diversity of positions reflects the diversity of approaches employed in the study of the topic and that it is under debate whether the different characterizations of self are actually connected by a unitary concept of selfhood.

In philosophy, several authors have defended that a pre-reflective, non-conceptual, or a minimal form of self-consciousness (i.e. of consciousness of oneself as oneself) is always present within cases of consciousness. Further, that such a minimal form of self-consciousness is necessary for the explanation of higher order forms of self-consciousness (Zahavi, 2005).

Within phenomenology, often a minimal or core version of the self (or self-consciousness) is proposed, which is in a subtle way experienced within phenomenal consciousness; phenomenal consciousness, which is always felt as mine, always entails a form of self-referentiality or for-me-ness. Moreover, self-experience is (thereby) not the result of stopping the interaction with the world and turning inwards, but always the self-experience of a world-immersed embodied agent[5] (Gallagher & Zahavi, 2008; 2015). On this phenomenological account, consciousness is thus always implying a pre-reflective, minimal form of self-consciousness (see also Sartre, 1957; Kriegel, 2009).

J. Smith (2017) discusses three forms in which self-consciousness might figure in experience[6]. First, as a (quasi-)perceptual awareness of the self as an object. Second, in a pre-reflective form of self-consciousness that does not involve awareness of the self as an object.

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[4] The early Husserl and early Sartre held related non-egological positions on consciousness.

[5] Having some form of self-awareness may actually be essential for survival, in the functional role of distinguishing self from non-self, as argued by Dennet (1991). Along similar lines, self-awareness is sometimes taken to be central to the understanding of immunology (for a treatment of the immunological self, see Pradeu (2012); for a discussion of a link between the immune self and the bodily self, see Constantini (2014)).

[6] As self-consciousness is a form of consciousness, consciousness obviously is a necessary condition on self-consciousness. A wide variety of reductive and non-reductive cases have been made for the claim that self-consciousness is also a necessary condition on consciousness.

Third, in experiences where one is aware of one's own states as one's own, i.e. involving a sense of ownership of one's own experiential states.

As a version of the first form, Brewer (1995) states that in experiencing bodily sensations a subject is aware of himself as a spatially extended body. In the intimate way in which these sensations make the subject's body parts appear as his own, he then also becomes aware of himself, as being an extended body (i.e. as an object) in space. In this way, Brewer defends that the inseparability of the mental and the physical presents itself in bodily awareness. Similar claims of through bodily awareness becoming aware of your body from the inside, i.e. as a bodily self, as you, have been made by several other authors (see J. Smith, 2017, section 3.1). As J. Smith rightly mentions, it can however still be debated whether one is indeed identical with one's body or not (e.g. Martin (1995) has argued against the assimilation of bodily awareness to self-awareness[7]).

Within philosophy, there is a long history of proposals how the self (as a thinking entity) might be related to the body. Descartes is notoriously known for his mental-material substance dualism, including the claim of there being some connection between the immaterial self and the material body without the person, or self, functioning as a captain on a ship, i.e. as having agency over the body without having sensory experiences of it. Then there are versions of materialism, claiming the self and the body are identical, and of constitutionalism, claiming the self is in some way constituted by the body without being identical with it (like a sculpture and the stone constituting it (Cassam, 2011)). Below, briefly some prominent recent proponents of embodied approaches to the self, included in the Oxford handbook of the self (Gallagher, 2011), will be mentioned.

Cassam defends the metaphysical claim that the self is embodied on the premises that (1) the self is that which perceives, acts, and thinks, and that (2) perceiving, acting, and thinking must be understood in bodily terms. Bermúdez argues for—what I think is a related claim, but at the level of experience—bodily awareness being a basic form of self-consciousness, through which perceiving agents are directly conscious of the bodily self (while at the same time rejecting the possibility of having a sense of body ownership). Both Legrand, as well as Henry and Thompson, defend a position where the self as the subject of experience is not only embodied—as when the body would in some special way belong to an essentially mental self—but bodily—resulting from the body constituting the subject of experience.

Further, work on the minimal conditions on (a minimal form of) self-consciousness has—in different ways—given a central role to the body. In their discussion of minimal phenomenal selfhood (MPS), Blanke and Metzinger stress passive forms of embodiment. Notably, body ownership (the experience of owning a body) is claimed to be sufficient for MPS (Blanke & Metzinger, 2009; Metzinger, 2003). A. J. T. Smith (2010) on the other hand, suggests an active

[7] Similarly, Cassam (1995) and Eilan (1995) have argued for the so-called elusiveness thesis, i.e. that there is something elusive about the subject of experience making it impossible for any awareness of an object to constitute awareness of oneself as a subject.

form of embodiment, i.e. embodied agency, to be a constitutive condition on phenomenal selfhood. How exactly the body is related to minimal forms of self-consciousness (in terms of necessary, sufficient and enabling conditions)—if at all—is a topic of ongoing investigation (A. J. T. Alsmith, 2012).

Considering that not only the question in what way, but also whether, a minimal form of self-consciousness is grounded in a form of embodiment has not yet been settled, it is of great interest not only to investigate philosophically, but also to test experimentally, how bodily experiences and experiences of self may be related. This thesis aims to contribute to the clarification of possible connections between the body and self(-consciousness), specifically by investigating bodily aspects of experienced self-location. The precise forms this has taken will be explained in the overviews of the specific experimental studies that have been performed, in sections 7, 9 and 11.

Where are you?

4. Self-localization

In this section, previous work will be presented that has experimentally studied self-location, with a focus on tasks investigating in which specific part or parts of the body people locate themselves.

The specific methods used in empirical research to investigate where people locate themselves depend on the notion of self-location under investigation (see section 2). Most studies have used what I have called the global notion, i.e. the bodily location people experience themselves to be in relative to external space. In the following section (4.1), some examples of studies investigating this notion of self-location will be described. However, in this thesis I am primarily interested in the more specific notion of self-location, i.e. the location(s) in their bodies where people experience themselves to be. Previous studies employing methods probing this more specific notion will therefore be presented next (section 4.2). Further, self-location is sometimes taken as the bodily location people consider to be the center from where they perceive the world, the center of their first-person frame of reference, or egocenter. This I have categorized as one of the more specific versions of the 1PP component of the bodily self (see section 2), but methods investigating the egocenter may also provide an indirect way of determining where it is that people experience themselves to be. Some studies illustrating this are included in the last two subsections (4.2 and 4.3) of the present section.

4.1. Studies of global self-location

In experimental studies investigating where people experience themselves to be in space, generally it is tested whether their experienced self-location can be manipulated, using techniques also used in the study of body ownership. Typically, in such studies, full-body illusions are induced by the synchronous presentation of manipulated multisensory (visuotactile, visuomotor, or visuovestibular) information about the body. By now, multiple studies have shown that people can experience a shift in their self-location to locations other than those of their own body.

Lenggenhager et al. (2007) have shown this using a head-mounted display (HMD) in which the participant saw a virtual body in front of him being stroked on the back, either synchronously or asynchronously with stroking actually performed on his own back. This resulted in the participant experiencing his self-location in the synchronous condition as shifted significantly more towards the virtual body's location (to a location outside of his actual physical body) compared to in the asynchronous condition.

Ehrsson (2007) showed the participant in a headset recordings of his own back, as from the perspective of a person sitting behind him. While seeing the illusory body behind him being stroked on the chest, the participant was actually synchronously or asynchronously stroked on his own chest. This resulted in the participant reporting sitting behind his physical location and looking at himself from there, as well as in larger threat-evoked (when the illusory body was 'hit' with a hammer) skin-conductance responses (SCRs) and stronger ratings of the illusion in the synchronous compared to the asynchronous stroking condition. This suggests, that not only manipulated correlations of visuotactile information, but also visual 1PP—in the sense of the origin of the visual field, from where you experience the world, or viewpoint—may determine where you experience yourself to be located.

Lenggenhager, Mouthon and Blanke (2009) employed experimentally induced OBEs, where self-location was indicated by the time a ball took to reach the ground in a mental ball-dropping task. They replicated self-location being experienced where touch is seen. Interestingly, they also found that self-location could be experimentally separated from both the location where the body is seen and from the 1PP origin.

In an fMRI study using an adaptation of the previous mental ball-dropping paradigm, Ionta et al. (2011) found the TPJ to reflect experimental manipulations in self-location, which also depended on the experienced *direction* of the 1PP. In a large lesion analysis study of patients with well-defined disturbances of self-localization, they found additional causal evidence for the TPJ encoding self-location. Combined, these findings provide evidence for the TPJ being involved in both the experience of being localized at a certain position in space and perceiving the world from that position and perspective.

In another study where OBEs were experimentally induced, Gutterstam, Björnsdottir, Gentile and Ehrsson (2015) could decode self-location from parieto-cingulate-hippocampal activity and concluded that the posterior cingulate cortex plays a crucial role in the integration of the senses of self-Location and body ownership.

4.2. Studies of specific self-location: body outline tasks and interviews

Several previous studies investigating where it is that people locate themselves specifically in their bodies, used outlines of human bodies and asked participants for the specific self-location either of themselves or of another person in or on these body outlines. Self-localization was thus performed on outlines of bodies not co-located with the participants' own bodies.

Limanowski and Hecht (2011) asked participants to indicate the center of the self by placing markers on human silhouettes and found a dominant role of the brain and the heart. At the individual level, they found that most people seem to believe there is one single point inside the human body where their self is located. Anglin (2014) used open questions and forced-choice self-localizing on a body silhouette and found, in contrast, that some participants reported that the self is not centralized in one location. Overall, she found participants tended to locate the self and mind in the head and the soul in the chest. Starmans and Bloom (2011, 2012) used implicit tasks, asking participants to judge when objects were closer to a depicted person, 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. Based on their results, they suggested that both adults and children locate the self mainly in the head and, more particularly, in or near the eyes. In studies 1 and 2 of this thesis, a self-localization pointing task on body outlines was included, i.e. the body template task introduced in section 6.2.

In interviews, Bertossa, Besa, Ferrari and Ferri (2008) asked participants for the I-that-perceives, the location from which they experienced previously located objects and body parts. 83 % of their respondents located this position within the temporal region of the head, midway behind the eyes. This study forms an example of how investigating the egocenter may also constitute an indirect way of determining where it is that people experience themselves to be.

4.3. Studies of specific self-location: behavioral tasks

Alsmith and Longo (2014) developed a behavioral task to elicit participants' judgments of precise self-location in their own bodies, instead of employing depictions of bodies or interviews. Their method allowed for the specification of multiple bodily locations across trials. They adapted a version of a task developed by Howard and Templeton (1966), originally designed for locating the point of projection of binocular vision. The original task required the subject to manually align a visually presented rod along the horizontal plane such that the near end pointed “directly at himself". Alsmith and Longo (2014) required subjects to align a rod along the sagittal plane such that it was pointing "directly at you", either haptically (whilst blindfolded) or visually (while verbally instructing the experimenter who was rotating the rod) (see Figure 1). Individual trials were split equally between two pointer starting directions, straight up and straight down. The pointer was located around chin height, between + and – ⅙ of body height. They found that participants’ judgments were not spread out homogeneously across the entire body, nor were they localized in any single point. They found two distinct regions appearing to be judged as where "I" am: the upper face and the upper torso, according to which participants reached first, i.e. modulated by the pointer starting direction. For the studies in this thesis, this self-directed pointing paradigm was extended for use in VR setups. Motivations for going to VR with this paradigm will be discussed in section 5. The VR pointing paradigm itself will be introduced in section 6.1.

Dixon (1972) used an indirect measure of self-location, by asking participants to indicate on three spatial dimensions (above/below/other, in front of/behind/other, and right/left/other) where certain body parts—which they had just manually stimulated and moved their attention to, with their eyes closed—were located from the vantage point of 'I' . 'I' was explained to the participants to be the point of reference, their subject-self, for these spatial judgments, while the body parts were their object-self. Participants were lastly also asked directly to describe where the 'I' seemed to be, when feeling the specific body part. He found some participants to be consistent head-localizers (i.e. locating their body parts relative to their heads), some consistent other-localizers, and that overall the location of the subject-self changed depending on which part of the body was touched and the direction of attention. Similarly, comparing behavioral methods to determine the egocenter, Barbeito and Ono (1979) argued that there may be a relation between the point subjects use as the self in methods directly probing self-location and the point from where directions are judged (the egocenter) as tested for by indirect methods.

Figure 1. The physical setup from Alsmith and Longo (2014). Here showing the haptic condition. Reused from Alsmith and Longo (2014) with permission from the publisher (Elsevier).

By rotating head and torso in opposite directions, an egocentric frame of reference centered upon the head may be misaligned with another frame centered upon the torso. In such a 'misalignment' situation, a single object may be 'to the right' with respect to the head and ‘to the left’ with respect to the torso. Following Peacocke's (1992) description of the phenomenology of experienced direction, it can be hypothesized that differences in experienced posture determine differences in egocentric perspectival experience. Misalignment situations may be effective to determine in a precise, quantitative way the respective contributions of the head and the torso to the organization of egocentric perspectival experience. Recently, Alsmith, Ferrè and Longo (2017) employed such a paradigm, where self-location might be implicated by the part(s) of the body used by participants to indicate the locations of external objects relative to themselves. Using this more implicit method, they found evidence for the use of a weighted combination of head and torso for self-location judgments. Again, this is an example of a study where a measure of the egocenter could be interpreted as an implicit measure of specific self-location.

In all the three articles included at the end of this thesis, this potential interpretation may have been stated too firmly as being advocated by Alsmith et al. (2017). Moreover, see Alsmith (2017) for the suggestion that an experience which is perspectival may not in itself represents its subject's location. There, Alsmith argues that only when an experience represents an object as the focus of its subject's possible action, does this experience contain self-locating content. With this, he argues against the perspectival self-location thesis (PST) and in favor of an agentive self-location thesis (AST). Further, he claims AST requires a unity of the body and thereby fits well with our intuition of being singly-located.

Wong (2017) suggests that balance and the vestibular system provide a master frame of reference, coordinating perception and action, and thereby are critical in agentive self-location (besides being important for body ownership and perceiving one's body's shape). He argues that the vestibular system anchors the self to its location and determines the referent of "here". Like Alsmith's account, Wong also provides an agentive account that could fit well with single self-location (although he does not specifically defend it), as the vestibular system likely provides an absolute, head-centered, frame of reference involved in the coding of (perception and) action.

Across previous studies, employing body outline tasks, interviews, and behavioral tasks, it must be concluded that the findings on specific self-location show a mixed picture. It is not well known, whether people typically locate themselves in one or more bodily locations, nor in which one(s) exactly. Therefore, several experiments were performed for this thesis to investigate specific self-location further. Section 5 argues why this was done primarily using VR setups; section 6 introduces the body template task and the VR paradigm used.

Where are you?

5. Motivations for investigating the bodily self in virtual reality

There can be several reasons for using VR in experimental work. Some of these are of a general nature; some are particularly relevant for studies of the bodily self. VR setups can provide relatively large experimental control and ecological validity compared with more traditional research setups, which are typically confined by the artificiality and limitations of research laboratories (Loomis, Blascovich & Beall, 1999; Reggente et al., 2018). The large parametric control over (visual) input variables (and output recordings) is extremely helpful for experimental work, where exactly this control is of central importance. Moreover, the (independent) manipulation of perceptual modalities is often more easily achieved in VR than outside of it and VR allows for some manipulations which would not otherwise be possible. A participant in a VR setup can e.g. be presented with specifically designed visual information of a body which is not his own, but which is co-located with his own body and tracks his movements, while other, directly 'body-based' cues (from proprioception, interoception, vestibulation, and somatosensation; for more on these cues see section 8.1) are unchanged and come from his own physical body. Such an unusual combination of multisensory cues cannot easily be created and studied without the use of VR technology (which here would include a display, a tracking system, and a computer-designed avatar). Particularly when using (self-)avatars, the different components of bodily self-consciousness, body ownership, self-location, 1PP, as well as bodily agency, can be manipulated and studied in relatively new and informative ways. In the example above, self-location and 1PP would be unchanged, whereas ownership and agency might be experienced over a virtual body. In the current thesis, VR is most importantly used in a similar way, i.e. as a tool for the experimental study of behavior and cognition; here specifically self- and body part localization. However, VR figures in this thesis in at least three more ways. These will be introduced briefly in the following paragraphs, in (more or less) decreasing order of relevance for the present work.

First, VR as constituting a special case for research. Even when you intend to use VR simply as a tool, it can always introduce some characteristics that are specific to the technology used, the virtual environments created, or the interaction of human participants with the technology. This unavoidably raises the question here, whether self- and body part localization function differently when using VR setups, or whether findings from VR can easily be extrapolated to situations outside of it (see e.g. Alsmith and Longo (forthcoming), discussing some specific elements of this issue). Although VR has been increasingly used in neuroscientific and behavioral research (for reviews see e.g. Bohil, Alicea & Biocca, 2011; Ehrsson, 2012; Slater & Sanchez-Vivez, 2016), the influence of VR technology on self- and body part localization has not yet been thoroughly investigated. Heydrich et al. (2013) did directly compare headsets using video-generated versus computer-generated visual information while discussing some of the potential differences these technologies introduce to the study of bodily self-consciousness. Other studies have also used LSIDs to study body and space perception (Piryankova, De la Rosa, Kloos, Bülthoff & Mohler, 2013; Mölbert et al., 2017). Both Heydrich et al. (2013) and Piryankova et al. (2013) report underestimation of egocentric distances in VR headsets (see also Loomis & Knapp, 2003; Renner, Velichkovsky & Helmert, 2013), although this distance underestimation has been found to have diminished for newer headsets (Creem-Regehr, Stefanucci, Thompson, Nash & Cardell, 2015; Young, Gaylor, Andrus & Bodenheimer, 2014). Piryankova et al. (2013) found underestimation also to occur in three different LSIDs. A comparison of different VR setups with respect to self- and body part localization was performed in study two of this thesis, introduced in section 9. Mohler, Creem-Regehr, Thompson and Bülthoff (2010) and Ries, Interrante, Kaeding and Anderson (2008) have shown the use of self-animated avatars to improve distance estimates in VR headsets. The reason for this is however not fully known. The effects of animated self-avatars (particularly as perceived from different viewpoints on the body) on self- and body part localization were investigated in study three, introduced in section 11. Overall, VR offers some large advantages for research, but one must be aware that some of its characteristics may also introduce general or specific error.

Second, VR as constituting a special case of reality. Recently, there have been huge advances in mobile and virtual/augmented technology, while consumer prices for the technology have decreased by at least a factor of 10. Moreover, VR is increasingly being used in a diversity of professional fields for purposes of training, telepresence, cooperation, and (physical and psychological) therapy. Where users experience themselves and their body parts to be located when using VR, may be important factors for the successful design of applications serving such purposes. Effectively, more aspects of our lives are becoming virtual. This makes it of increasing interest in itself, to know how behavior and cognition in general, and here self- and body part localization specifically, might function differently under these technological conditions. This speaks for fully acknowledging VR as a special (or perhaps only specific), but common, case of reality, deserving of being investigated in its own right, for its own characteristics.

Third, VR as a technology of interest. Investigating human behavior and cognition using state-of-the-art VR setups may reveal specific characteristics of the technology or of the functioning of virtual environments. More likely, it may reveal typical characteristics of the interactions of humans with VR technology. This project has indeed revealed some typical characteristics of such human-machine interactions, concerning mainly the accuracy of the perception of one's own body when using VR. These will be presented in the discussions of the respective experimental findings of this thesis.

6. The present pointing paradigm and body template task

One of the goals of this thesis has been to make novel contributions in the form of experimental paradigms for the investigation of self-location and body part localization. The three studies for this thesis have used a self-directed, 1PP pointing paradigm, adapted from Alsmith and Longo's (2014) self-directed pointing paradigm using a physical setup (discussed in section 4.3), implemented in, several different, VR setups for the first time. In study one, this paradigm was used for self-localization only; in study two and three, it was also used for body part localization. Studies 1 and 2 have additionally used a new 3PP body template self-localization pointing task, outside of VR, inspired by the Limanowski and Hecht (2011) and the Anglin (2014) tasks of indicating self-location on body silhouettes (discussed in section 4.2). Both the VR pointing paradigm and the body template task will be introduced generally below. How they have exactly been implemented in the present experiments, will be discussed in the overviews of the specific studies (sections 7, 9, and 11).

6.1. The VR pointing paradigm

As explained in the previous section, for reasons of experimental control and manipulation, and to be able to compare VR results with previous findings outside of VR, Alsmith and Longo's (2014) pointing paradigm using a physical setup (see section 4.3 and figure 1) was adapted for use in VR. The design of their setup was matched as closely as possible in a digital version developed in Unity, which could be implemented in a variety of VR setups, including different headsets and an LSID. To this end, a virtual environment was designed, consisting of empty space with a blue background. On each trial, the standing participant saw a round pointing stick with a blunt backside and a pointy front side (see figure 2.A for an example). The backside of the pointer was fixed to a virtual (i.e. non-visible) vertical plane orthogonal to the participant's viewing direction. The pointer had a light-grey color and had a fixed lighting source straight above (creating some shadow, providing a depth cue). The pointer's dimensions and its distance from the participant differed between experiments and are given in the overviews of the specific studies (sections 7, 9, and 11). Likewise depending on the specific experiment, different pointer starting directions (straight down or 0°, perpendicular to the participant or 90°, and straight up or 180°) and different pointer heights (either spread across and around the individual participant's head height, or spread out across the whole height of the individual participant's body) were included in the experimental design (see figure 2.B for an example abstract image of the setup). As in the Alsmith and Longo (2014) study, the independent variables pointer starting direction and pointer height were included to test for their possible influences on participants' judgements, as well as to make the task more diverse. The factorial designs and the planned analyses for each experiment will also be given in the overviews of the specific studies.

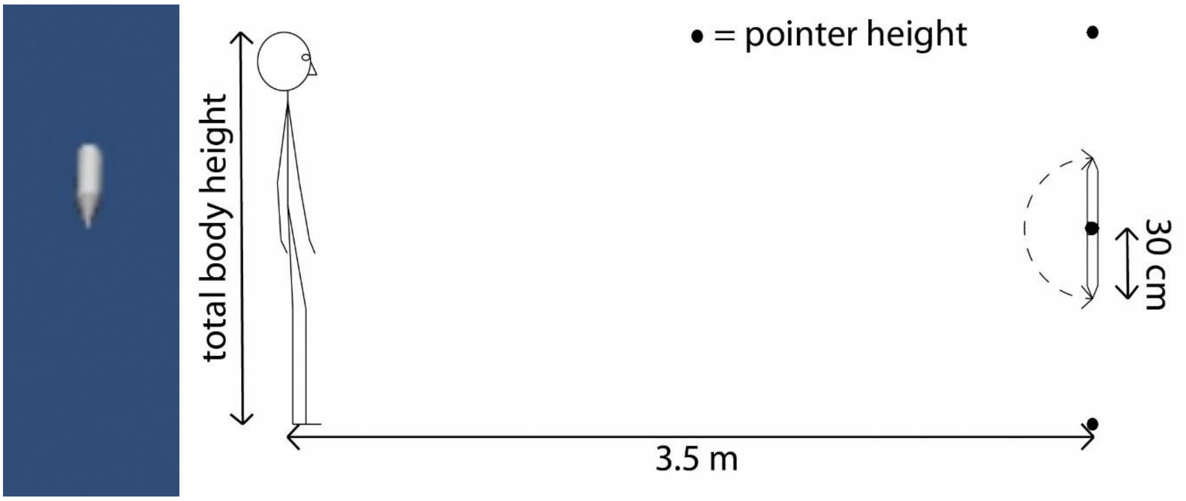

Figure 2.A. (left) An example pointer stimulus (from study three). **B. (right) A schematic depiction of an example set-up during the VR pointing task** (also from study three). The dotted line indicates the range of possible pointer rotations. The pointer length was here 30 cm. The pointer starting direction was here either straight up or down; three pointer heights were used, spread out across the complete height of the individual participant's body, i.e. at 0, 0.5, and 1 x total body height. The viewing distance was 3.5 m.

The paradigm introduced above was used in all studies for this thesis to investigate self-localization, with participants being instructed to rotate the pointer such that it was pointing "directly at you". In studies two and three it was also used for body part localization, where participants were instructed to point at several of their body parts (depending on the experiment these could include: the top of the head, eyes, nose, chin, shoulders, waist, hips, knees, and feet), which they would hear over loudspeakers one at a time as targets (more background on body part localization will be provided in section 8). To perform the task, the participant used the joystick on the left-hand side of a Microsoft Xbox controller to rotate the pointer upwards or downwards (both directions were permitted at all times) through their sagittal plane, with the speed proportional to the pressure administered on the joystick (the maximum speed was 75°/s). They confirmed their preferred position by pressing a button on the right-hand side of the controller. Participants were always asked to respond as accurately and quickly as possible, and to stand still throughout the experiment.

The 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 pressed the button for confirmation of their choice. Using the individualized height of the pointer, this angle was recomputed into the height at which the virtual extension of the pointer would intersect with the participant's body. As in Alsmith and Longo (2014), for self-localization, based on this intersection with the body, each response was coded as falling into one of seven bodily regions, which were determined by individual body measurements (performed before the start of the experiment): 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 for classification because we found substantial amounts of pointing there). These regions were chosen according to salient boundaries to facilitate coding, which correspond roughly to nameable body parts. For body part localization, a difference measure (in cm) was taken between the actual height of the individual participant's target body part (as measured before the start of the experiment) and the height on the body pointed at.

In study one, this VR pointing paradigm was used to investigate self-localization using the Oculus Rift DK2 headset. Study two extended the VR pointing paradigm to include both self- and body part localization, implemented for comparison in both the Oculus Rift DK2 and an LSID. In study three, again self- and body part localization was investigated, now in the HTC Vive, with the addition of an avatar adaptation phase where a 1PP (co-located) and 3PP (mirror- view) tracked, scaled and gender-matched self-avatar was experienced from a viewpoint at either eye-height or chest-height.

6.2. The body template task

In studies 1 and 2, an additional, new, body template self-localization task was implemented, performed by the participants after the VR pointing. This task consisted of pointing "directly at you" with a pen (making a small mark) on an A4 print of an outline of a body, under the assumption that this was a picture of yourself. This task thus existed in pointing outside of VR, on a body seen from a 3PP (which was therefore not co-located with the participants own body). As the measure, the pointing height on the template body in percent of the total template body height was taken.

In experiment one, only one image, of a frontal body outline (see figure 3, left image), was used. In experiment two, different perspectives on the body were added. Beside the frontal view, two outlines of a body seen from the side, one with and one without an arm visible (figure 3, center and right images respectively), were used.

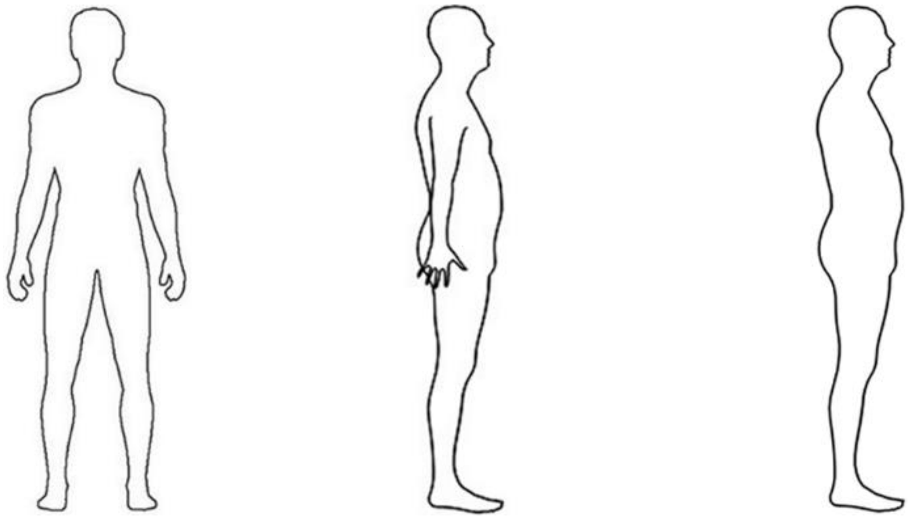

Figure 3. Body outlines used in the body template self-localization pointing task. Left: Frontal view (studies 1 and 2). **Center: side view with arm visible** (study two only). **Right: side view without arm visible** (study two only).

T-tests and Pearson correlation tests were performed to test for differences and correlations between the self-localization pointing heights in (specific setup) VR and on the body templates. In study two, t-tests were also performed to test for differences between the pointing heights on the different perspective body templates.

7. Overview of study 1: Self-localization in a VR headset

As concluded in section 4, it is not well known where people typically locate themselves precisely in their bodies. In section 5, motivations for investigating self-location in VR were provided, followed by a general introduction of the current VR pointing paradigm and the new body template task in section 6. In the first experimental study of this thesis, specific self-localization in the body was investigated in the Oculus Rift DK2, as well as using the body template task outside of VR.

The primary aim of this first study was to test where people locate themselves within their body when using VR and to compare the findings with results from outside of VR, from both Alsmith and Longo's (2014) study (the upper torso and the upper face) and the present body template task. To this end, a within-subject design was run with three factors: 2 x pointer starting direction (straight up and straight down), 5 x pointer height (chin height, chin height +/- 1/12 of total body height, and +/- 2/12 of total body height), and 10 x repetition (resulting in a total of 2 x 5 x 10 = 100 trials per participant); and one measure: pointing height on the body, categorized into five body regions for analysis (none of the responses were scored as below the upper torso and therefore the regions lower torso and below the torso were not included in the analysis). These pointer heights and starting directions are the same as in Alsmith and Longo (2014).

In this experiment, the pointer was 25 cm long and 2 cm wide, and the distance of the pointer from the participant was 1.3 m (the distance of the simulated focal plane in this VR headset, i.e. the distance of accommodation, equaled by the distance of vergence by putting the stimuli at this distance). Twenty-three people (thirteen female) participated in the study, all with (corrected-to-)normal vision, including stereopsis. Before the pointing task started, the following body heights were measured for later classification of the self-pointing heights based on individual body regions: the top of the head (more precisely, the cranial vertex), eyes (pupils), chin (gnathion), shoulders (acromion), and hips (greater trochanter). The participants received the following task instructions: in English: "Your task is to adjust the direction in which the stick is pointing so that it is pointing directly at you", or in German (the experiment was run completely in German with German speaking participants[8]): "Ihre Aufgabe ist es, die Richtung des Zeigestocks so zu verändern, dass dieser genau auf Sie zeigt". The percentages of responses for the different body regions were analyzed using a repeated measures analysis of variance (RM-ANOVA), with within-subject factors pointer starting direction (2 levels), pointer height (5 levels), and body region (5 levels).

After the VR pointing task had ended, participants were asked to perform the body template task, on a frontal body outline. They were asked to "Point directly at you", under the assumption that the printed image was a picture of themselves. It was tested whether a significant difference, or correlation, was present between the pointing heights in the VR

[8] With the exception of the post-questionnaire, which was only available in English for studies one and two; it was available in both German and English for study three.

setup and on the body template. Lastly, participants filled out an in-house developed paper-and-pencil post-questionnaire with questions concerning demographics, lifestyle, and well-being, as well as task strategies used (see supplement 1).

Our main findings for this study were the following. In the VR task, responses were not evenly distributed across the different body regions and a very strong preference was seen for pointing at the upper face; but not for the upper torso, as in Alsmith & Longo's (2014) bimodal results. Our findings are also not in line with the results from Alsmith et al. (2017), finding both head and torso, or Dixon (1972), finding mainly but not only the head for self-location. Pointing on the body templates was found to be significantly lower on the body than in the VR setups; no significant correlation was present between the two measures. More than half of the participants pointed to the upper torso in the body template task, and the rest to the (upper) face, while pointing to self in the VR setup was primarily to the upper face. These template findings are not in line with previous results from studies using body outlines (Anglin, 2014; Limanowski & Hecht, 2011; Starmans & Bloom, 2011; 2012) or interviews (Bertossa, Besa, Ferrari & Ferri, 2008), which mainly reported (locations related to) the face as the self-location indicated most. The present template results are more in line with the previous behavioral findings, whereas the present VR behavioral findings are more in line with the previous body outline and interview findings. Finally, most participants reported on the post-questionnaire that they had tried to point to the head or the eyes in the VR task, indicating that it had been a conscious strategy for most participants to point to a region or location in the upper face.

The results suggest that wearing a VR headset might alter where people locate themselves, specifically making them more head-centered. The strong head-focus in the VR task could be resulting from the use of the (specific) VR headset, VR more generally, or from not seeing one's own body (blocked by the headset, no self-avatar was provided; however, Alsmith and Longo (2014) did not report a qualitative difference between their blindfolded and seeing conditions, only one of precision). The headset may have particularly put focus on the head by being a large, heavy, pressing object on the participants' heads. In the template task, participants were outside of VR and did not have a device on their head, besides having a 3PP on a depiction of a body.

In the second study of this thesis, it was therefore further investigated whether VR technology in general might make people more head-centered, or if the HMD might play a role. To this end, a comparison was made between the same VR headset and an LSID (see section 9 for an overview of this study), employing the same VR pointing paradigm. Using an LSID, participants can experience VR without having a headset on their heads. Further, an LSID allows for some visual access to one's own body. This VR setup comparison thus explores whether having visual access to your body or wearing a device on your head may influence where you perceive yourself to be. Another way of providing visual information about one's body is by means of a scaled self-avatar, which was implemented in a motion-tracking version in study three of this thesis. A way of disentangling the effects of a 3PP perspective on the body and employing VR is to implement a 3PP localization task in VR, for comparison with the 3PP outside of VR results on the template task.

Moreover, in study two, the VR pointing paradigm was extended to include the localization of several body parts, beside self-localization. This was done to find out how accurately people can actually indicate where their body parts are located, when employing different VR setups (a headset vs an LISD). The various motivations for this inclusion of pointing to body parts will be provided more extensively at the beginning of section 9, in which an overview of study two is given. To provide some background, in the following section first some previous body part localization tasks and results will be discussed.

Where are you?

8. Body part localization

Both in clinical and in healthy populations, systematic distortions in the perception and the representations of one's own body have been found. In the first subsection (8.1) of the present section, some of these findings will be discussed, along with the introduction of various tasks that have been used for the investigation of body part localization or position sense. In study two, pointing to several of one's own body parts was included in the VR pointing paradigm, in order to complement the self-pointing methodology as employed in the first study. The accuracy of body part localization when using VR is of interest in itself, but here specifically as it provides a 'baseline' for the self-localization pointing, as well as the possibility to interpret the self-localization in terms of how participants perceive their bodies in VR (besides in terms of their physical bodies; see section 9). In the second subsection (8.2) of this section, the body representations which may be involved in body part localization will be further introduced.

8.1. Body part localization studies and tasks

Many neurological and psychological disorders of body awareness and representation have been described in the literature. De Vignemont (2010) e.g. gives a fairly comprehensive list of disorders of bodily awareness in the context of her evaluation of the body image and the body schema, whereas Semenza (2010) provides an overview of (the assessment of) the main disorders of awareness and representation specifically of body parts in a handbook of clinical neuropsychology. Many of these disorders are rare and difficult to dissociate. Many of them can have inaccuracies in the localization of body parts among their (more, or less, central) symptoms, though. In the next paragraph, the main (groups of) disorders of body *part* awareness (Semenza, 2010) will be described.

The most specific clinical disorder involving disturbed body part localization would be autotopagnosia, which consists in the mislocalization of parts and sensations of one's own body, as well as an inability to orient different of one's body parts. The concept, as well as the existence of autotopagnosia have been debated, but see Guariglia, Piccardi, Puglisi, Allegra and Traballesi (2002) for a discussion of a pure case. Pointing tasks are the most common way of diagnosing autotopagnosia. For conceptual and testing difficulties connected to this disorder, see e.g. Semenza (2010). Personal neglect (hemisomatognosia) is the neglect of one half of one's body, typically the left one resulting from a right-hemispheric lesion. Disorders which are often considered related to personal neglect are: allochiria (stimuli are mislocalized to the corresponding location on the opposite side of the body); anosognosia (being unaware of a deficit) for deficits contralateral to the lesion; somatoparaphrenia (confabulation with regard to the affected side, e.g. in the form of the attribution of one's own limb to someone else); extinction of contralesional stimuli to bilateral stimulation; and distal extinction to unilateral double tactile stimulation. Altered muscular proprioception, either in the form of proprioceptive deafferentation (loss of peripheral afferent input) resulting from peripheral pathology, or as deafferentation after a central (typically parietal) lesion, gives patients the feeling of using their bodies as tools, while being heavily dependent on visual feedback for performing bodily actions. The continued experience of a so-called phantom limb is common after amputation of a limb. Phantoms do however also occur for other parts of the body and can result from other causes than amputation, or even be congenital. Lastly, it has often been claimed that patients with eating disorders show distorted (vision-based) judgements of their body sizes, however this is now contested (Mölbert et al., 2018). Autoscopic phenomena, where you perceive a double of yourself, have been discussed in section 2. For other disorders of bodily awareness that may also involve distorted awareness of body parts, see De Vignemont (2010). Numbsense constitutes the paradigmatic contrasting clinical case, where having lost feeling in part or the whole of the body, patients can still react to stimuli in the affected area.

For the normal case, in contrast with these clinical cases, it has been assumed that the somatosensory system has access to accurate information about the body's size and shape (Soechting, 1982; Van Beers et al., 1998). However, to prevent drawings of human bodies from showing several systematic distortions (Kahill, 1984), most people must be taught how to draw body proportions correctly (Fairbanks & Fairbanks, 2005). Moreover, multiple studies have shown systematic distortions in several aspects of the awareness of one's own body to occur in healthy populations as well. Tamè, Bumpus, Linkenauger and Longo (2017) showed the robustness (specifically to differences in experimental instructions) of the distortions in the representations underlying three different aspects of own body perception in healthy adults, i.e. position sense, tactile distance perception and the conscious body image (measured judgments of hand size).

Regarding own body awareness, this thesis investigates how accurately people can indicate (point to) the locations of their body parts (in VR). Depending on the experimental condition, participants either had some visual access to their bodies during pointing to their body parts (LSID condition of study two), or none (VR headset condition of study two), or could have additional information in memory about their body part locations based on a previous experience with a scaled and tracked self-avatar (study three). Depending on the condition, they thus had (a) different type(s) of information available concerning the locations of their body parts: visual, proprioceptive, or from memory (based on vision and kinesthesis (movement sense or active proprioception) during the avatar phase). More comprehensively, besides visual cues, the non-visual body-based cues that may contribute to experienced body part locations are: proprioceptive (signals coming from muscle spindles and Golgi tendon organs) and interoceptive (signals carrying information about the states of internal organs of the body), but also vestibular (signals coming from the otoliths and semicircular canals), tactile (signals coming from cutaneous mechanoreceptors), as well as of other somatosensory nature (signals coming from e.g. nociceptors or thermoreceptors). During the pointing tasks, the participants were standing still and, in most conditions, had no visual access to their own body, which likely makes position sense key to their ability to locate their body parts. Position sense is generally considered to be the sense of the relative positions of one's body parts (a form of passive proprioception, i.e. separate from (self-initiated) movement, and from vision). Multiple studies have now shown systematic distortions in position sense in healthy populations, which may involve distortions in body representations (Fuentes et al., 2013; Hach & Schütz-Bosbach, 2010; Linkenauger et al., 2015; Longo, 2017; Longo & Haggard, 2010, 2012; Saulton, Dodds, Bülthoff, & de la Rosa, 2015).

There exist several methodologies for measuring body part localization on the physical body. When testing patients' abilities to localize body parts, it is common to have them point to specific parts of their own or the examiner's body (Sirigu, Grafman, Bressler & Sunderland, 1991; Felician, Ceccaldi, Didic, Thinus-Blanc & Poncet, 2003), or to objects placed on specific locations of their own body. In these clinical tests, target instructions can be in various forms: spoken, written, pictorial, pointing, or touching (Felician et al., 2003). To test for patients' ability to *identify* body parts, Semenza and Goodglass (1985) used a variety of tasks involving pointing to and touching of one's own and depicted bodies and body parts.

Using several methodologies pertaining to the research for this thesis, scientists have confirmed systematic distortions in own body part localization performance in healthy populations. 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 & Schütz-Bosbach, 2010), and to body parts on one's own body imagined in front of oneself (Hach, Ishihara, Keller, & Schütz-Bosbach, 2011). They found for self-directed pointing with one's own hand that shoulder, waist and hip widths were overestimated. Longo and colleagues (Longo & Haggard, 2010; Tamè et al., 2017) had participants indicate with a baton where they perceived specific spatial landmarks on their occluded hands. They found specific distortions relative to the physical hand, namely overestimation of hand width and underestimation of finger length. These body part localization paradigms rely on physical, self-directed pointing with the finger or an apparatus, either to one's own (physical) body or on a plane occluding the body from vision.

Fuentes, Longo and Haggard's (2013) desktop body image task (BIT) focuses on participants providing estimates of body part locations on a not co-located body. On a computer screen a head was seen as a mirror-image of yourself 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 and 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.

After having discussed these paradigms and findings from body part localization studies, the focus in the next section will be on the body representations involved in locating one's body parts.

8.2. Body representations involved in body part localization

Longo and Haggard (2012) found that the implicit representation underlying position sense (as measured with pointing to spatial landmarks on one's occluded hand) and the conscious body image, when tested with a metric measure (comparison of a body (part) with a non-body standard), are likely not independent. They concluded that metric measures might not be a pure measures of body image, but some combination of visual and somatosensory body representations. Analogously, I think that for position sense (or body part localization) a combination of implicit and explicit (visual) representations may be employed as well.

For a review of the body representations and the types of information processing that may be involved in pointing to body parts, as well as the disorders it is affected by, see De Vignemont (2010). In section 3 of that review, De Vignemont discusses how (at least) both the body schema and the body image may be involved in pointing to one's body parts. Pointing to body parts would, as a measure of the body schema, be impaired in deafferentiation but not in numbsense and, as a measure of body image(s), in autotopagnosia but not in apraxia. Further, she defends that it might also depend on the target (e.g. one of one's own body parts vs a map of a body part), on the type of errors measured (e.g. spatial versus categorical), and on the type of movements performed (e.g. a slow visually guided gesture vs a fast ballistic movement), which different types of body representations are recruited.

The combined use of the terms body image and body schema goes back at least as far as Head and Holmes (1911-1912). The body image is generally considered to be a conscious (or consciously accessible) mental representation of what one's body looks like and to be mainly based on present bodily sensations combined with perceptual and social information related to one's body from memory. Information about one's body in the visual modality is suggested to form the main basis for the body image, while less is known about the influences of non-visual bodily information (Thaler, Geuss & Mohler, 2018). The body image is often considered to consist of (at least) a perceptual and an attitudinal component (Gardner & Brown, 2014; Slade, 1994). The body schema in contrast, is generally considered to be an unconscious representation of the body used for action (Dijkerman & De Haan, 2007; Paillard, 1999). Whereas aspects of body posture and movement may become conscious, Gallagher (2005) characterizes the body schema itself—while constantly regulating posture and movement—as always remaining in excess of what can become conscious. He further argues that the body image—in contrast to the body schema—normally entails a personal-level experience of the body involving a sense of ownership over the body; involves abstract and partial representations of the body, instead of functioning in a more integrated and holistic way; and is differentiated from the environment, instead of functioning in integration with it.

For general overviews of the representation of one's own body, see e.g. Longo, Azañón and Haggard (2010), Longo (2016), or Medina and Coslett (2010). As Azañon et al. (2016) point out, so far too little attention may have been given to the relation between (goal-directed) action and body representations, although particularly from tool-use examples are well-known (e.g. Cardinali, Frassinetti, Brozzoli, Urquizar, Roy & Farnè, 2009). Longo (2017) lists several different representations which have been proposed beside the body image and schema, all of which I can image being involved in pointing to body parts, depending on the exact task: the superficial schema, mediating localization of stimuli onto the body surface; the body structural description, underlying representation of the spatial layout of body parts; the body model, specifying the metric properties of the body; and body semantics, underlying general knowledge about the body and words for body parts. Particularly De Vignemont's (2010) review makes it clear, how intricate the seemingly straightforward task of indicating the locations of one's own body parts by pointing to them is in terms of information processing and body representations. It will therefore unfortunately not be possible within the scope of this thesis to provide a comprehensive interpretation of all findings in terms of the body representations involved.

Where are you?

9. Overview of study 2: Self- and body part localization using a VR headset and a large-screen immersive display

Concluding from study one (finding self-localization mainly in the upper face), wearing a VR headset might alter where people locate themselves, specifically making them more head-centered. In study two, it was therefore investigated whether VR technology in general might make people more head-centered, or if the HMD might play a role. This was done by comparing the same VR headset with an LSID (see figure 4), employing the same VR pointing paradigm as in study one. In addition, using the LSID, participants could experience VR without having a headset on their heads and with some visual access to their own bodies.

Moreover, to find out how accurately people can actually indicate where their body parts are located when employing different VR setups, the VR pointing paradigm was extended to include the localization of several body parts. Also, to investigate further how self-localization in the template task differs from in VR, this task was included again, with additional outlines showing different perspectives on the body (i.e. from the side, with and without an arm visible, in addition to from the front; see figure 3).

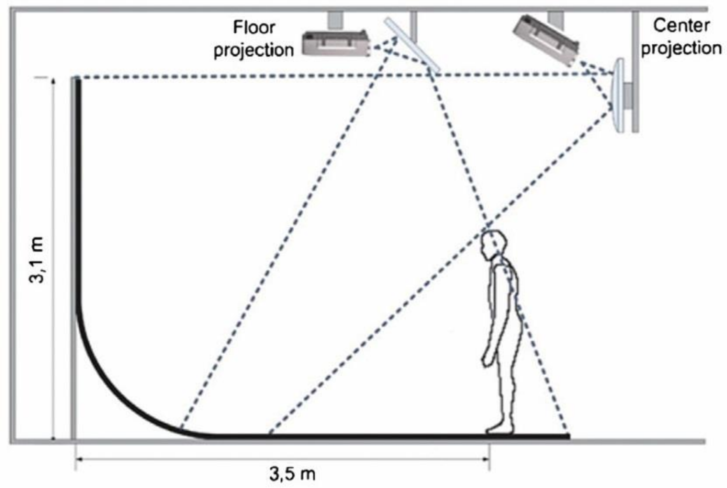

Figure 4. A schematic depiction of the Panoramic LSID experimental setup, located at the Max Planck Institute (MPI) for Biological Cybernetics, Tübingen, Germany. Reused from Piryankova, De La Rosa, Kloos, Bülthoff & Mohler (2013) with permission from the publisher (Elsevier).

After the experimental tasks, the awareness scale of the Body Perception Questionnaire (BPQ; Porges, 1993; see supplements 2, for the English version, and 3, for the German version) was administered, to investigate whether there was a correlation between the accuracy of body part localization or the height on the body for self-localization, and the score on this measure of interoceptive sensibility.

The following were the main research questions for study two. (1) Does pointing to self and body parts differ between a VR headset and an LSID? (2) Is indicated self-location in the body template task outside of VR similar to self-localization in VR? (3) Where do people precisely locate themselves in their bodies? Connected to these questions, the following were the main predictions. (1) Differences between the VR setups (specifically, visual access to the body, presence of a headset, and differences in spatial perception) will result in differences in self- and body part localization between the two VR setups. (2) In contrast to the VR setups, where overall (upper) face possibly followed by upper torso is expected, participants will indicate mainly the upper torso, followed by the upper face, as self-location in the body template task (as in study one). (3) Participants will primarily point to the (upper) face and possibly also the upper torso in VR for self-location (Alsmith & Longo, 2014; study one), and, if distortions in body part localization are present, self-location will differ in terms of physical vs perceived body regions. First, the changes in the design and methods relative to study one will be introduced, followed by the various ways in which the body part localization findings are of interest. After that, an overview of the results and their interpretation will be presented.

Participants performed a pointing to self task in the two VR setups, i.e. a VR headset (Oculus Rift DK2, as in study one) and an LSID. The order of the two VR setups was counterbalanced. After completing the self-pointing task, they performed a pointing to body parts task, again counterbalanced in terms of VR setup. Following all VR pointing tasks, the participants performed the body template task and filled out the BPQ. The complete VR part of an experimental session consisted of a fully within-subjects design with four runs. For self-localization there were three factors: 2 x VR setup (= 2 runs) + 3 x pointing starting direction (straight up, straight down and perpendicular to the participant) + 7 x pointer height (0, 0.25, 0.5, 0.75, and 1 x total body height; middle of the neck; middle between ground level and knee height); and one measure: body region (with substantial data for all regions, so all seven regions were included in the analysis). For body part localization there were 4 factors: 2 x VR setup (= 2 runs) + 9 x target (feet, knees, hips, waist, neck, chin, nose, eyes, top of the head) + 3 x pointing starting direction (straight up, straight down, and perpendicular to the participant) + 7 x pointer height (0, 0.25, 0.5, 0.75, and 1 x total body height; middle of the neck; middle between ground level and knee height); and one measure: error distance from the physical body part location (in cm; directional/signed, i.e. it can be negative (pointing below the target) or positive (pointing above the target)). This resulted in a total of 2 x (3 x 7) + 2 x (9 x 3 x 7) = 420 trials per participant. The additional pointer heights (spread across the whole height of the body, instead of across and around the face only) and the additional pointer starting direction (perpendicular to the participant; see sections 2.5.1 and 3.1 of Van der Veer, Longo, et al. (2019; included this thesis after the synopsis as article 2), for how this was used to test for a possible hysteresis effect), compared to Alsmith & Longo (2014) and study one, were added to prevent priming by the pointer.

In this experiment, the pointer was 30 cm long and 4 cm wide (making the pointer a bit larger than in study one, for better visibility), and the distance of the pointer from the participant was 3.5 m (the distance of the LSID physical screen, i.e. the distance of accommodation). Thirty people (eighteen female) participated in the study, all with (corrected-to-)normal vision, including stereopsis. Before the pointing task started, the following body heights were measured: the *top of the head* (the cranial vertex), *eyes* (pupils), (tip of the) nose, *chin* (gnathion), *shoulders* (acromion), elbows (the most laterally protruding part of the bone), waist (where the circumference of the lower torso is smallest), *hips* (where the circumference is largest), *knees* (top of the knee cap), and *feet* (above the talus). During these measurements, the names of the respective body parts were mentioned to the participants, their specific locations on the body were explained, and the participants were tapped on these locations (where possible), so that, when they would hear body part targets (the ones above in italics) over the loudspeakers during the experimental runs, it would be clear what was meant exactly. As in study one, these measurements were also used for later classification of the self-pointing heights based on individual body regions. For the self-localization tasks, the participants received the following task instructions, in English: "[…] to adjust the direction in which the stick is pointing, so that it is *pointing directly at you.*", or in German (the experiment was run completely in German with German speaking participants): "[…] die Richtung des Zeigestocks so zu verändern, dass dieser *genau auf Sie zeigt.*"; and for the body part localization tasks, in English: "[…] to adjust the direction in which the stick is pointing, so that it is *pointing at different of your own body parts.*", or in German: "[…] die Richtung des Zeigestocks so zu verändern, dass dieser *auf verschiedene Ihrer Körperteile zeigt.*". As in study one, after the VR pointing tasks the body template task was performed. Now, three body outlines were presented to the participant, one at a time, with the side-views in counterbalanced order first or third and the frontal view always as the second one. After this task, the paper-and-pencil awareness scale of the BPQ was administered, which is a self-measure questionnaire with forty-five items, to be answered on five-option Likert scales ranging from "never" to "always". Finally, participants filled out a paper-and-pencil post-questionnaire, adapted from study one (see supplement 4).

As discussed in section 8, both in clinical and in healthy populations systematic distortions in the perception and representation of one's own body have been found, including distortions in body part localization. In study two, the VR pointing paradigm was extended to include pointing to body parts. The accuracy of body part localization (in different VR setups) is of interest in itself, but here particularly so, as it provides a 'baseline' or background against which to interpret the self-pointing. One way of taking into account the possible presence of distortions in body part localization—both general ones and those related to visual perception in VR—is not to assume the physical body as the best baseline for determining where people point to themselves. Indicated (i.e. pointed at) body part locations provide the possibility to interpret indicated self-locations in terms of how participants perceive their bodies. This was achieved by taking the mean heights of body parts as indicated in the pointing to body part task, per individual and VR setup, and using these as the borders of the body regions into which the self-pointing trials were classified. Besides that every self-pointing trial can be scored as falling into a specific region of the individual participant's physical body, it can thus be scored as falling into a specific region of the participant's perceived body. The analysis of the self-localization data was subsequently redone, in the same way as before, but now based on the perceived body. This way, self-localization could be compared between physical and perceived bodies, by setup. Additionally, average bodies were depicted, scaled by both the physical body part locations, as well as by the perceived body part locations per VR setup. For the present sample of participants, these average bodies can be seen in figure 6 of Van der Veer, Longo et al. (2019). Fuentes et al. (2013) and Linkenauger et al. (2015) are previous studies employing the rescaling of body shapes based on experimentally determined perceived body part locations.

The percentages of responses for the different body regions were analyzed using a repeated measures analysis of variance (RM-ANOVA), with within-subject factors VR setup (2 levels) and body region (7 levels). This was done, first for the regions of the physical, and second for the regions of the perceived body. The error distances for the different body parts were analyzed in the same way, with the factors VR setup (2 levels) and target (9 levels). Further, it was tested whether a significant difference, or correlation, was present between the pointing heights in the VR setups and on the body templates. It was also tested, whether there were differences between the pointing heights on the different body outlines of the template task. Finally, it was tested whether there was a correlation between the accuracy of body part localization, or the height on the body for self-localization, and the score on the BPQ awareness scale (the mean, between 1 and 5, over all 45 items).

The main findings for this study were the following. For self-localization in terms of the physical body, there was a main effect for body region: pointing was not evenly spread out across the body, but mainly to the regions from the upper torso upwards, as well as above the head. This effect was modulated by a significant interaction between VR setup and body region; specifically, there was significantly less pointing to the upper and lower face, and more above the head, for the VR headset compared to the LSID. The self-location results from study one (predominantly upper face) were not replicated by the present VR headset findings (mainly spread across all regions from the upper torso upwards, as well as above the head). Why this is, is not fully clear. The most likely candidate for part of the explanation is the added lower pointer heights, which may have reduced pointing accuracy particularly to higher regions, promoting spread around the (upper) face and the overshooting above the head.

Considering the mean error distances for body part localization, significant effects were found for the factors target and VR setup, as well as for their interaction. Participants were able to point reasonably accurately (with mean error distances of around +/− 10 cm) to most of their body parts in the LSID, but much less so in the VR headset. In the VR headset, the mean height of the top of the head was much overestimated and the mean heights of the feet, knees, and hips were much underestimated. In the LSID the mean height to the top of the head was overestimated and the mean height of the feet was underestimated, but both less so than in the headset. In specific comparisons, there were significant differences between the two setups for all body parts, except the nose. Concluding, body part localization differed between VR setups. As was discussed further in section 4.1 of Van der Veer, Longo et al. (2019), this may be due to differences in visual access (possibly causing having less sense of one's body boundaries in the VR headset), physical setup (having a heavy device on the head or not), human-machine interaction (particularly possible differences in egocentric distance estimation), or distance of natural vergence. Whether these findings also reflect inaccuracies in body part localization of a general nature (see section 8), or general to VR (see section 5), is still difficult to say. Answering this question would greatly benefit from further modifications to the pointing to body parts task in the current paradigm, both in VR and to outside of VR.

Since body part localization showed large inaccuracies, and differed per VR setup, there was indeed good motivation to redo the analysis of self-location using the individual perceived bodies, per setup, as described above. For self-localization in terms of the perceived body, a main effect was found for body region: pointing was now mostly to the face (upper followed by lower), followed by the torso (upper followed by lower), while hardly any pointing above the head was left. There was no longer an interaction between VR setup and body region. In specific comparisons, particularly salient was that the upper and the lower face had received significantly more pointing than all other regions (except the other face region). The large amount of pointing to the face for the LSID was somewhat unexpected though, as there no special emphasis was placed on the head and participants had visual access to their bodies. Rather than attracting attention to the face, the headset might have been blocking the face from being pointed at, but this would leave the predominant pointing to the upper face in experiment one unexplained. Overall, the self-localization in terms of the perceived body looks much more like the bimodal results from previous behavioral studies (Alsmith & Longo, 2014; Alsmith et al., 2017; Dixon, 1972) than it did in terms of the physical body. In terms of the physical body, there were differences in self-localization between the VR setups (as described above), but in terms of the perceived body these largely disappeared. Distortions in body perception in VR may therefore be confined to inaccurate body part localization, while not involving self-location as such.

Overall, the normalized pointing height on the body templates was lower than the pointing height normalized to the physical body in either of the VR setups, significantly lower only compared to the LSID however (which was somewhat unexpected, as the tasks both involved visual access to a body and not having a device on the head). In VR, participants pointed mainly to the upper face, and to a lesser extent to the lower face and the upper torso. On the body templates, participants pointed mainly to the upper torso and to a lesser extent to the face. There was no significant correlation between the pointing heights on the body template task and either of the VR setups. No significant differences were found between the pointing heights on the different body outlines used in the template task. These body template results largely replicate those from study one. Possible causes for the different results for the template and the VR tasks are discussed in section 4.2 of Van der Veer, Longo et al. (2019) and in the general discussion in section 12.

There were no significant correlations between the BPQ awareness scale and body part localization accuracy, or self-localization pointing height. Possible causes of this null-result are discussed in section 3.5.1 of Van der Veer, Longo et al. (2019).

Across the participants who reported on the post-questionnaire that they had tried to point to specific bodily locations for self-location (about two-thirds of the sample), these locations were almost equally split between head/eyes and chest. This differs from study one, where most participants reported to have tried to point to the head or eyes. This additional intention to point to the chest in study two might be reflected in the larger amount of self-localization in terms of the perceived body found in the upper torso for the LSID compared to the VR headset. This difference with the VR headset also makes the LSID findings more similar to those from outside of VR (Alsmith & Longo, 2014), with which it has visual access to the body in common. The bimodal self-pointing intentions in study two are somewhat reflected by the behavioral results for both setups (mainly face, followed by torso), although not as clearly as the unimodal intentions in study one were mirrored by behavioral results. For body part localization, the strategy reported most (by more than half of the sample) was trying to feel where their body parts were.

Overall, it seems that people mostly do localize themselves in the (upper) face and the (upper) torso. Specifically, using different VR technologies, with and without a device on one's head, and with and without visual access to one's own body—when it is taken into account how people perceive their bodies when using the different VR setups—the indicated self-locations are largely the same, i.e. face followed by torso; and torso followed by face in the 3PP task outside of VR.

Additional modifications to the current paradigm, to be considered after this study, include the following: the implementation of an avatar with individually scaled bodily dimensions, as an alternative way of providing feedback about one's body, in order to test whether this changes the localization of body parts (e.g. becoming more accurate) or yourself (e.g. becoming more like outside of VR) in VR. A specific version of this avatar modification was implemented in study three, summarized in section 12. First, in the following section, some background will be provided on the use of VR self-avatars.

10. Virtual reality and self-avatars

In previous sections (mainly 4 and 5), the increasing use of VR technology, both in applications and in research, has been discussed. For a review of the use of VR in the study of bodily self-consciousness and body representations, see e.g. Blanke et al. (2015). Within VR applications and research, the implementation of (self-)avatars is becoming more common. Self-avatars are particularly useful in ergonomic applications, where the fit between humans, products and procedures can be tested virtually before production (Colombo, Regazzoni & Rizzi, 2013; Honglun, Shouqian & Yunhe, 2007). Additionally, it has been recently shown that (partial) self-avatars can improve collaboration in virtual environments (Beck, Kunert, Kulik & Froehlich, 2013; Rabätje, Menzel & Wochnig, 2017). Cyberpsychology is yet another area where avatars have since some time found substantial application, both in assessment and in therapy (Freeman et al., 2017; Mölbert et al., 2017; Rizzo, Koenig & Talbot, 2018). Knowing how self-avatars in a VR headset may alter experiences of one's body and self in terms of their locations, can be important for the design of specific exposure or testing protocols for these application areas.

Lenggenhager et al. (2007) had shown that participants can be made to mislocalize their global self-location towards a virtual body seen in front of them in an HMD by manipulating visuotactile information, i.e. stroking the participant's back in synchrony with him seeing stroking of the virtual body's back (visuotactile synchrony). Subsequently, Petkova and Ehrsson (2008) had participants experience full-body ownership (ownership with respect to the whole body) over a virtual body seen in 1PP (looking down) in an HMD by means of similar visuotactile synchrony. For a review of the work on the embodiment of virtual bodies, see Slater & Sanchez-Vives (2016). A lot of this work has focused on the relative contributions of 1PP (vs 3PP) (Petkova, Khoshnevis & Ehrsson, 2011; Slater, Spanlang, Sanchez-Vives & Blanke, 2010), and visuotactile and visuomotor synchrony (Aspell, Lenggenhager & Blanke, 2009; Gonzalez-Franco, Perez-Marcos, Spanlang & Slater, 2010; Kokkinara & Slater, 2014) in full-body illusions. Several other studies have investigated body size experiences involving manipulations of the visual body (Piryankova et al., 2014; Van der Hoort, Guterstam & Ehrsson, 2011).

Slater et al. (2010) showed that a 1PP on a virtual body could suffice for a body transfer illusion to occur. Several studies using virtual bodies have found indications of a tight link between (the direction of the) 1PP and self-location (Ionta et al., 2011; Pfeiffer et al., 2013). Gonzalez-Franco et al. (2010) showed that virtual mirror (3PP) exploration of a synchronously animated avatar could result in embodiment of the virtual avatar.

Understanding how animated self-avatars and differences in viewpoint influence body part and self-localization has implications for both basic research and applications that provide the user with an animated self-avatar or a visual perspective from an altered viewpoint. The next section gives an overview of study three of this thesis, where an individually scaled and animated self-avatar, experienced from different viewpoints on the body, was implemented between two sessions of self- and body part localization performed in the present VR pointing paradigm.

11. Overview of study 3: Self- and body part localization after a self-avatar adaptation phase experienced from different viewpoints on the body

To investigate the role of multisensory feedback and perspective in bodily awareness further, a self-avatar was implemented in study three, which was experienced in 1PP (co-located) and in a 3PP (mirror-view), from different viewpoints (origins of the visual field) on the body.

As mentioned at the ends of sections 7 and 8, an alternative to using an LSID for providing visual information about one's body in VR is by means of a scaled self-avatar. In study three, an individually scaled and gender-matched self-avatar (see figure 5), animated by the tracked movements of the participant and seen from 1PP (co-located) and a 3PP (mirror-view), was implemented to provide rich visual and body-based cues about the participant's body. Self- and body part localization was performed in a VR headset using the same VR pointing paradigm as in the previous studies (without avatar present), before and after a five-minute adaptation phase of free movement and exploration of the self-avatar. The rich, multisensory feedback about the participant's body during this adaptation phase was provided to test whether (a form of memory based on) vision and kinesthesis (movement sense or active proprioception) from this phase would change self- and body part localization, e.g. make body part localization more accurate. Moreover, it is known that the experience with a self-animated avatar improves distance estimates in VR headsets (Mohler et al., 2010; Ries et al., 2008), which might also help improve accuracy in the present VR pointing paradigm.

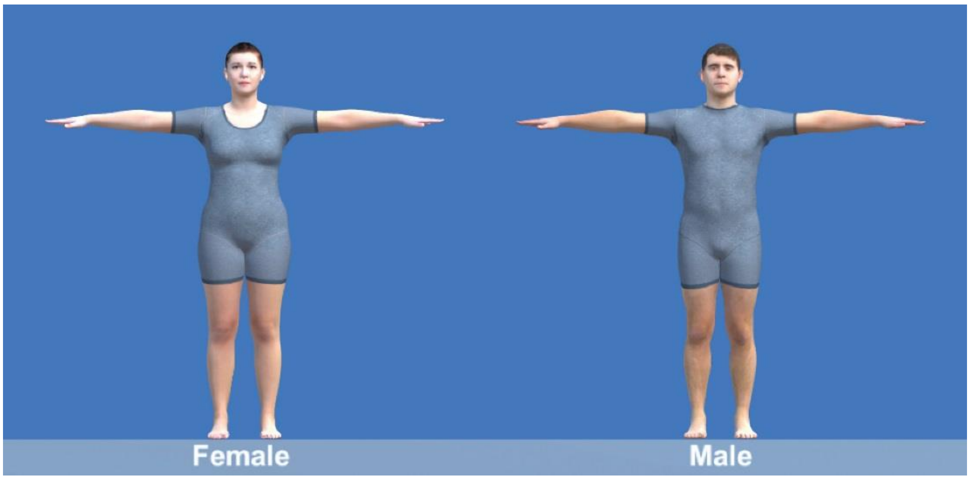

Figure 5: the female and male SMPL avatars used in the experiment.

As concluded after study two, people seem to self-locate mainly in the (upper) face and the (upper) torso. The viewpoint from the body during the self-avatar adaptation phase was therefore manipulated to either eye-height or chest-height (see figures 6A and 6B, respectively), to investigate whether this would change self- and body part localization, e.g.

shift self-location towards the experienced viewpoint. This means, the self-avatar was experienced in 1PP and 3PP from a viewpoint (origin of the visual field) at one of two heights on the body, i.e. eye-height or chest-height, while all other parameters of the self-avatar were kept the same between the viewpoint conditions.

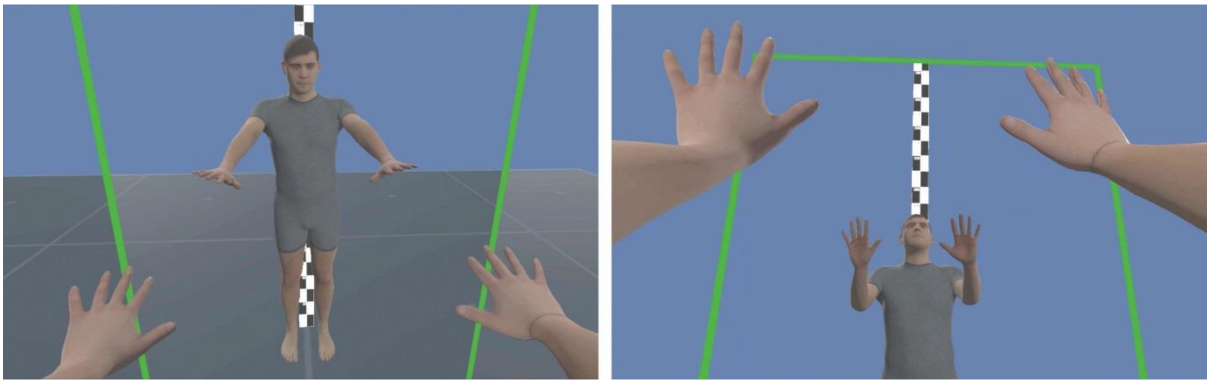

Figure 6.A. (left) Image of the avatar adaptation phase from the viewpoint at eye-height. B. (right) Idem at chest-height.

Following the VR tasks, the participants filled out an adapted version (seven of the original twenty-seven questions did not apply) of the Conscious Full-body Self-perception Questionnaire (CFBSPQ; Dobricky & De la Rosa, 2013; see supplements 5, for the English version, and 6, for the German version), to investigate whether there was a difference between the two viewpoint conditions in the extent to which the avatar was embodied.

The main questions in study three were the following. (1) Does a previous experience with an individually scaled and animated self-avatar change pointing to self- and body parts in VR? (2) Does the viewpoint from the body during the previous experience with this self-avatar modulate pointing to self- and body parts in VR? Connected to these questions, there were the following main predictions. (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 locations, 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 being experienced as higher. (3) In terms of the difference between post-avatar and pre-avatar self-location, there will be a relative shift downwards, towards the upper torso, for chest-height compared to eye-height. Specific self-location in the body is expected to be influenced by the viewpoint in the body. Manipulating viewpoint in this way obviously does not change the physical location where you receive visual information, which is still in the eyes. It does however change the origin of your visual field and it may change the center of your egocentric frame of reference. Thereby it may change the experienced self-location in the body. However, an alternative expectation (3) is a relative shift upward for chest-height compared to eye-height, to occur when self-location is influenced by the body parts being perceived as higher, rather than by the viewpoint being lowered. Moreover, the viewpoint manipulation changes visual input, but naturally not body-based cues (proprioception, interoception, vestibular information, somatosensation, the experienced location of your eyes), nor memory of what your body looks like. Next, the changes in the design and methods relative to study two will be introduced, followed by an overview of the results of study three and their interpretation.

Using the same VR pointing paradigm as in the previous two studies, participants performed interleaved pointing to self and several body parts in an HTC Vive VR headset, before and after the self-avatar adaptation phase discussed above. A gender-matched, SMPL (average body model) avatar was used (Loper, Mahmood, Romero, Pons-Moll & Black, 2015), scaled in width by the individual participant's arm span and in height by the participant's total body height. For its more extensive tracking possibilities, the HTC Vive was used for the complete experiment instead of the previous Oculus Rift DK2. During the adaptation phase, participants freely moved and explored the avatar in 1PP (co-located) and in a 3PP (mirror- view) from eye- or chest-height for five minutes, while the Valve Lighthouse inside-out infrared laser tracking system tracked the headset and the two wand hand-held controllers of the HTC Vive, providing real-time self-animation of the avatar. During the pre- and post-avatar pointing tasks, the Xbox controller was again used for rotating the pointer.

This study employed a mixed design, with four within-subjects factors (target, pointer starting direction, pointer height, and test (pre- and post-avatar)), one between-subjects factor (viewpoint group (eye- or chest-height during the adaptation phase; balanced for gender)), and three runs: a pre-avatar run of interleaved and randomized self- and body part localization, the self-avatar adaptation phase, and a post-avatar self- and body part localization run (the same as the pre-avatar run, apart from being separately randomized). The pointing part of the session had four within-subjects factors: 8 x target (self, top of the head, eyes, chin, shoulders, hips, knees, feet) + 2 x pointer starting direction (straight up and straight down) + 3 x pointer height (0, 0.5, and 1 x total body height) + 2 x test (pre- and post-avatar test); and two measures: body region for self (7 levels) and error distance (cm; directional) for the body parts. This resulted in a total of 8 x 2 x 3 x 2 = 96 trials per participant, 48 during the pre- and 48 during the post-avatar test. The number of pointer heights and starting directions was reduced relative to study two, to prevent the complete experimental sessions becoming too long.

In this experiment, the pointer was again 30 cm long and 4 cm wide, and located at 3.5 m from the participant. Twenty-three people (thirteen female) participated in the study, all with (corrected-to-)normal vision, including stereopsis. Before the pointing task started, the following body heights were measured: the *top of the head* (the cranial vertex), *eyes* (pupils), (tip of the) nose, *chin* (gnathion), *shoulders* (acromion), elbows (the most laterally protruding part of the bone), waist (where the circumference of the lower torso is smallest), *hips* (where the circumference is largest), *knees* (top of the knee cap), and *feet* (above the talus). The body parts used as targets are listed above in italics and these target locations were explained to the participants as in study two. The body height measurements were also used for classification of the self-pointing heights into scores for the physical body regions, as in the previous two studies. Additionally, arm span was measured, which was used together with total body height to individually scale the self-avatar. Participants received the following instructions for the pre- and post-avatar pointing tasks, in English: "[...] 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." The targets were again presented as audio over loudspeakers, with "yourself" or "Sie" on self-localization trials. Following the VR tasks, the participants filled out a digital version of the CFBSPQ on a laptop, which in the present adapted version was a self-measure questionnaire with twenty items, to be answered on visual analogue scales (VAS) with "not at all" as the minimum and "very much" as the maximum. Lastly, participants filled out a paper-and-pencil post-questionnaire, adapted from study two (see supplements 7, for the English version, and 8, for the German version).

To analyze whether the different viewpoints during the avatar adaptation phase affected where participants located their body parts, the difference in error distance was computed (post-test – pre-test) for each trial (matched individually by the levels of the factors), for both viewpoints. These differences in error distances were analyzed using an ANOVA, with one between-subjects factor, viewpoint (two levels: eye-height and chest-height), and one within-subject factor, target body part (seven levels: feet, knees, hips, shoulders, chin, eyes, top of the head). Similarly, to analyze whether viewpoint affected indicated self-location, the difference between the percentages of pointing was computed for each body region (post-test – pre-test), for both viewpoints. These differences in percentages were also analyzed using an ANOVA, with one between-subject factor, viewpoint (2 levels), and one within-subject factor, body region (7 levels). For the CFBSPQ, an ANOVA was run with viewpoint as between-subjects factor, questionnaire component (self-identification, spatial presence, and agency) as within-subjects factor and the questionnaire (component) score (% of maximum possible score) as the measure. Furthermore, it was specifically tested whether there were significant differences between the scores on the sub-scales of this questionnaire. Lastly, it was tested whether the questionnaire score correlated with changes (post- compared to pre-test, per viewpoint) in self-localization or overall body part localization accuracy.

The main findings for this study were the following. In the pre-test, participants did not perceive the locations of most of their body parts accurately, particularly at the boundaries of the body. Pointing was much too low for the lower body parts (the feet, knees, and hips) and much too high for the top of the head, forming a ('amplified') replication of the VR headset body part localization in study two. Participants pointed mostly to the upper torso and the upper face for self, with some pointing to all regions of the body, as well as above the head. These self-localization results partially replicate the findings from study two (in terms of the physical body), with as main differences more pointing to the upper torso and less above the head for study three. The differences in the findings relative to study one could be due to the different VR headsets used (the HTC Vive here vs the Oculus Rift DK2 in study one), the different pointer heights (spread across the whole body here vs around the head only in study one), or the different distances of the pointer to the participant (3.5 m here and 1.3 m in study one) (see section 6 of Van der Veer, Alsmith et al. (2019), included in this thesis after the synopsis as article 3). The findings are largely in line with Alsmith & Longo (2014), as well as with Alsmith et al. (2017).

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, expectation (1) was not confirmed. Changing the viewpoint did alter body part localization, though. Pointing to body parts 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. So, expectation (2)(a) and (b) did get confirmation. An explanation could be the 'simple' scaling upwards by the fraction that the viewpoint was manipulated down (see Dixon, Wraga, Proffitt & Williams (2000) for findings suggesting eye-height scaling of absolute heights of objects), but these fractions do not match very well here. An explanation for why particularly the locations of the body parts below the eyes were shifted up may be that those body parts were seen closer (than normally), and thereby as higher, in 1PP when looking down. See section 5.1 of Van der Veer, Alsmith et al. (2019), for further possible explanations of the present body part localization results. The self-avatar as such did not change self-localization, as the post- and the pre-test self-localization pointing was not different for the eye-height group. Changing the viewpoint also did not alter self-localization. There was no significant difference between the chest-height and the eye-height group in (post-test – pre-test) self-localization. So, none of the two alternative expectations (3) was supported. Manipulating perspective in terms of the origin of the visual field may not be enough to manipulate experienced self-location. There was an interesting *trend* though, towards higher self-location post-test for the chest-height group, showing in decreased pointing to the upper torso and increased pointing above the head. This might alternatively suggest experienced self-location being influenced by body parts being perceived as higher from chest-height (second alternative for expectation (3)).

There was no significant difference in CFBSPQ (subscale) score between viewpoints. Thus, somewhat unexpectedly, viewpoint did not significantly influence the embodiment of the self-avatar. There was a significant main effect of subscale and all subscale scores were significantly different from each other, with self-identification having the lowest score, then spatial presence, and agency the highest. There were no significant correlations between the questionnaire score and changes (post- compared to pre-test, per viewpoint) in self-localization or overall body part localization accuracy.

The results from study three confirm that people do not perceive their body part locations (in VR) very accurately (particularly at the borders of their bodies), as well as that people seem to locate themselves mainly in the (upper) face and (upper) torso. Overall, experienced body part locations seem more plastic (influenced by viewpoint) than experienced self-location. Providing a self-avatar does not seem to improve or alter body part localization in VR (which is not very accurate anyway). Possibly, providing an individually matched self-avatar even reinforces structurally existing distortions in position sense. However, when altering the viewpoint, then body part localization can be altered. These results caution the use of altered viewpoints in applications (using self-avatars) where veridical body part localization is important, e.g. applications involving spatial precision or actions.

Besides an embodiment scale, it should be considered to include a presence scale in a future version of this paradigm, to test in which space participants actually feel present, the virtual or the physical. It would also be interesting to implement richer cue environments (e.g. other avatars and objects) and more commonly used viewpoints (e.g. over-the-shoulder, top-down or from behind). The 3PP localization task in VR, as suggested at the end of section 7 as a follow-up, would also be of particular interest after an experience with a self-avatar in a 3PP (vs 1PP).

12. Conclusions and general discussion

For the three individual studies of this thesis, overviews of the results, conclusions and discussions were included in sections 7, 9 and 11, and can be found more extensively in the corresponding articles following this section. Therefore, after a brief summary of the main findings and conclusions of the three studies with some additional discussion, this section will consist mainly of some discussion points of a general or more hypothetical nature, and suggestions for further studies.

12.1. Study 1

For this thesis, it was investigated where people specifically locate themselves in their bodies, as well as how accurately they can locate their body parts, employing several VR setups. In the first experimental study of this thesis, specific self-localization in the body was investigated in the Oculus Rift DK2, as well as with the body template task outside of VR (see section 7 and Van der Veer et al., 2018). On the VR task, self-localization was mainly in the upper face, on the template task mainly in the upper torso, followed by in the face. Possible explanations for the difference in self-localization between the VR and template tasks will be discussed below, in a separate subsection (12.4) of this section. The main conclusion from the first study was that a VR headset might make people more head-centered.

12.2. Study 2

Therefore, in study two a comparison was made between self-localization in a VR headset and when using an LSID (see section 9 and Van der Veer, Longo, et al. (2019)). Additionally, a rescaling of self-locations was performed in terms of the perceived body, based on indicated body part locations in VR. The self-localization on templates outside of VR was extended, using additional templates.

Participants were able to point reasonably accurately to many of their body parts in the LSID, but much less so in the VR headset. In the VR headset, the mean height of the top of the head was much overestimated and the mean heights of the feet, knees, and hips were much underestimated. In the LSID the mean height to the top of the head was overestimated and the mean height of the feet was underestimated, but both less so than in the headset. Several possible explanations for these different findings between the setups were discussed (see section 9 and, particularly, section 4.1 of Van der Veer, Longo et al. (2019)).

Using the different VR technologies, with and without a device on one's head, and with and without visual access to one's own body—when it was taken into account how people perceive their bodies when using the different VR setups—the indicated self-locations were largely the same, i.e. mainly the face (the upper followed by the lower), as well as some torso (again the upper followed by the lower).

In the template task, pointing was mainly to the upper torso, followed by the face. No significant differences were found between the pointing heights on the different perspective (frontal and side-views) body outlines.

The main conclusions from the second study were that people mostly localize themselves in the (upper) face and the (upper) torso, and that VR setups do not seem to influence where people locate themselves per se, but rather where they locate their body parts. When using VR as a tool in the study of aspects of the bodily self and body perception, it should therefore be taken into consideration that the technology itself may influence body part localization; as well as self-localization if inaccuracies in body part localization in the specific VR setup are not taken into account. Users may thus be uncertain of where exactly their body parts (especially their bodies' boundaries) are when using VR. Since how you perceive and how you act are tightly connected, this may result in acting differently in VR, which is a realization of increasing importance (e.g. for developers of VR applications) now the use of VR is so much on the rise.

12.3. Study 3

In study three, an adaptation phase with an individually scaled, self-animated, gender-matched self-avatar, seen from 1PP (co-located) and a 3PP (mirror-view), was implemented between a pre- and a post-test of self- and body part localization, as a means of providing participants with rich multisensory feedback about their bodies in a VR headset (see section 11 and Van der Veer, Alsmith et al. (2019)). Moreover, the viewpoint from the body during the avatar phase was manipulated to either eye- or chest-height, to test for its effect on self- and body part localization.

In line with the growing body of work showing systematic distortions in position sense in healthy populations (see section 8), study three confirmed the findings from study two that people do not perceive their body part locations (in VR) very accurately (particularly at the borders of their bodies), as well as that people seem to locate themselves mainly in the (upper) face and (upper) torso.

Counter to expectation, the self-avatar as such (i.e. with the viewpoint at eye-height) did not reduce inaccuracies in body part localization. Similarly however, Thaler, Geuss & Mohler (2018) found overestimations of body part widths to occur regardless of the visual information provided about one's own body (no visual access vs 1PP vs 3PP mirror-view). It cannot be excluded that an individually matched self-avatar even reinforces structurally existing distortions in position sense. Changing the viewpoint did alter body part localization. Pointing to body parts 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 body part localization. Several possible explanations for this shift upwards were discussed (see section 11 and, particularly, section 5.1 of Van der Veer, Alsmith et al. (2019)).

The self-avatar as such did not change self-localization, as the post- and the pre-test self-localization pointing was not different for the eye-height group. Counter to expectation, changing the viewpoint also did not alter self-localization. Lastly, the embodiment of the self-avatar did not significantly differ between viewpoints.

The main conclusions from study three were that experienced body part locations seem more plastic (influenced by viewpoint) than experienced self-location and that this finding should caution the use of altered viewpoints in applications (using self-avatars) when veridical body part localization is important. Conversely, concerning experienced body part locations, our findings show that VR setups and particularly viewpoint manipulations when using self-avatars may have great potential to tap into, as Slater (2014) phrased it, our brain's illusion generating capacity.

Overall, the three studies for this thesis taken together argue for a differential involvement of multi-sensory information processing in our experienced specific self-location and in our position sense or ability to locate our body parts. Self-localization seems to be less flexible, possibly because it is strongly grounded in the 'bodily senses', while body part localization appears more adaptable to the manipulation of sensory stimuli, at least in the visual modality.

12.4. The body template vs the VR tasks

The difference in self-localization on the VR ((upper) face, followed by the (upper) torso) compared to the template tasks (upper torso, followed by the face) may have been influenced by several factors: (a) the perspective on the body, i.e. 1PP vs 3PP; (b) lower identification with the body outlines compared to with one's own body; (c) a possibly general tendency to point to the center of an object (or, on the medial axis skeleton, see Firestone & Scholl (2014)).

In a perspective-taking study, it was found that people value their own minds more than their bodies, but often fail to realize that others do so as well, assuming that others value their own bodies more than their minds (Jordan, Gebert, & Looser, 2017). Pointing on the template in a 3PP (cf. factor (a) above) may resemble pointing to someone else, notwithstanding the task's instructions to take the outline as an image of yourself. This may (partially) explain the smaller amount of pointing to the (upper) face, where typically the mind is thought to reside, for the template 3PP compared to the VR 1PP task. Factor (b), low identification with the body outlines, might have reinforced this effect; as it may have reinforced the effect of factor (c), by making the outline seem rather like a depiction of an external object.

The template findings are in line with Alsmith et al.'s (2017) findings of (alter-)egocentric spatial judgments relying on both head and torso, with larger contributions for the torso. In that study, self-locations might be implicated by these body parts, used by participants to indicate the locations of external objects relative to a person depicted on a screen. A possibly relevant factor, shared by this task and the template task, is that performed actions were not directed at one's own physical body.

As mentioned at the end of section 7, for disentangling the effects of perspective and employing VR, implementing a 3PP self-localization task in VR would be of particular interest.

12.5. The bodily self and virtual reality revisited

Alsmith and Longo (forthcoming) discuss promising VR research investigating our self-conception[9], while pointing out two issues of concern with this type of research. First, flexibility in self-conception demonstrated in VR (in the sense of self-ascribing to distinctly other entities than our actual bodies, e.g. avatars) runs the risk of just reflecting flexibility of our imagination instead of in actual self-conception. Second, VR might alter the user's perception such that the structure of the relation between his virtual body and himself is different from that between his actual body and himself. Specifically, self-ascriptions to particular parts of the body may differ depending on environmental factors and these may differ in particularly relevant ways between within VR and outside of it. With respect to the present study one (see section 7 and Van der Veer et al. (2018)), Alsmith and Longo indicate—as was also done in the discussion section of Van der Veer et al. (2018)—that the reported strong preference for self-localization in the upper face may have resulted from merely the wearing of the VR headset. They now added the interesting suggestion that wearing the VR headset may have affected how the participants thought about the relation between their bodies and themselves. Particularly this second issue points out that when using VR for the study of the bodily self, or specifically self-ascriptions, one should be wary that the technology may bring in (additional) distortions and that a virtual body or avatar may not be unproblematic as a means for providing feedback about a person's own body or self. However, study two of this thesis does show that self-localization is largely the same across the different VR technologies used (and comparable with outside of VR (Alsmith &Longo, 2014)), when the inaccuracies in body part localization that were found are taken into account. Whereas study three shows that an adaptation phase with a self-animated, scaled self-avatar does not as such modulate self- and body part localization in a VR setup. A way forward may lie in the further careful design of comparable paradigms both in- and outside of VR.

12.6. Follow-up studies

This final subsection will briefly present suggestions for further research. Some aim at further disentangling the effects on self- and body part localization of variables that have been identified earlier in this thesis as of (possible) influence. Some aim at testing the effects of additional variables.

Different pointer distances

Up to now, the pointer distance was not introduced as a specific factor to test for and the implemented distances were matched with the distances of the focal planes resulting from the VR technology, i.e. 1.3 m for the Oculus Rift DK2 (used as the pointer distance in study

[9] Alsmith and Longo (forthcoming) discern self-conception, as a concept which can be variable in its application, from the concept of the self, having a true referent.

one), 3.5 m for the LSID (the distance to the physical screen; used for both the LSID and the Oculus Rift in study two) and infinity for the HTC Vive (the distance of 3.5 m was also used in study three). It would be particularly interesting to test for shorter pointer distances, bringing the stimulus into peripersonal or action space. Humans may be better adapted at spatial perception and action within spaces of such extents.

Richer cue environments

Thus far, the minimal situation was investigated regarding the available visual information in the environment (apart from the avatar adaptation phase in study three). Visually richer environments, particularly when providing familiar size cues, might change self- and (improve accuracy of) body part localization. Various objects, non-self-avatars, or ground planes could e.g. be implemented to investigate this.

Visual access to the body

Visual access to the body can be provided in different ways. In study two, his own body was visible to the participant in the LSID setup; in study three, a self-avatar was implemented. Augmented reality is another option, where one's own body is visible in a see-through headset while additional virtual stimuli can be added. Moreover, by manipulating the overall size or the size of body parts of a self-avatar, the effect of a dimensionally changed body on the location of self and body parts can be further investigated.

Different viewpoints

In study three, a viewpoint on the body manipulated to chest-height was implemented. Testing viewpoints which are more common in VR (and other visual media), e.g. over-the-shoulder, top-down, or from behind, may be of interest, also because participants may be more acquainted with them.

Presence questionnaire

It may also be interesting to ask people in which space they experience themselves to be, the virtual or the physical, when e.g. playing video games with different perspective avatars. After experimental sessions, a presence scale could be included to find out in which space(s) participants actually felt present during the (different phases) of the experiment. Possible effects of employing VR setups on experienced self- and body part locations may or may not be modulated by the (type of) space people experience themselves to be in.

Moving a ball task

To get a better handle on which findings are specific to (a certain type of) VR or to a certain task, implementing a variety of measures asking the same questions, within and outside of VR, should be informative. Instead of pointing, moving a ball to bodily locations could e.g. be implemented. Fuentes, Longo & Haggard (2013), used a relative measure for the localization of body parts, where participants moved a ball to locations of body parts relative to a head, depicted on a desktop screen. In a follow-up study, this paradigm can be adapted into VR, in a similar 3PP condition, but also in 1PP. In a VR headset, the participant would move a ball to locations relative to a depicted head in front of him (3PP), or on his own, invisible, body (1PP). This study would provide self- and body part localization data from a different task and may help determine to what extent the results in the previous studies resulted from having to put a pointer at different angles during the pointing task. The 3PP condition of the study may also clarify to what extent the difference in self-localization between the previous VR pointing (1PP) and template results (3PP) was due to VR. Having both a 1PP and a 3PP localization task in VR, it could also be tested whether these are differentially influenced by exposure to the experience of a self-avatar in 1PP vs a 3PP.

Moving a ball task

Indicating locations on the body (e.g. by pointing or moving a ball) that were touched would likely make the task more perceptual and possibly less based on certain body representation (body semantics; the body structural description). A task with visual target stimuli (at the, seen or unseen, body surface), could serve as a test for pointing abilities (towards one's body) per se.

Different postures

To test, whether body posture influences experienced self- and body part locations, the current VR paradigm could be used while participants are e.g. sitting, lying down, or being tilted under various degrees. It could e.g. be that our body structural description is more accurate for certain (more usual?) orientations or positions of the body than for others, possibly promoting more accurate body part localization in some orientations and positions than others. Also, changes in the orientation of the human body can change the effect of gravity on the vestibular system. As Wong (2017) argues, the vestibular system may play a central role in anchoring the self to its location (i.e. to its body and to its situation in the world), making the manipulation of vestibular processing of bodily orientation a candidate for having a modulating effect on experienced self-location (see also the next topic).

Multisensory processing

Information in different modalities which normally co-varies, can sometimes be manipulated independently, to test for differential effects of the modalities. Vestibular cues (e.g. from different postures or (galvanic or caloric) vestibular stimulation) and visual cues (e.g. viewpoint or visual angle on the environment, using visual manipulations (in VR)) can be varied independently. E.g., while the participant is not tilted, the (virtual) environment may be tilted, so a tilt is seen by the participant that is not actually made by his body; or the reverse, while the participant is tilted, the (virtual) environment may be counter-rotated so that the actual tilt made by his body is not seen. See Lenggenhager and Lopez (2015) for a review on the contributions of the vestibular system to the sense of self-location (and other components of bodily self-consciousness).

Heartbeat tracking

A heartbeat tracking or discrimination task (behavioral, objective measures of interoceptive accuracy (Garfinkel, Seth, Barrett, Suzuki & Critchley, 2015)) could be added as a potentially more relevant measure of interoception than the BPQ awareness scale (measuring interoceptive sensibility) implemented in study two. Tsakiris, Tajadura-Jiménez & Constantini (2011) found evidence for a relation between body ownership and heartbeat monitoring (i.e. between a stronger RHI and lower heartbeat accuracy)[10]. Craig (2009) states that both interoceptive information and information related to self-awareness are processed in the (right) anterior insular cortex (AIC). A problem with the heartbeat tasks is that most people underestimate their heartrate, and that it is not well known why. Alternatively, bodily arousal, or the sense of fullness may be interesting to manipulate, as they might also modulate bodily (self-)awareness.

Hedging

Pointers (or balls) can be presented at different heights (and with different angles), to ask the participant to give hedged judgments (e.g. somewhat, more or less, directly; Lakoff, 1973) of whether they are pointing directly at him, or at a specific body part. This provides the possibility for the responses to be given in various weighted distributions. Hedged judgments may prove particularly interesting for self-location, which may be experienced across regions in a gradual way, rather than in one or more specific locations. This task can also be implemented in a relative version, asking to judge which of two objects is closer to (or farther away from) you, or a self- or other-avatar. Starmans and Bloom (2012) asked to make such relative judgments for sets of two images of flies located on different parts of a person's body. Similarly, it could be asked to judge whether pointers point at (or balls are located on), below, or above you, to investigate the extent of self-locations.

Cultural comparisons

Particularly for specific self-localization in the body there may be cultural differences. There seem to be differences between cultures in the importance they give to specific parts of the body that may play a role in how people conceive of themselves. E.g., in Japanese medical

[10] Moreover, Tsakiris (2017) proposes that interoception (in integration with exteroception) is fundamental to both the unity and the stability of the bodily self, in analogy with homeostasis at the physiological level. Intereception would provide unity of the self by providing an experience of a coherent, non-hollow body; stability of the self by providing a distinctive, self-specific experience in response to external change (cf. Pradeu (2012) and Constantini (2014) for discussions of a link between the immune system and the bodily self).

and martial arts traditions, as well as in zen Buddhism, the hara, located in the stomach, is a central concept; in many yoga and meditation schools, as well as in Vedic and Hindu cultures at large, chakra's, which are spread out along the midline of the (mostly upper) body, have an important role; some cultures might focus more on e.g. the head and brain, others more on the heart. These differences between cultures in the focus on, and meaning attached to, specific parts of the body, might be reflected in differences in self-localization within the body by individuals with different cultural backgrounds.

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Where are you?

Statement of contributions

The three studies for this thesis have been performed within the framework of the interdisciplinary, international collaborative project *Finding perspective: Determining the embodiment of perspectival experience,* funded by the Volkswagen Foundation (principle investigators: Dr. Adrian J. T. Alsmith, currently at Institut Jean Nicod, DEC, ENS, EHESS, CNRS, PSL University, Paris, France; Prof. Dr. Matthew R. Longo, Department of Psychological Sciences, Birkbeck, University of London, London, United Kingdom; Prof. Dr. Christophe Lopez, CNRS and University of Aix-Marseille, Marseille, France; Dr. Betty J. Mohler, currently at Amazon, Tübingen, Germany; Prof. Dr. Hong Yu Wong, Werner Reichardt Centre for Integrative Neuroscience and Philosophisches Seminar, University of Tübingen, Germany). All studies were coordinated by the author of this thesis, Albert van der Veer, under supervision of the members of his advisory board, Betty Mohler (first supervisor), Matthew Longo (second supervisor), Adrian Alsmith and Hong Yu Wong. Below are listed the individual contributions of each of the authors, by article. All respective authors have approved initial and final submitted versions of the articles. Albert van der Veer functions as the corresponding author for all the articles.

Article 1: Where am I in virtual reality?

Van der Veer, A. H., Alsmith, A. J. T., Longo, M. R., Wong, H. Y., & Mohler, B. J. (2018). Where am I in virtual reality? PLOS One, 13(10): e0204358. doi:10.1371/journal.pone.0204358

- Albert van der Veer: conceptualization; methodology; investigation; analysis; visualization; writing: original draft; writing: review and editing.
- Adrian Alsmith: conceptualization; methodology; writing: review and editing.
- Matthew Longo: conceptualization; methodology; writing: review and editing.
- Hong Yu Wong: writing: review and editing.
- Betty Mohler: conceptualization; methodology; analysis; writing: original draft; writing: review and editing.

Article 2: Self and body part localization in virtual reality: Comparing a headset and a large-screen immersive display

Van der Veer, A. H., Longo, M. R., Alsmith, A. J. T., Wong, H. Y., & Mohler, B. J. (2019). Self and body part localization in virtual reality: Comparing a headset and a large-screen immersive display. *Frontiers in Robotics and AI*, 6(33). doi:10.3389/frobt.2019.00033

- Albert van der Veer: conceptualization; methodology; investigation; analysis; visualization; writing: original draft; writing: review and editing.
- Matthew Longo: conceptualization; methodology; writing: review and editing.
- Adrian Alsmith: conceptualization; methodology; writing: review and editing.

- Hong Yu Wong: conceptualization; writing: review and editing.
- Betty Mohler: conceptualization; methodology; analysis; visualization; writing: original draft; writing: review and editing.

Article 3: The influence of the viewpoint in a self-avatar on body part and self-localization

Van der Veer, A. H., Alsmith, A. J. T., Longo, M. R., Wong, H. Y., Diers, D., Bues, M., …, & Mohler, B. J. (2019). The influence of the viewpoint in a self-avatar on body part and self-localization. Proceedings of the ACM Symposium on Applied Perception 2019 (SAP ’19). New York, NY: ACM. doi:10.1145/3343036.3343124

- Albert van der Veer: conceptualization; methodology; investigation; analysis; visualization; writing: original draft; writing: review and editing.
- Adrian Alsmith: conceptualization; methodology.
- Matthew Longo: conceptualization; methodology.
- Hong Yu Wong: conceptualization.
- Daniel Diers: methodology.
- Anna Giron: analysis; investigation; visualization; writing: original draft.
- Matthias Bues: writing: original draft.
- Betty Mohler: conceptualization; analysis; methodology; visualization; writing: original draft; writing: review and editing.

Article 1
Where am I in virtual reality?

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Table of contents

Where am I in virtual reality?

Abstract
It is currently not well understood whether people experience themselves to be located in one or more specific part(s) of their body. Virtual reality (VR) is increasingly used as a tool to study aspects of bodily perception and self-consciousness, due to its strong experimental control and ease in manipulating multi-sensory aspects of bodily experience. To investigate where people self-locate in their body within virtual reality, we asked participants to point directly at themselves with a virtual pointer, in a VR headset. In previous work employing a physical pointer, participants mainly located themselves in the upper face and upper torso. In this study, using a VR headset, participants mainly located themselves in the upper face. In an additional body template task where participants pointed at themselves on a picture of a simple body outline, participants pointed most often to the upper torso, followed by the (upper) face. These results raise the question as to whether head-mounted virtual reality might alter where people locate themselves making them more "head-centred".

Keywords
Body; self-location; self; first-person perspective; pointing; bodily self-consciousness; virtual reality; body template.

1. Introduction
Generally, people locate themselves where their bodies are. Here we ask more specifically: Where do people locate themselves in their bodies? Currently it is unknown whether people locate themselves in one or more specific part(s) of their body. The specific methods used in empirical research to investigate where people locate themselves depend largely on which of several possible notions of self-location is under investigation. In the literature, at least the following dominant notions of bodily self-location can be found. (1) Self-location as the bodily location people consider to be the centre from which they perceive the world, the centre of their first-person frame of reference, or egocentre [1,2]; (2) the bodily location people experience themselves to be in relative to external space [3]; (3) the location in or on their body where people experience themselves to be, or the part(s) of their bodies people associate themselves with the most [4,5]. Whether these different conceptions of self-location can be completely distinguished experimentally, in terms of their underlying sources of information, psychological mechanisms and neuronal structures, as well as metaphysically and phenomenologically, is however a topic that requires further integration of several lines of research.

Alsmith and Longo [6] operationalised self-location as the location resulting from pointing "directly at you" in 1PP, and interpreted it as the bodily location one judges to be one's ultimate location, which is very close to conceptualisation (3) above. Alsmith and Longo found that participants' judgements were not spread out homogeneously across the entire body, nor is it localised in any single point. In their study, participants were asked to stop a pointer when it was pointing "directly at you"—either by manual manipulation of a physical pointer whilst blindfolded, or by visually discerning whether the physical pointer manipulated by an experimenter was in the correct position. They found two distinct regions to be judged as where "I" am inside my body: the upper face and the upper torso, according to which participants reached first.

Most literature has focused on self-location using an outline of a human body where the task does not involve pointing to oneself but rather general localization of or on another person. Limanowski and Hecht found a dominant role for the brain (which was reported most) and the heart for self-location in humans, when participants were asked to indicate the “centre of the self” by placing markers on human silhouettes [5]. Moreover, they found that most people seem to believe there is one single point inside the human body where their self is located. Starmans and Bloom, based on people's judgments of when objects are closer to a person [7] and on a task of erasing as much as possible of a picture of a stick figure named Sally, while still leaving Sally in the picture [8], argued that people locate the self mainly in the head and, more particularly, in or near the eyes. In a study using open questions and forced-choice self-localizing on a body silhouette, Anglin, on the contrary found, that some participants reported that the self is not centralized in one location and that, overall, participants tended to locate the self and mind in the head and the soul in the chest [4]. Using a more implicit method, Alsmith, Ferrè and Longo recently found evidence for the use of a weighted combination of head and torso for self-location judgments [9].

The primary aim of the current paper is to investigate where people locate themselves within their body *in virtual reality* (VR). The paradigm from Alsmith and Longo [6] was adapted with the only change being that VR technology was used. More specifically, the aim of this study was to see if the findings from Alsmith and Longo would also be found in a virtual world, particularly the two distinct locations for pointing to self, the upper torso and the upper face. To test this, we used a commonly available VR setup, a VR headset. A body template task, inspired by Limanowski and Hecht [5] and Anglin [4], was included to explore where participants point, when asked to point at themselves outside of VR and to see whether this pointing would be consistent with the self-locations found in the VR headset.

VR headsets have been increasingly used to study body ownership and body swap illusions [10-12], as well as the manipulation of specific bodily experiences [13-16]. However, the influence of VR headsets on self-location has not been thoroughly investigated and may play a role in those studies. Also, in VR environments being designed for health applications, entertainment and training/education, the user's experienced self-location may be an important factor for the intended effects to be achieved. These issues illustrate the importance of an investigation of self-location in VR.

2. Methods

2.1. Participants

Twenty-three volunteers (thirteen female; mean age: 30.0 (SD = 9.0) years, range: 20-56 years, 19 right-handed by self-report), naïve to the purpose of the experiment, participated, all with normal or corrected-to-normal vision (including stereo depth vision, tested with the Stereo fly test (Stereo Optical Co., Inc., Chicago, IL)). The participants were recruited from the participant database of the Max Planck Institute for Biological Cybernetics in Tübingen, Germany. All participants gave written informed consent. Procedures were in accordance with the principles of the Declaration of Helsinki and approved by the Ethics Committee of the University Hospital Tübingen.

The individual depicted in Fig 1A has given written informed consent (as outlined in the PLOS consent form) to appear identifiably in this publication.

2.2. Procedure

2.2.1. VR pointing task

Participants read an information sheet and signed an informed consent form. The experimenter measured the height of the top of the participant's head (cranial vertex), eyes (pupils), chin (gnathion), shoulders (acromion) and hips (greater trochanter), followed by a test for binocular stereo vision. The participant then put on the VR headset. After a calibration of the VR headset, the experiment began (see Fig 1A). Based on Alsmith & Longo [6] we predicted that participants would point towards the upper torso and upper face.

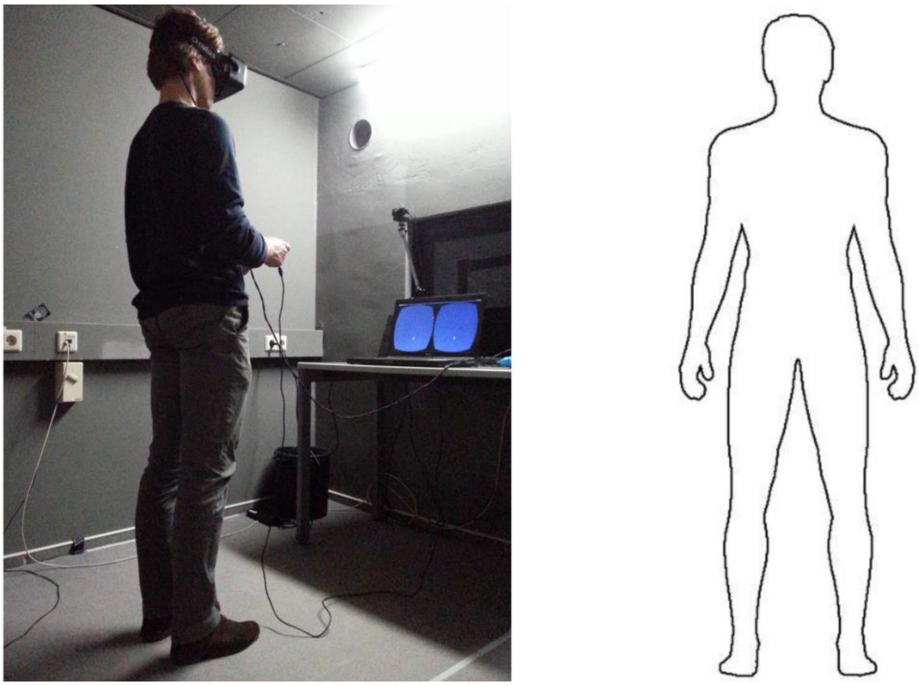

Fig 1. The VR headset experimental setup and the body template. (A) The participant was standing still, wearing the VR headset and holding the controller. The participant's task was to rotate a virtual pointer in their sagittal plane until they felt it was pointing 'directly at you'. The individual depicted has given written informed consent (as outlined in PLOS consent form) to appear identifiably in this publication (left image). (B) On this picture of an outline of a body participants were asked to "Point directly at you", under the assumption this was a picture of themselves (right image).

2.2.2. Body template task

Following the VR pointing task, a few minutes after the VR headset had been removed from them, the participants performed a body template task, where they were asked to "Point directly at you" on an A4 print of a drawn frontal body outline (see Fig 1B), under the assumption this was a picture of themselves. Based on previous literature [4,5] we predicted that participants in the body template task would point mainly towards the head and possibly also the chest.

2.2.3. Survey questions

After the two tasks, several questions about the employed strategy, demographics and psychological state were asked in a pen-and-paper survey (see S1 Post-questionnaire).

2.3. Experimental setup

During the experiment the participant stood in front of a table on which a Dell Precision M6700 laptop was positioned, running the experiment (see Fig 1A). The computer had an Intel Core i7-3940XM central processor running at 3.00 GHz and an NVIDIA Quadro K5000M graphics card. An Oculus Rift development kit 2 VR headset was used for stimulus presentation. The VR headset has a diagonal field of view (FOV) of 96°. The experiment was designed in Unity 4.6.7f1. The tracking camera of the Oculus Rift was mounted on a separate stand positioned on the table. The participant held a Microsoft Xbox 360 controller, moved the pointer with the left hand using a joystick and confirmed the decision by pressing a button with the right hand.

2.4. Stimuli and design

The virtual environment consisted of empty space with a blue background. On each trial, the participant saw a round pointing stick with a blunt backside and a pointy front side (see Fig 2A). The backside of the pointer was fixed to a virtual (non-visible) vertical plane orthogonal to the participant's viewing direction at 1.3 m distance from the participant (the distance of vergence in this VR headset). The pointer had a virtual length of 25 cm and a diameter of 2 cm, was a light-grey colour and had a fixed lighting source straight above.

The starting direction of the pointer was pointing straight down or straight up, at one of five fixed backside heights: the participant's chin height, chin height +/- 1/12 of the participant's total body height, chin height +/- 2/12 of body height (see schematic in Fig 2B). As in the Alsmith and Longo [6] study, the independent variables, pointer starting direction and pointer height, were included to test for their possible influences on participants' judgements, as well as to make the task more diverse. Ten blocks of trials were administered, each containing one trial of every type in random order, making a total of one hundred trials.

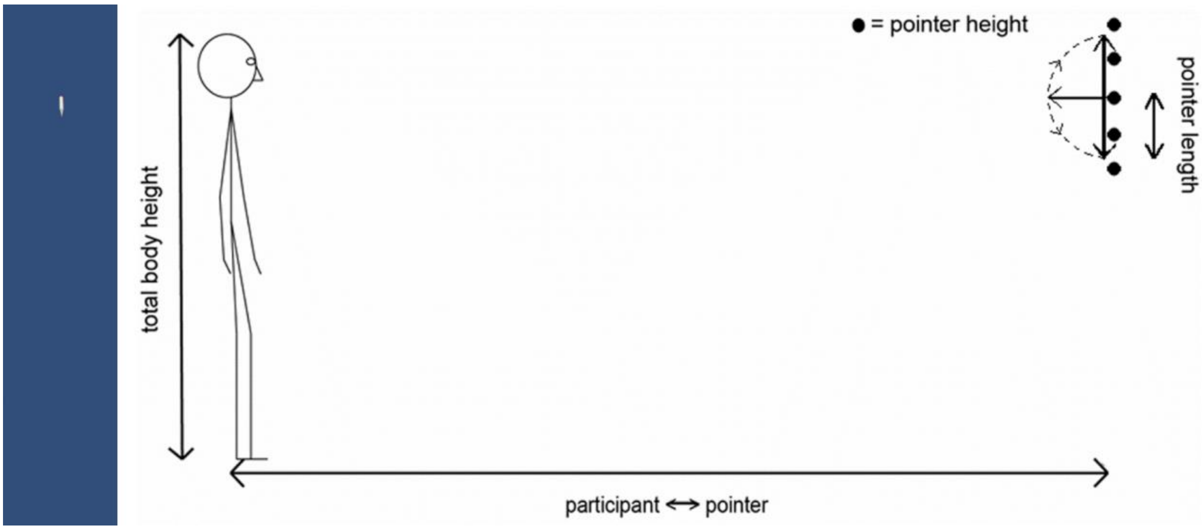

Fig 2. The pointer stimulus and schematic overview of the setup used in the experiment. (A) An example image of the pointer stimulus, here with an angle of + 48.2° from straight down, showing a field of view of about 20° horizontal and 100° vertical (out of about 100° total for both directions) (left image). (B) The dotted line indicates the range of possible pointer rotations. The pointer heights were chin height and the chin +/- 1/12 and +/- 2/12 of total body height (right image).

The experiment had a within-subject design with three factors: 2 x pointer starting direction, 5 x pointer height and 10 x repetition (blocks), and one measure: scored body region (data analysis was done in terms of percentages of trials per body region; for the computation of the measure see section 2.6)

2.5. Task

The participants received the following instructions: in English: "Your task is to adjust the direction in which the stick is pointing so that it is pointing directly at you", or in German (the experiment was run completely in German with German speaking participants): "Ihre Aufgabe ist es, die Richtung des Zeigestocks so zu verändern, dass dieser genau auf Sie zeigt". To perform the task, the participant used the joystick on the left-hand side of a controller to rotate the pointer upwards or downwards (both directions were permitted at all times) through their sagittal plane, with the speed proportional to the pressure administered on the joystick (maximum speed was 75°/s). 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.

2.6. Analysis

The 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”. Using the individualised height of the pointer, this angle was recomputed into the height at which the virtual extension of the pointer would intersect with the plane of the participant’s body. As in Alsmith and Longo [6], depending on this intersection with the body each response was coded as falling into one of seven bodily regions, based on individual body measurements: 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 is added for classification, 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.

The numbers of responses for the different body regions, were analysed using a repeated measures analysis of variance (RM-ANOVA), with within-subject factors pointer starting direction (2 levels), pointer height (5 levels) and body region (5 levels), and $\bar{\alpha} = .05$.

It was tested whether a significant correlation was present between the pointing heights in the VR setup and on the body template.

3. Results

3.1. VR pointing task

None of the responses were scored as below the upper torso. Therefore, no body regions below the upper torso were included in further analyses. All results reported here are Greenhouse-Geisser corrected, because of failed Mauchly’s tests of sphericity. There was a significant main effect of body region ($F(1.58, 34.8) = 59.2$, $p < .001$, $\eta_p^2 = .73$), indicating that the responses were not evenly distributed across the different body regions. Overall, a strong preference can be seen for pointing at upper face. This effect of region was modulated by significant interactions between body region and pointer height ($F(5.40, 119) = 4.43$, $p = .001$,

η_p^2 = .17; see Fig 3A). There was no significant interaction between body region and pointer starting direction (F(2.99, 65.8) = 2.24, p = .092, η_p^2 = .092; see Fig 3B), nor a three-way interaction between body region, pointer starting position and pointer height (F(5.19, 114) = .58, p = .723, η_p^2 = .026).

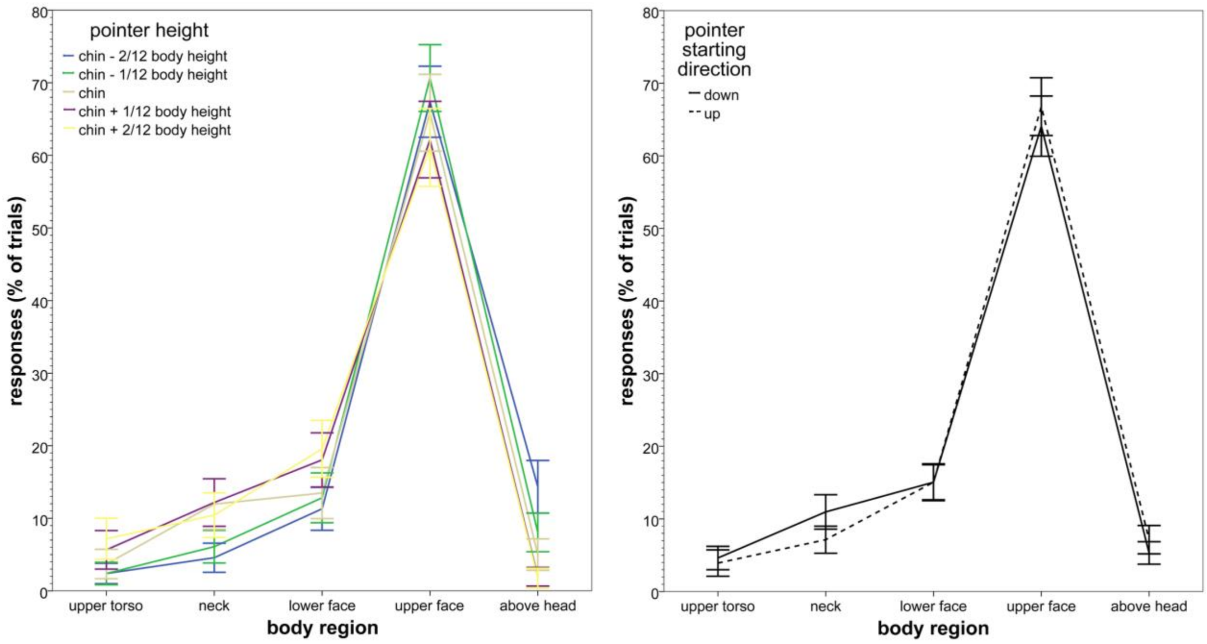

Fig 3. Body region pointed at for pointing at self. A (left). By pointer height, in percentage of trials (error bars: +/- 2 SE). **B (right). By pointer starting direction, in percentage of trials** (error bars: +/- 2 SE).

The interaction between body region and pointer height showed the following pattern: a larger proportion of the pointing at higher regions (upper face and above head) for the lower pointer heights (chin – 2/12 and chin – 1/12 of total body height) and a larger proportion of the pointing at lower regions (upper torso, neck and lower face) for the higher pointer heights (chin height, chin + 1/12 and chin + 2/12 of total body height) (with, in absolute numbers, the upper face being the most prevalent for each pointer height).

3.2. Body template task

Pointing on the body templates was found to be lower on the body (M = 78.4 (% of total template body height), SD = 11.7, n = 23) than in the VR setups (M = 92.5 (% of total physical body height), SD = 3.2, n = 23) on a paired-samples t-test (t(22) = 5.17, p < .001, Cohen's d_z = 1.09) (see Fig 4). More than half of the participants pointed to the upper torso, and the rest to the (upper) face in the body template task, while pointing to self in the VR setup was primarily to the upper face.

No significant correlation was present between the pointing to self in the VR setup and on the body template (r = -.297, n = 23, p (two-tailed) = .169).

3.3. Survey questions

On the survey question "Did you use a specific strategy for deciding where to direct the pointer? yes/no If so, what did you do?" it was reported by the large majority of participants that they had tried to point to the head or the eyes (16 out of the total of 23, vs 2 with the

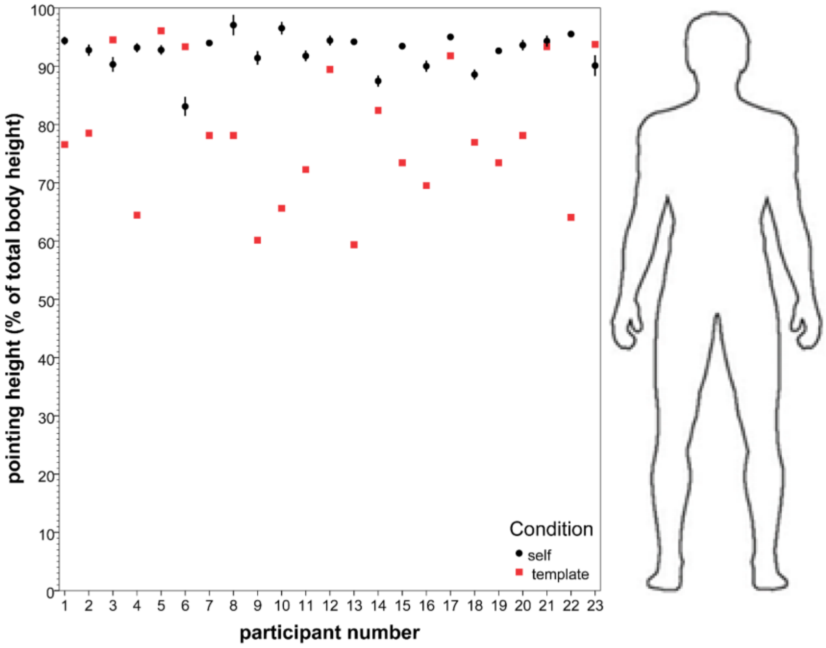

Fig 4. Pointing at self on one's own body compared to on the body template. The mean pointing height on the body for the VR pointing task (in percentage of total physical body height) compared to on the body template task (in percentage of total template body height), per participant (error bars: +/- 2 SE). An image of the body template is added to provide reference, in terms of the template used, as well as in terms of an approximately average body.

upper torso or the heart as chosen target and 5 with "no strategy"), either directly (4 head and 8 eyes), or indirectly (4) by making the pointer appear like a dot.

4. Discussion

The main finding in the present experiment was the overall strong preference for pointing at the upper face when asked to "point directly at you" while wearing a VR Headset. As in Alsmith and Longo's [6] study, the number of responses towards the upper torso and the neck—possibly interesting regions with regard to embodied self-location—were not extremely small though (4.3 and 9.0 percentage of the total number of responses, respectively). Alsmith and Longo found a very small number of responses towards the lower torso, in the present study there were none.

Employing the experimental design from the Alsmith and Longo [6] study, their bimodal result of upper torso and upper face as main locations where participants on average indicated themselves to be was thus not found to occur with a VR headset. Also, their finding that participants stopped at the overall preferred regions which they reached first, was not replicated in the current study: only one overall preferred region was found and, moreover, no significant interaction between body region and pointer starting direction was present.

The predominant pointing to the upper face found here, may show the spread of pointing across one area considered to be the location of the self, i.e. the upper part of the face or head, or it may result from (inaccuracy in) pointing to one specific location within this larger area, e.g. the eyes. However, the specific pattern found seems not to be the result of averaging over participants, as most individual participants (19 out of the 23) showed a clear preference for pointing at the upper face.

The pointing found here being largely to the upper face may (partially) be a result of the technical setup used. Wearing the VR headset, participants did not have any visual access to their bodies, possibly reducing their ability to point to other parts of their body than the face (and neck), to which normally they would have visual access. Moreover, this lack of visual access to their body may also have promoted participants to point at the experienced origin of their perception, which is typically the eyes (or a derived egocentre located in the head).

Egocentric distance (the distance from oneself to another location) has typically been found to be underestimated in VR headsets [17,18] and may have played a role in our results. However, egocentric distance has been found to be less underestimated in the Oculus Rift, than in older VR headsets [19-20], although results are still somewhat mixed and seem to partially depend on the measure of distance estimation used [21].

Additionally, the (upper) face may have been highly salient and the area of the body most easily located, as a result of sensations of weight and pressure from wearing the headset. To further test for effects of visual access to one's own body, potential VR headset related visual distortions, as well as of having a heavy piece of equipment on one's head, in follow-up studies different virtual reality setups should be employed, including one using a large immersive screen and not a headset. Additionally, in future studies this methodology should be used with richer cue environments.

Visual access to one's own body was also not provided by giving the participant a self-avatar in the virtual environment or by instead using augmented reality. Another potentially interesting future study would therefore be to investigate whether a self-avatar would result in different self-pointing behaviour.

In several clinical conditions distortions of body representations are involved. Recently, also in healthy participants structural distortions of body representations have been found [22-24]. Possibly these play some role in either or both of our tasks.

In the body template task participants most often indicated the upper torso as where they were located, followed by the (upper) face. This difference with the findings for the pointing to self in the current 1PP experiments in VR (largely to the upper face) is not in line with the studies discussed earlier [4,5,7,8], which all reported (locations related to) the face as the self-location found most. An important distinction between the VR task and the body template task was that participants had visual access to their own body in the body template task and were not wearing the VR headset anymore, which might be reasons for the different results between the two tasks. A possible way to evaluate this would be to do the body template task or a similar task also in the VR headset.

Starmans and Bloom [7,8] found very similar results for self-location in children and in adults (mainly the head, more particularly in or near the eyes). This combined with their specific tasks getting at self indirectly (judging when objects are closer to a person and erasing as much of a picture of a person while leaving the person in), they interpreted as support for the idea that experienced self-location is not so much based on cultural learning but rather has a natural-intuitive character. Answers on our survey questions showed the participants in the current study to come from a diversity of cultural backgrounds (with regard to being religious or not, nationality and countries lived in). No systematic comparison for self-location between cultural backgrounds was included in this study though. Considering that the notion of self-location under study here could well be (in part) socially or culturally constructed, a controlled follow-up study across cultures would be of interest.

The large majority of participants reporting in the survey that they had tried to point to the head or the eyes in the VR task, indicates that it had been a conscious strategy for most participants to point to a region or location in the upper face. Regardless what the underlying cause(s) for the strong behavioural preference for the upper face may have been, the intended strategies were thus largely in line with it.

These results suggest that wearing a VR headset might alter where people locate themselves, specifically making them more head-centred. More research is needed to determine if this is true for different virtual reality technologies such as augmented displays or large screen immersive displays, as well as in richer cue environments including (self-)avatars.

Supporting information

S1 Questionnaire. The set of survey questions the participants answered on paper at the end of the experimental session. https://doi.org/10.1371/journal.pone.0204358.s001 (PDF) (= Supplement 1 of this thesis).

S1 Dataset. The complete merged raw dataset, with variable annotations. https://doi.org/10.1371/journal.pone.0204358.s002 (XLSX).

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Article 2:

Self and body part localization in virtual reality: Comparing a headset and a large-screen immersive display

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Self and body part localization in virtual reality: Comparing a headset and a large-screen immersive display

Abstract

It is currently not fully understood where people precisely locate themselves in their bodies, particularly in virtual reality. To investigate this, we asked participants to point directly at themselves and to several of their body parts with a virtual pointer, in two virtual reality (VR) setups, a VR headset and a large-screen immersive display (LSID). There was a difference in distance error in pointing to body parts depending on VR setup. Participants pointed relatively accurately to many of their body parts (i.e., eyes, nose, chin, shoulders, and waist). However, in both VR setups when pointing to the feet and the knees they pointed too low, and for the top of the head too high (to larger extents in the VR headset). Taking these distortions into account, the locations found for pointing to self were considered in terms of perceived bodies, based on where the participants had pointed to their body parts in the two VR setups. Pointing to self in terms of the perceived body was mostly to the face, the upper followed by the lower, as well as some to the torso regions. There was no significant overall effect of VR condition for pointing to self in terms of the perceived body (but there was a significant effect of VR if only the physical body (as measured) was considered). In a paper-and-pencil task outside of VR, performed by pointing on a picture of a simple body outline (body template task), participants pointed most to the upper torso. Possible explanations for the differences between pointing to self in the VR setups and the body template task are discussed. The main finding of this study is that the VR setup influences where people point to their body parts, but not to themselves, when perceived and not physical body parts are considered.

Keywords

self-consciousness; VR headset; multisensory cues; self-location; bodily self; large-screen immersive display; body part locations; body perception.

Abbreviations

- AN : anorexia nervosa
- BIT : body image task
- BPQ : Body perception questionnaire (Porges, 1993)
- FOV : field of view
- LSID : large-screen immersive display
- Pano-LSID : panoramic large-screen immersive display
- RM-ANOVA : repeated-measures analysis of variance; VR, virtual reality

1. Introduction

In recent years, virtual reality technology has been increasingly used for basic and clinical neuroscience and behavioral research, see e.g., reviews by Alsmith and Longo (2019), Bohil et al. (2011), Slater and Sanchez-Vives (2016), and Ehrsson (2012). VR technologies can vary significantly in terms of the visual and bodily cues available to users. Heydrich et al. (2013) directly compared headsets using video-generated vs. computer-generated visual information and discussed the potential differences these technologies introduce to the study of bodily self-consciousness, while other studies have also used large-screen immersive displays (LSIDs) to study body and space perception (Piryankova et al., 2013; Mölbert et al., 2017). Both Heydrich et al. (2013), as well as Piryankova et al. (2013), report underestimation of egocentric distances in VR headsets (also: Loomis and Knapp, 2003; Renner et al., 2013), although egocentric distance has been found to be underestimated less (under 20%) in the Oculus Rift headset, than in older VR headsets (up to 60%) (Young et al., 2014; Creem-Regehr et al., 2015). Piryankova et al. (2013) investigated distance estimation also in large screen displays and found underestimation to occur in three different LSIDs. For the panoramic LSID (Pano-LSID) also employed in the current study, Piryankova et al. (2013) found that the distance to the screen influenced distance estimates such that these distances were "pulled toward" the distance to the screen. Mohler et al. (2010) and Ries et al. (2008) demonstrated that experience with a self-animated avatar improves distance estimates in VR headsets, although the reason for this is not fully known.

1.1. Self-location

Generally, people locate themselves where their bodies are. Although counter-examples are known, involving e.g., self-perception from the third-person perspective (Galvan Debarba et al., 2017; Gorisse et al., 2017), autoscopic phenomena (Blanke et al., 2008), or full-body illusions (Lenggenhager et al., 2007), it is more typically the case that people would indicate their bodies as where they are. In the present study, we investigate a specification of this bodily self-location. By asking participants to point directly at themselves, we aim to determine whether there is a bodily location, or set of locations, in which people think of themselves as precisely located.

Most literature focusing on specifying self-location in the body has used an outline of a human body where the task did not involve pointing to oneself but rather localization of a person or on a depiction of a person. Limanowski and Hecht (2011) asked participants to indicate the "center of the self" by placing markers on human silhouettes and found a dominant role for the brain. They also found that most individuals seem to believe there is one single point inside the human body where their self is located. Anglin (2014) used open questions and forced-choice self-localizing on a body silhouette and found in contrast that some participants reported that the self is not centralized in one location. Overall, she found participants locating the self and mind in the head and the soul in the chest. Starmans and Bloom (2012) asked people to judge when objects were closer to a depicted person, 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). They suggested on the basis of their results that people locate the self mainly in the head and, more particularly, in or near the eyes. Van der Veer et al. (2018) found in a paper-and-pencil task of pointing to oneself on a body outline that people pointed primarily to the upper torso, followed by the upper face.

Alsmith and Longo (2014) developed a method for eliciting precise self-location judgments concerning one's own body, rather than a depiction of a body, which also allowed specification of multiple bodily locations across trials. They adapted a version of a task developed by Howard and Templeton (1966), originally designed for locating the point of projection of binocular vision. The task required the subject to manually align a visually presented rod along the horizontal plane such that the near end pointed "directly at himself." Alsmith and Longo (2014) adapted this task, requiring subjects to either haptically or visually align a rod along a sagittal plane, with individual trials split equally between two directions of rotation (upwards or downwards). They found that participants' judgments were not spread out homogeneously across the entire body, nor were they localized in any single point.

Specifically, pointing was mainly to the upper face and the upper torso. Van der Veer et al. (2018) extended Alsmith and Longo's paradigm in a VR headset and found almost exclusively pointing to the upper face, followed by a much smaller amount to the upper torso. Recently, Alsmith et al. (2017) employed a paradigm where self-location is implicated by the part(s) of the body used by participants to indicate the locations of external objects relative to themselves. Using this more implicit method, they found evidence for the use of a weighted combination of head and torso for self-location judgments. All these self-location paradigms, except Van der Veer et al. (2018), are performed without the use of VR technology.

1.2. Body part localization

It has been assumed, that the somatosensory system has access to accurate information of one's body size and shape (Soechting, 1982; Van Beers et al., 1998). However, most individuals have to be taught to correctly draw human body proportions (Fairbanks and Fairbanks, 2005), otherwise their drawings demonstrate several systematic distortions (Kahill, 1984). Moreover, multiple studies have shown structural distortions in position sense in healthy populations, which may involve distortions in body representations (Hach and Schütz-Bosbach, 2010; Longo and Haggard, 2010, 2012; Fuentes et al., 2013; Linkenauger et al., 2015; Saulton et al., 2015; Longo, 2017). Comparable methods have been used in patient populations, finding distortions in body size perception [in anorexia nervosa (AN): Gardner and Brown (2014), in AN and bulimia nervosa: Mölbert et al. (2017)].

There exist several methodologies for measuring body part localization on the physical body. When testing patients' abilities to localize body parts, it is common to have them point to specific parts of their own or the examiner's body (Sirigu et al., 1991; Felician et al., 2003), or to objects placed on specific locations of their own body. The body part target instructions can be in one of a diversity of forms, e.g., spoken, written, pictorial, pointing, or touching (Felician et al., 2003). To test for patients' ability to identify body parts, Semenza and Goodglass (1985) used a variety of tasks involving pointing to and touching of one's own and a depicted body and body parts. Also, in the study of body representations, pointing to one's own body parts with one's own hand has been employed as a measure of body part locating ability (Paillard, 1999). In studies of personal or body space (the space that your physical body occupies), Hach and colleagues asked participants to point with their hand—with or without the help of a laser pointer—to several landmarks on their own physical bodies while their body except their face was hidden from view (Hach and Schütz-Bosbach, 2010), and to body parts on their own bodies imagined in front of oneself (Hach et al., 2011). Longo and colleagues (Longo and Haggard, 2010; Tamè et al., 2017) had participants indicate with a baton where they perceived specific spatial landmarks on their occluded hands. They found specific distortions relative to the physical hand, namely overestimation of hand width and underestimation of finger length. These paradigms rely on physical self-directed pointing with the finger or an apparatus, either to one's own (physical) body or on a plane occluding the body from vision. Fuentes et al. (2013) had participants provide estimates of body part locations on a non-co-located body in a desktop body image task (BIT). On a computer screen a head was seen which was to be imagined as a mirror image of yourself and several body parts were to be located relative to this head. For a review of the body representations and the types of information processing involved in pointing to body parts, as well as the disorders it is affected by, see De Vignemont (2010).

1.3. The current study

Although VR has become a widely used research tool for studying multisensory body perception and self-consciousness (Bohil et al., 2011; Ehrsson, 2012; Blanke et al., 2015; Slater and Sanchez-Vives, 2016), the influence of VR technology on self or body part localization has not been thoroughly investigated. In the current study, we investigate self- and body part localization in two VR setups (Pano-LSID and a VR headset) with the intention of directly comparing the results. We ask participants to indicate their self-location and several of their body parts' locations by rotating a virtual pointing stick through their sagittal plane. One way of considering the possible presence of distortions in body part localization—both general ones and those related to visual perception in VR—is not to assume the physical body as the best baseline for determining where people point to themselves. Therefore, a measure of where participants locate their body parts in VR is assessed to take into account the possible effects of such distortions on the measure of self-location by allowing for the normalization of pointing to self with regard to participants "perceived" body part locations. Fuentes et al. (2013) and Linkenauger et al. (2015) are previous studies employing the rescaling of body shapes on the basis of experimentally found perceived body part locations. Following the VR experimental trials, we also perform a body template task as in Van der Veer et al. (2018).

We have the following three main research questions. (1) Does pointing to self and body parts differ between an LSID and a VR headset? (2) Is indicated self-location in the body template task outside of VR similar to self-localization in VR? (3) Where do people precisely locate themselves (point to themselves) in their bodies?

Connected to these questions we have the following three predictions. (1) We predict that differences between the VR setups (specifically, visual access to the body, presence of a headset, and differences in spatial perception) will result in differences in self- and body part localization between the two VR setups. (2) In contrast to the VR Setups, where we expect face followed by torso, we expect participants to mainly indicate the upper torso, followed by the upper face (Van der Veer et al., 2018) as self-location in the body template task. (3) Given the most relevant previous literature (Alsmith and Longo, 2014; Van der Veer et al., 2018), we expect that participants will primarily point to the face and possibly also the upper torso in VR for self-location and that, if distortions in body part localization are present, that self-location will also differ in terms of physical vs. perceived body regions.

2. Methods

2.1. Participants

Thirty healthy volunteers [18 female; age: M = 29.2, SD = 9.8, range: 19–60 years; 27 right-handed (assessed by self-report)], naive to the purpose of the experiment, participated, all with normal, or corrected-to-normal vision (including stereo depth vision). The participants were recruited from the participant database of the Max Planck Institute for Biological Cybernetics in Tübingen, Germany. All participants gave written informed consent. Procedures were in accordance with the principles of the Declaration of Helsinki and approved by the Ethics Committee of the University Hospital Tübingen.

2.2. Procedure

The experiment was completely run in either German (18 participants) or in English (12 participants). The participants read an information sheet and signed an informed consent form. They were tested for stereo depth vision (Stereo Optical Co., Inc., Chicago, IL). Then the experimenter measured the height of the top of the participant's head (cranial vertex;

Kopfspitze), eyes (pupils; Augen), chin (gnathion; Kin), shoulders (acromion; Schultern), hips (where the circumference is largest; Hüften), (tip of the) nose (Nase), elbows (the most laterally protruding part of the bone; Ellbogen), waist (where the circumference of the lower torso is smallest; Taille), knees (top of the knee cap; Knie), and feet (where the foot borders on the ankle; Füße) with a wooden folding ruler taped to a wall. During the measurement of these heights, the participant was instructed explicitly where the respective body parts are exactly located on the body (specified in brackets after the names in the list above) and which names they would hear for them over the loudspeakers during the experiment (these names are in italics in the list above; the German names are added in italics in brackets; elbows were not used for pointing). In order to ensure exact locations were known to the participants, they were briefly tapped on all the locations where they were to point at, while again the names of the locations were mentioned before the pointing task began.

Participants were instructed that they would be asked to do a pointing to self-task in two VR setups: a VR headset (see Figure 1**,** Left) and a panoramic large-screen immersive display (Pano-LSID) (see Figure 1, Middle and Right). The order of the two VR setups was counterbalanced. After completing the self-pointing task, they were given instructions for a pointing to body part task (again counterbalanced in terms of VR setup). Following all VR pointing tasks the participants performed a body template task and two questionnaires.

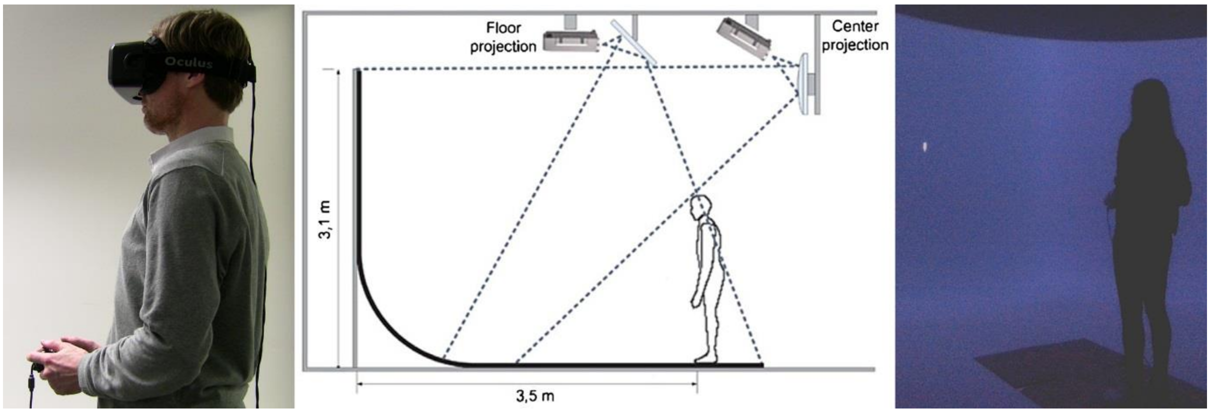

Figure 1. (Left) A photo of the VR headset experimental setup. The participant was standing still, wearing the VR headset, and holding the controller. The individual depicted has given written informed consent to appear identifiably in this publication. **(Middle) A schematic depiction of the Pano-LSID experimental setup.** Reused from Piryankova et al. (2013) with kind permission from the publisher (Elsevier). **(Right) A photo of the Pano-LSID experimental setup.** The participant was standing still in front of the Pano-LSID and holding the controller. In both setups the participant's task was to rotate a virtual pointer in their sagittal plane until they felt it was pointing "directly at you" or to a specific body part.

2.2.1. VR pointing tasks

In the self-pointing task, the participants were asked: "[…] to adjust the direction in which the stick is pointing, so that it is pointing directly at you." (or in German: "[…] die Richtung des Zeigestocks so zu verändern, dass dieser genau auf Sie zeigt."). For the pointing to specific body parts task, the participants heard the previously instructed names of the body parts over the loudspeakers and were asked: "[…] to adjust the direction in which the stick is pointing, so that it is pointing at different of your own body parts." (or in German: "[…] die Richtung des Zeigestocks so zu verändern, dass dieser auf verschiedene Ihrer Körperteile zeigt."). For both pointing tasks, the participant used the joystick on the left-hand side of a controller to rotate the pointer upwards or downwards (both directions were permitted at all times) through their sagittal plane. 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.

Participants first completed the pointing to self-task in both VR-setups, then they completed the pointing to particular body parts in both VR-setups. Each time, before switching the VR setup, participants were allowed a short break where they were asked to sit down on a chair. Besides the breaks between the VR-setups, there was an extra break in the middle of each pointing at body parts block, where the participants could move a bit to stretch their legs. In the VR headset setup, the headset was kept on during these extra breaks.

2.2.2. Body template task

After the VR pointing tasks were finished, participants performed a body template task, where they were asked to “Point directly at you” on an A4 print of a drawn body outline with a pen, under the assumption this was a picture of themselves. Participants performed this task on one frontal picture and on two side-view pictures, one with and one without an arm depicted (see Figure 2). The pictures were administered in counterbalanced order, with the frontal one always being the second. Based on our previous findings (Van der Veer et al., 2018), we predicted that participants in the body template task would point mainly toward the upper torso and to a lesser extent to the upper face.

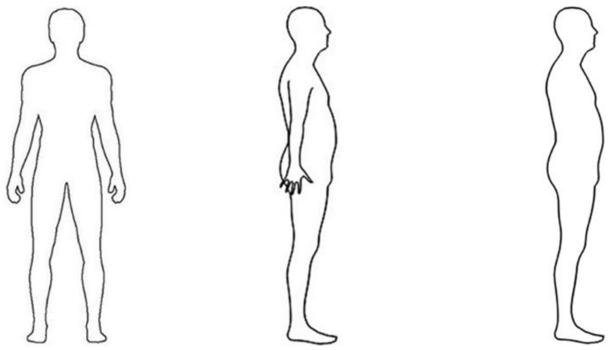

Figure 2. The body templates. The participant was asked to point “directly at you” on these three pictures of an outline of a body, under the assumption they were pictures of themselves.

2.2.3. Questionnaires

After the VR and the body template tasks, the awareness scale of the Body Perception Questionnaire (BPQ; self-measure, 45 items, five-option Likert scales) was administered (Porges, 1993). This questionnaire was included to test for possible correlations between task performances and a subjective self-report measure probing perceived interoceptive aptitude or interoceptive sensibility (for a discussion of these and other measures of interoception, see Garfinkel et al. (2015), where the term interoceptive awareness is reserved for the metacognitive level of the relationship between interoceptive accuracy and the awareness of this accuracy). Our interest in this questionnaire was to test if higher interoceptive sensibility correlates with more accurate body part localization. Correlations between interoceptive sensibility and pointing to self in the VR headset, the Pano-LSID, as well as on the body templates, were also tested.

Finally, a post-questionnaire (added to this article as a supplementary material) was filled out by the participant, with several questions about employed strategy.

2.3. Experimental setup

2.3.1. VR headset

During the VR headset blocks (see Figure 1, Left), the participant stood in front of a table on which a Dell Precision M6700 laptop was positioned running the experiment. The computer had an Intel Core i7-3940XM central processor running at 3.00 GHz and an NVIDIA Quadro K5000M graphics card. An Oculus Rift development kit 2 VR headset with a diagonal field of view (FOV) of 96, a resolution of 1920 × 1080 pixels (960 × 1080 per eye), and a frame rate of 60–75 Hz was used for stimulus presentation. The tracking camera of the Oculus Rift was mounted on a separate stand behind the table.

2.3.2. Pano-LSID

During the Pano-LSID blocks (see Figure 1, Middle and Right), the participant stood in front of a quarter-spherical panoramic large-screen immersive display with a radius of 3.5 m, a horizontal FOV of 230 (±115) and a vertical FOV of 125 (25 upwards and 100 downwards onto the floor, up to 1 m behind the participant). Participants stood 3.5 m from the vertical screen (in all directions). The projection was done by six Eyevis LED DLP (ESP-LWXT-0.5) projectors, set up with 5 front projectors in portrait mode (1200 vertical × ∼4500 horizontal pixels, 60 HZ) and 1 floor projector in landscape mode. Image rendering and warping and blending (performed through NVIDIA, GPU core) was done on a high-end cluster system consisting of seven computers, one client image generation PC for each projector plus a master PC where the experiment was run and the data recording was coordinated. All PCs were HP Z800 Workstations running at 3.47 GHz with ZOTAC nVIDIA GeForce 9800 GT graphics cards.

2.3.3. Both setups

All the experimental blocks were run with lights out in the same room. The participant held a Microsoft Xbox 360 controller, moved the pointer using a joystick with the left hand and confirmed the decision by pressing a button with the right hand. Maximum speed of the pointer was 75◦/s for the VR headset and 60◦/s for the Pano-LSID, with the difference resulting from the different refresh rates of the setups.

2.4. VR stimuli and experimental design

The experiment was designed in Unity 4.6.7f1 for the VR headset and in version 4.2.1f4 for the Pano-LSID, employing the same code, resulting in completely analogous versions of the experiment in the two setups.

The virtual environment consisted of an empty space with a blue background. In each trial the participant saw a cylindrical pointing stick with a blunt backside and a pointy front side. 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 distance to the vertical screen in the Pano-LSID). The pointer had a virtual length of 30 cm and a diameter of 4 cm, was a light-gray color, and had a fixed lighting source straight above, providing some shadow at the underside of the pointer (see Figure 3, Left). The starting direction of the pointer was pointing straight up, straight down, or perpendicular to the participant, at one of seven fixed backside heights: 0, 0.25, 0.5, 0.75, and 1 × total body height, the middle between shoulder and chin height, and the middle between ground level and knee height (see schematic in Figure 3). These different pointer starting directions and heights were included to make the task more diverse and to not cue participants, which might result from a more specific selection of angles and heights. The pointer starting direction perpendicular to the participant was also specifically added to test whether for the pointer height at the middle of the neck, i.e., between two regions of interest, the face and the torso, participants would choose to move the pointer substantially more up or more down to point at their self-location.

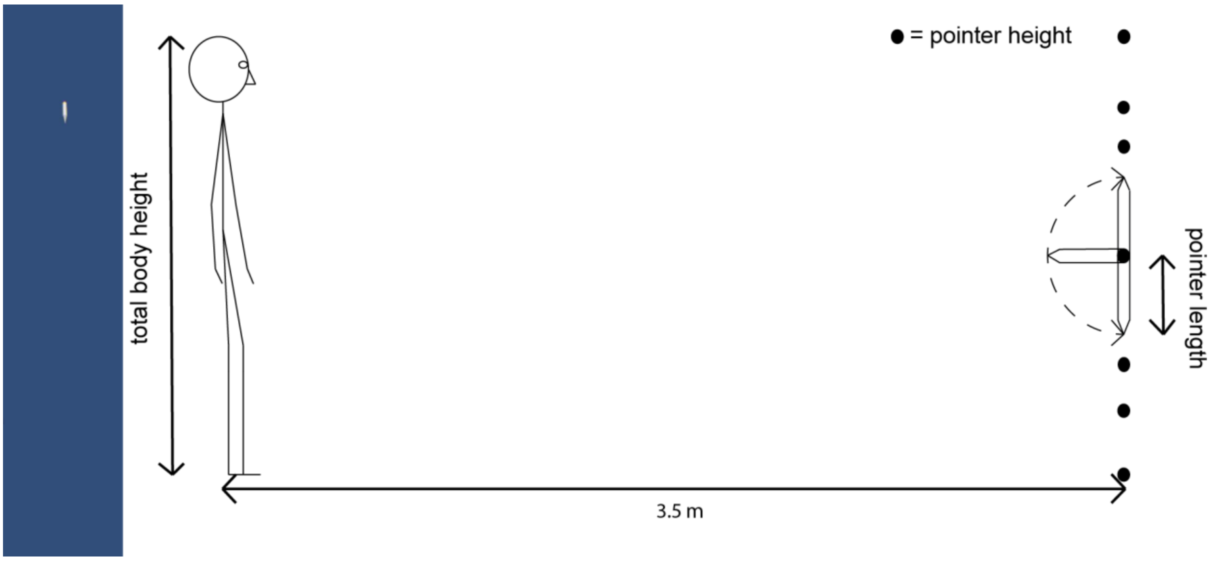

Figure 3. (Left) The pointer stimulus. An example image of the pointer stimulus, here with an angle of + 48.2◦ up from straight down, showing a field of view of about 20◦ horizontal and 100◦ vertical. **(Right) Schematic depiction of the setup.** The dotted line indicates the range of possible pointer rotations. The pointer starting direction was either straight up, straight down, or perpendicular to the participant. Seven pointer heights were spread out across the complete height of the participant's body: 0, 0.25, 0.5, 0.75, and 1 × total body height, middle between shoulder and chin height, middle between ground level and knee height.

The complete experiment had a within-subject design with four factors: 2 × VR setup, 3 × pointer starting direction, 7 × pointer height, and 10 × target (self and 9 body parts), and one measure: pointing height (where an extension of the pointer at the chosen angle would intersect with the front of the participant's body). The number of trials was 3 (pointer starting directions) × 7 (pointer heights) = 21 per target for each VR setup, making 2 × 10 × 21 = 420 trials in total per participant. These trials took approximately 60 min to complete.

2.5. Analysis

The 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 to 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 front of the participant's body (the front of the body was taken as the virtual plane orthogonal to the participant's viewing direction, extending from the location of his eyes). All statistical analyses were performed in SPSS.

2.5.1. VR self-location on the physical body

For self-pointing using the participant's individual body height measurements the height on the body was then classified as a score for one of seven regions of the body (in Figures 4, 8 these 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), 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). 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 a region between them, the neck, bounded by chin, and shoulders. The responses were analyzed using a RM-ANOVA, with factors body region (7 levels) and VR setup (2 levels). In case of (a) significant effect(s), relevant t-tests (corrected for false positives) were performed to further localize the effect.

For the trials with the pointer starting straight ahead and at the height of the neck, the percentages of trials pointed to the neck, to regions below the neck and to regions above the neck were compared; as well as the percentages of trials pointed down relative to the straight-ahead starting direction, up relative to this starting direction, and with no movement of the pointer.

2.5.2. VR body part localization

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). The error distances were analyzed using a RM-ANOVA, with factors VR setup (2 levels) and target body part (9 levels). In case of (a) significant effect(s), relevant t-tests (corrected for false positives) were performed to further localize the effect.

The locations pointed at for the various body parts were subsequently used to rescale the average body across the sample, now based on the perceived body part locations instead of the physical body part locations, separately for the VR headset and the Pano-LSID. Pictures of the outline of the average body across the sample were made for the physical body, the body as perceived in the VR headset and the body as perceived in the Pano-LSID.

2.5.3. VR self-location on the perceived body

The pointed at body part locations were then used to recompute the regions of the body (see section 2.5.2. VR Body Part Localization) used to categorize the height on the body for self-pointing. For each participant separately, these regions were recoded into new perceived body regions based on the pointed at body part locations (in Figures 7, 8 these responses are shown in terms of percentages of trials per body region), instead of on the physical body part locations. Subsequent recategorizing the self-pointing responses—considering where participants pointed out their body parts to be in the two VR setups—likely better reflects where they actually experienced themselves to be. Using the recategorized responses, i.e., numbers/percentages of trials scored per perceived body region, the RM-ANOVA was redone, to see whether the self-pointing for the two VR setups were different in terms of perceived body regions. In case of (a) significant effect(s), relevant t-tests (corrected for false positives) were performed to further localize the effect.

2.5.4. Body template task

Paired-samples t-tests were performed to test for differences between the pointing heights for the different body outlines used in the template task. It was also tested whether a significant correlation was present between the pointing heights for self in either VR setup (in percentages of total physical body heights) and on the body template (in percentages of total template body heights).

2.5.5. Questionnaires

The total score on the BPQ awareness scale was computed, as the mean score over all 45 items (scored from 1 to 5 each), with a higher score reflecting higher sensibility. It was tested whether a significant correlation was present between BPQ awareness score and absolute error distance for pointing to body parts (a negative correlation was hypothesized), or the pointing height on the body (as a percentage of total physical body height) for self-location in the VR headset, the Pano-LSID, or on the body template (all two-tailed Pearson correlations).

3. Results

3.1. VR self-location on the physical body

All results reported here are Greenhouse-Geisser corrected, because of failed Mauchly's tests of sphericity. There was a significant main effect of body region [$F(3.30, 95.7) = 12.0$, $p < 0.001$, $\eta_p^2 = 0.29$; see Figure 4 for the responses per body region by VR condition]. Participants did not point to all regions of the body equally, nor did they point to one particular region only. They pointed mainly to the upper face (M = 31.7%, SD = 18.01), above the head (M = 17.9%, SD = 15.34), the upper torso (M = 14.4%, SD = 17.53), the lower face (M = 14.0%, SD = 9.31), as well as to the neck (M = 12.4%, SD = 10.41), with the upper face as the region pointed to most.

This effect of body region was modulated by a significant interaction between region and VR setup [$F(3.57, 103) = 9.32$, $p < 0.001$, $\eta_p^2 = 0.24$]. Simple main effects of body region were found to be significant for each VR condition separately [VR headset: $F(6, 24) = 4.03$, $p = 0.006$, $\eta_p^2 = 0.50$; Pano-LSID: $F(6, 24) = 27.4$, $p < 0.001$, $\eta_p^2 = 0.87$].

Specific comparisons were made between the VR conditions for each body region (7 comparisons) using the Holm-Bonferroni correction procedure. Holm-Bonferroni corrected paired-samples t-tests showed significantly less pointing for the VR headset compared to the Pano-LSID for the lower face (p = 0.0017) and the upper face (p = 0.0071), while more pointing was found above the head in the VR headset (p = 0.0050) (see Figure 4).

For the pointer at the height in the middle between shoulders and chin (i.e., the middle of the neck) and starting straight ahead, pointing was mostly to the neck (36.7% for both setups), followed by upper and lower face [VR headset: upper face (30.0%), then lower face (13.3%); Pano-LSID: lower face (36.7%), then upper face (23.3%), and little pointing to the upper torso (VR headset: 13.3%, Pano-LSID: 3.3%)]. In terms of directions, pointing was mostly up from the starting direction (VR headset: 60.0%; Pano-LSID: 60.0%), followed by no pointer movement (VR headset: 16.7%; Pano-LSID: 30.0%) and down from the starting direction (VR headset: 23.3%, Pano-LSID: 10%). So, in terms of directions participants showed a clear

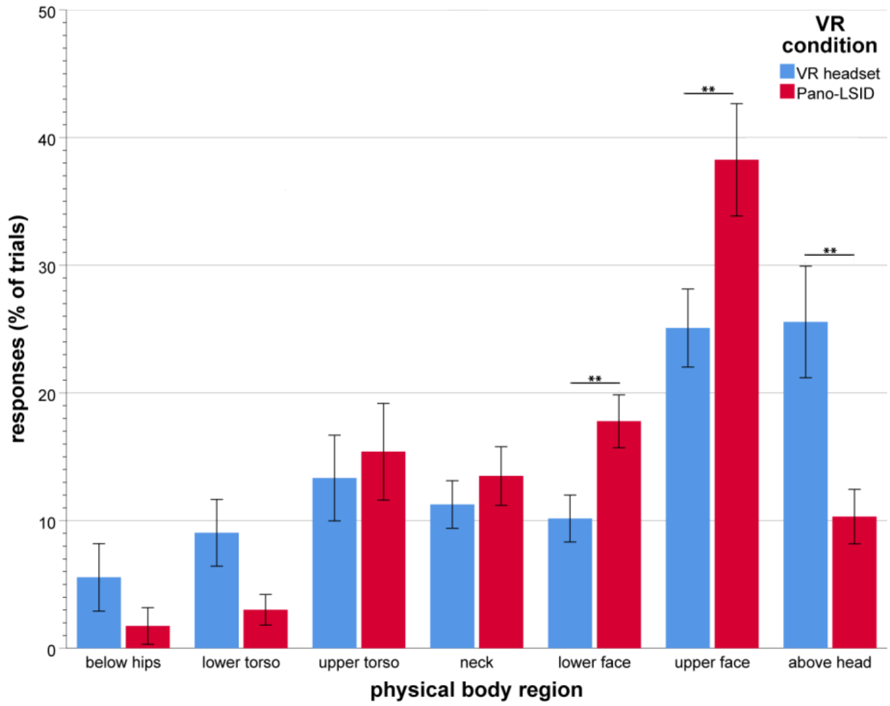

Figure 4. Self-pointing in terms of physical body regions (in mean percentage of trials per VR setup), by VR setup (N = 30; error bars: ± 1 SE; **p < 0.01).

preference for going up rather than down when the pointer was starting out straight ahead at the neck.

3.2. VR body part localization

Five extreme outlier responses (from 4 participants; out of a total of 11,340 trials), which were the result of the task not having been correctly performed for the respective trials (the pointer was left in the starting direction, either straight up or straight down), were removed and values of 0 were imputed.

Where Mauchley's test indicated violation of the sphericity assumption, the Greenhouse-Geisser correction was applied. Significant main effects were found for target [$F(1.23, 35.7) = 9.57$, p = 0.002, $\eta_p^2 = 0.25$), as well as for VR setup [$F(1, 29) = 91.3$, p < 0.001, $\eta_p^2 = 0.76$] (see Figure 5 for the error distances per target by VR condition). The following trend for target is observed: from large undershooting for the lowest to large overshooting for the highest target (feet: M = −48.32 cm, SD = 108.61; knees: −13.69 cm, SD = 56.61; hips: −9.10 cm, SD = 33.09; waist: −3.45 cm, SD = 29.80; shoulders: 2.25 cm, SD = 14.55; chin: −5.97 cm, SD = 17.87; nose: 5.01 cm, SD = 12.25; eyes: 12.46 cm, SD = 13.63; top of head: 38.15 cm, SD = 34.11). For VR condition the following was observed: large mean undershooting for the VR headset (M = −10.22 cm, SD = 25.80) and small mean overshooting for the Pano-LSID (M = 5.44 cm, SD = 25.0).

The two main effects of target and VR condition were modulated by an interaction between these two factors [$F(2.23, 64.7) = 37.4$, p < 0.001, = 0.56; see Figure 5]. Considering the mean error distances, participants were able to point reasonably accurately (with mean error distances of around ±10 cm) to most of their body parts in the Pano-LSID, but much less so in the VR headset. In the VR headset mean pointing height to the top of the head was overestimated (M = 46.67 cm, SD = 34.58) and mean pointing to the feet (M = −78.87 cm,

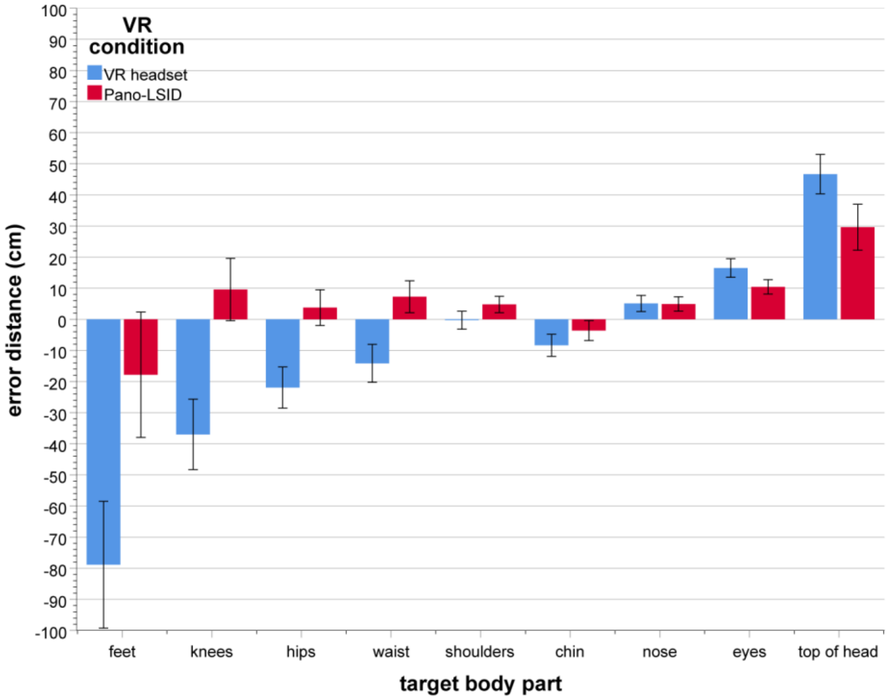

Figure 5. Mean error distance (in cm) between pointed at and physical body part location, per target body part, by VR setup (N = 30; error bars: ± 1 SE). The error distances are directional, with negative being down and positive being up relative to the physical height of the target body part per participant.

SD = 111.57), knees (M = −36.98 cm, SD = 61.99), and hips (M = −21.92 cm, SD = 36.17) were underestimated. In the Pano-LSID mean pointing height to the top of the head was overestimated (M = 29.63 cm, SD = 44.45) and pointing to the feet was underestimated (M = −17.81 cm, SD = 110.42). Inconsistency in the pointing—as indicated by large standard errors—can be observed particularly for the top of the head, the feet, and the knees, for both setups.

Simple main effects of target were found to be significant for each of the two VR setups separately [VR headset: $F(8, 22) = 5.16$, $p = 0.001$, $\eta_p^2 = 0.65$; Pano-LSID: $F(8, 22) = 9.74$, $p < 0.001$, $\eta_p^2 = 0.78$].

Specific comparisons were made between the VR conditions for each body part (9 comparisons) using the Holm-Bonferroni correction procedure. Holm-Bonferroni corrected paired-samples t-tests showed significant differences between the mean error distances for the VR headset and the Pano-LSID for all body parts, except the nose. The mean negative error distance for the feet was significantly larger for the VR headset compared to the Pano-LSID ($p < 0.001$). There was a significant difference between the negative mean error distance for the VR headset and the positive mean error distance for the Pano-LSID for the knees ($p < 0.001$), hips ($p < 0.001$), waist ($p < 0.001$), shoulders ($p = 0.0053$), and chin ($p = 0.035$). Finally, the mean positive error distance was significantly larger for the VR headset compared to the Pano-LSID for the eyes ($p = 0.015$) and the top of the head ($p = 0.019$).

There is some intrinsic mathematical bias in how the pointing heights on the body are derived. The mapping from angle to projected height on the body is not fully linear, but promotes a skewed distribution. This bias is not yet present at the level of the original pointing angles, so averaging over pointing angles first, before mapping onto pointing heights on the body, (partially) minimizes this bias. Therefore, new pointing heights were computed based on pointing angles averaged over several trials (of the same participant, target, VR condition, and pointer height). Statistical analyses were (re)run separately for the new and for the previous pointing heights (computed from pointing angles on a trial-by-trial basis), for body parts and for self. Comparing the results for the new and the previous pointing heights revealed only slight differences in the test statistics and no differences with respect to significant effects, for both body parts and self. The results from performing the alternative analyses of our data, partially reducing the effect of the mapping bias, do not call for a change in the interpretation of the data or our conclusions. We believe, it is therefore warranted to analyze the body heights computed from pointing angles on a trial-by-trial basis.

We rescaled the average physical body of the sample of participants, which is based on the average measured body part locations, to average perceived bodies for the sample, based on the average heights pointed at for the different body parts. As the pointing at body parts was performed for the VR headset and for the Pano-LSID separately, we arrived at two perceived bodies, one for the VR headset and one for the Pano-LSID. The results in the form of simple line drawings of these average bodies can be seen in Figure 6. Linkenauger et al. (2015) formed the main inspiration for rescaling the body based on perceived body part locations in this way.

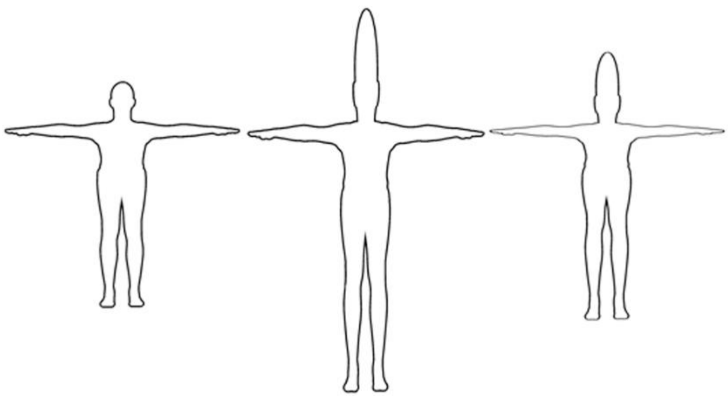

Figure 6. Physical and perceived bodies. Average bodies across participants: **(Left) physical, based on the measured body heights; (Middle) perceived, based on the pointed-out body part locations in the VR headset; (Right) perceived, based on the pointed-out body part locations in the Pano-LSID.** Scaling is in the vertical dimension only and the arms are not considered in the scaling.

The two rescaled bodies model the same distortions—relative to the physical body (left)—as can be seen in the Figure 5 bar graph, for the VR headset (middle) and the Pano-LSID (right), respectively. What can be seen here as well, are mainly the particularly large overshooting for the top of the head and large undershooting for feet and knees for the VR headset, as well as the large overshooting for the top of the head for the Pano-LSID. Note, that the analyses of self-localization in terms of the perceived body involve individually recomputed body regions and recategorized self-location responses, in contrast to the average rescaled bodies depicted in Figure 6.

3.3. VR self-location on the perceived body

Since body part localization has large inaccuracies as well as differs per VR setup, for the rest of the analysis of self-location we will use the perceived body per participant. Recomputing the regions of the body in terms of the perceived body and recategorizing the pointing at self-responses in terms of these new body regions, provides a way of looking at the results for self-locating while taking into account how participants perceived their bodies in the two VR setups. Using the recoded responses, the RM-ANOVA was done, in the same way as before (see sections 2.5.1. and 3.1. VR self-location on the physical body).

All results reported here are Greenhouse-Geisser corrected, because of failed Mauchly's tests of sphericity. A significant main effect was found for responses per perceived body region [$F(2.37, 68.6) = 28.80$, $p < 0.001$, $\eta_p^2 = 0.50$]. There was no significant interaction between body region and VR setup for pointing to self in terms of perceived body regions [$F(2.89, 83.7) = 2.34$, $p = 0.081$, $\eta_p^2 = 0.75$; see Figure 7 for the responses per perceived body region by VR setup].

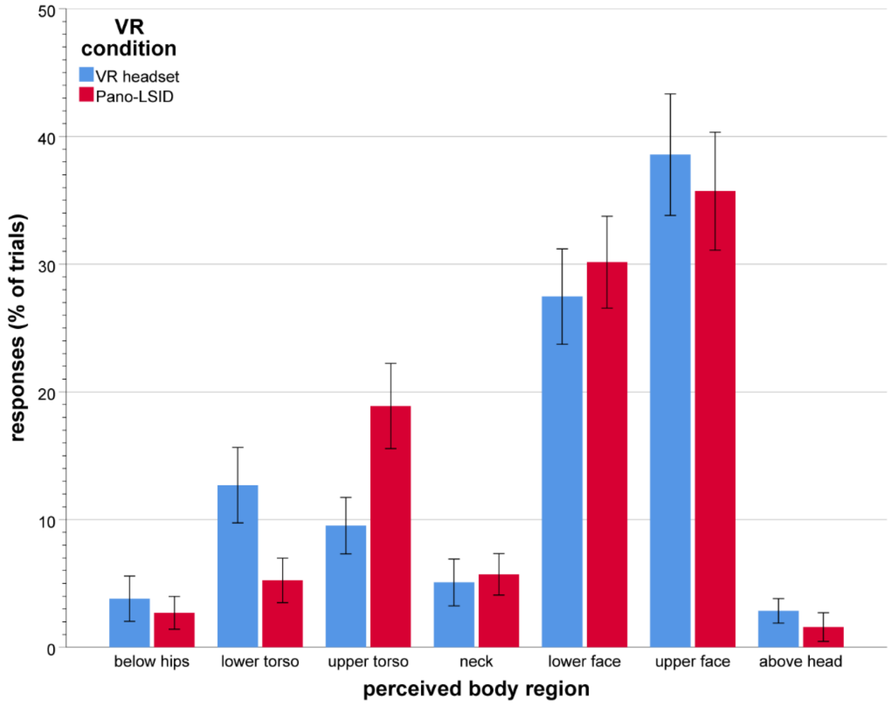

Figure 7. Self-pointing in terms of perceived body regions (in mean percentage of trials per VR setup), by VR setup (N = 30; error bars: ± 1 SE).

Participants did not point to all regions of the body equally, nor did they point to one particular region only. When considering the perceived body, they clearly pointed mostly to the upper face (M = 37.1%, SD = 23.2), followed by the lower face (M = 28.8%, SD = 14.0), followed by pointing to the upper torso (M = 14.2%, SD = 11.8), and then to the lower torso (M = 9.0%, SD = 11.3). Hardly any pointing above the head remained after rescaling from physical to perceived body regions. Overall, collapsed over both VR setups, the amounts of pointing remained similar or went up for all body regions after rescaling, except for the neck and below the hips.

Comparisons were made between all body regions (21 comparisons) using the Holm-Bonferroni correction procedure. Holm-Bonferroni corrected paired-samples t-tests showed significantly larger amounts of responses for the upper and for the lower face, compared to all other regions, except each other [all $p < 0.001$, except for the comparisons with the upper torso (for the lower face: p = 0029; for the upper face: p = 0062)]. Significantly larger amounts of responses were also found for the upper torso compared to below the hips (p = 0.0023), the neck (p = 0.018), and above the head (p = 0.00074), as well as for lower torso compared to below the hips (p = 0.0496).

Body region is actually not a truly balanced within subject variable and the pointing percentages do not have similar variances across the levels of this variable, nor across the differences between the various levels of body region. Therefore, the self-localization data was analyzed again using a bootstrapping methodology, which does not assume normality of the data. New analysis results were subsequently compared with those from our previous specific comparisons using Holm-Bonferroni corrected paired samples t-tests (see paragraph 3 of section 3.1. VR self-location on the physical body and paragraph 4 of the current section). Bootstrapping versions (resampling 10,000 times) were run of the t-tests testing for each physical body region whether there is a significant difference in the mean percentages of trials pointed to it between the two VR conditions (7 comparisons). These alternative bootstrapping t-tests yielded similar results as the previous non-bootstrapping t-test (section 3.1. VR Self-Location on the Physical Body) and the same comparisons showed significant differences (for the lower face, the upper face, and above the head). We also ran bootstrapping versions of the t-tests comparing all perceived body regions with each other for significant differences in the mean percentages pointed to them (21 comparisons). These alternative bootstrapping t-tests also yielded similar results as the previous non-bootstrapping t-tests (in this section) and again the same comparisons showed significant differences as before. As the alternative bootstrapping analyses—not making assumptions about the data distribution—yielded very similar results as our previous analyses, they do not call for a change in the interpretation of the data or our conclusions. We therefore believe, that it is also in this case warranted to keep our initial analyses.

The main effects of rescaling the body regions in terms of perceived body are the following. (1) No longer a significant overall effect of VR condition for pointing to self. (2) An increase in pointing to the face, the upper followed by the lower; with almost no pointing for self above the head anymore. (3) As the torso regions also have substantial pointing to them, the results now look more like the bimodal results from the physical setup (Alsmith and Longo, 2014) than after the analysis in terms of regions of the physical body.

3.4. Body template task

Overall, pointing height on the body templates as a percentage of total template body height was lower [M = 81.2% (of total template body height), SD = 9.3] than pointing height as a percentage of total physical body height in the VR setups (M = 87.5 %, SD = 20.5 for the VR headset and M = 88.2, SD = 9.3 for the Pano-LSID). In paired-samples t-tests, the difference in mean percent pointing height across participants was significantly different for the templates compared to the Pano-LSID [$t(29) = 3.27$, p = 0.003, Cohen's $d_z = 0.61$], but not for the templates compared to the VR headset [$t(29) = 1.48$, p = 0.145, Cohen's $d_z = 0.28$]. No significant correlations (two-tailed Pearson) were present between the pointing height on the body templates and the pointing height on the physical body in either of the VR setups [templates—VR headset: $r(28) = -0.073$, p = 0.700; templates—Pano-LSID: $r(28) = -0.038$, p = 0.841). In paired-samples t-tests, no significant differences were found between the pointing heights on the different body outlines used in the template task (p >> 0.05).

Individual distributions of the responses over the regions of the body are depicted in Figure 8 for the physical body regions, the perceived body regions and regions of the body templates. For the **physical body** in the VR headset, the largest amount of pointing per individual participant was most frequently above the head (11 of the 30 participants), followed by the upper face (8) and the upper torso (6) (2 to the lower face) (see Figure 8, Upper Left). For the physical body in the Pano-LSID, the largest amount of pointing per individual participant was most frequently to the upper face (19 from the 30 participants), followed by the upper torso (6) and the lower face (4) (2 above the head) (see Figure 8, Upper right). For the **perceived body** in the VR headset, the largest amount of pointing per individual participant was most frequently to the upper face (13 of the 30 participants) and the lower face (13) (1 to the upper torso and 0 above the head) (see Figure 8, Middle left). For the perceived body in the Pano-LSID, the largest amount of pointing per individual participant was most frequently the upper face (14 from the 30 participants), followed by the lower face (11) (6 to the upper torso and 0 above the head) (see Figure 8, Middle right). For the template bodies, the largest amount of pointing per individual participant was most frequently to the upper torso (20 of the 30 participants), followed by the upper face (9) (see Figure 8, Bottom). Note, that participants can figure more than once in the numbers given in this paragraph on individual distributions of responses over body regions, in case they pointed to more than one region equally, but this was rare.

3.5. Questionnaires

3.5.1. Body Perception Questionnaire

On the BPQ, the current sample showed a lower mean score and a higher standard deviation than the norm values for the scale (sample: M = 2.526, SD = 0.909; norm: M = 3.026, SD = 0.797). Higher interoceptive sensibility was hypothesized to correlate with more accurate body part localization, to be reflected in a negative correlation between BPQ awareness scores and error distances for pointing to body parts. However, no significant two-tailed Pearson correlation was found between BPQ awareness score and absolute error distance for pointing to body parts [$r(28) = 0.31$, $p = 0.100$]. Also, no significant two-tailed Pearson correlations were found between BPQ awareness score and pointing height on the body (as a percentage of total physical body height) for any of the self-location tasks [VR headset: $r(28)$
$= -0.12$, $p = 0.544$; Pano-LSID: $r(28) = 0.027$, $p = 0.889$; body templates: $r(28) = 0.083$, $p = 0.663$].

Not finding support for our hypothesis that there might be a correlation between BPQ and pointing performance, might be due to several factors. It could be that the scale we used is actually not very adequate for measuring interoceptive sensibility. It could also be that interoceptive sensibility is not the component of interoception that is most correlated with the ability to locate your body parts [it being a subjective sensibility measure without guarantee of relating to the strength of interoceptive signals, or to objective measures of accuracy on interoception tasks (Garfinkel et al., 2015)]. And it could also be, that there is simply no correlation between interoception and the accuracy in locating body parts in the form hypothesized here. Another option is, that the absence of a significant correlation is somehow related to the current sample having a relatively low mean score on the awareness scale.

3.5.2. Post-questionnaire

On the post-questionnaire (see the supplementary material), there were three questions concerning the strategies participants had used. On the first, general one (question 3 of the post-questionnaire), eleven of the thirty participants reported to have (on some of the trials) first put the pointer straight at their eyes and then moved it from there to point at other

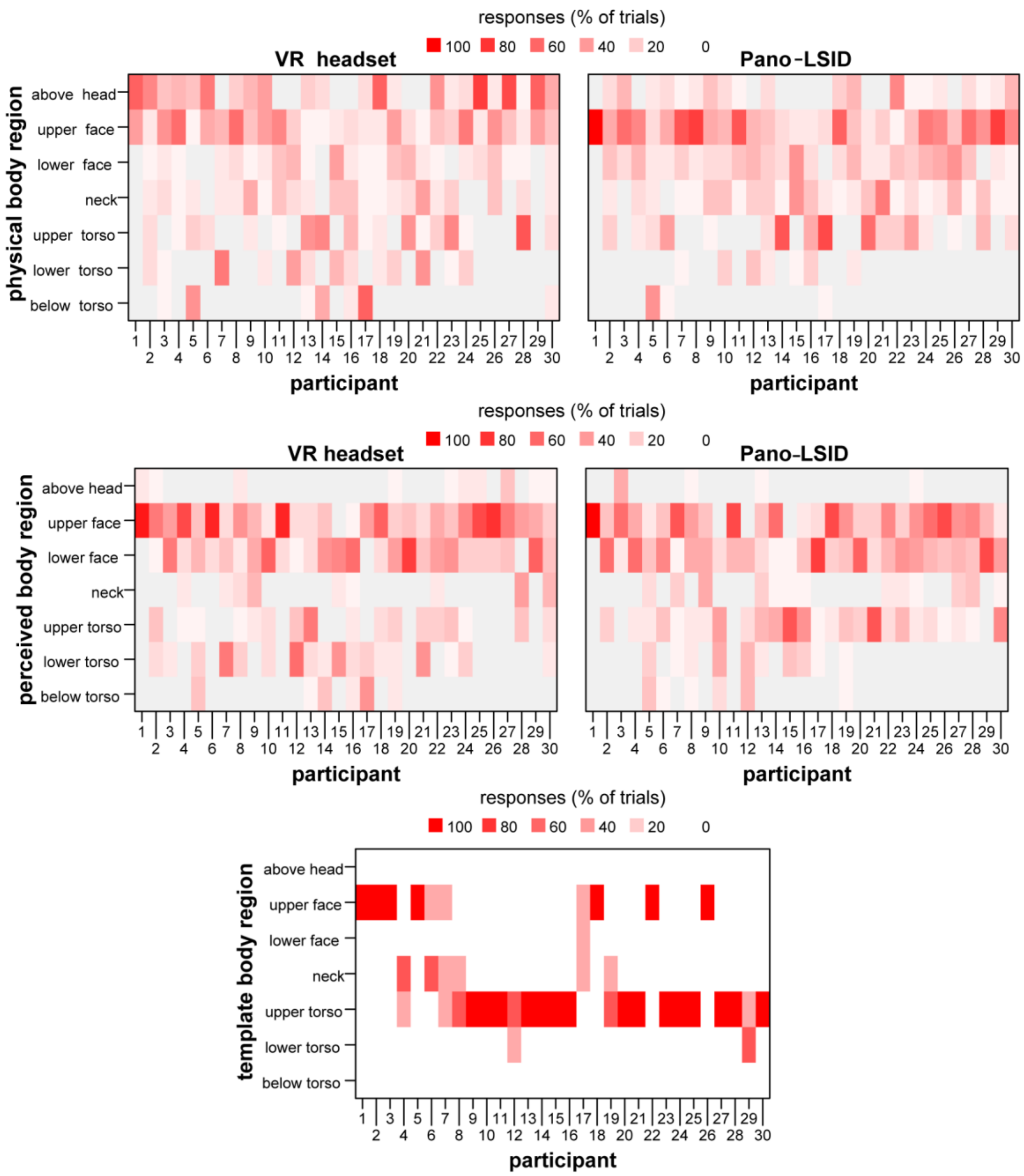

Figure 8. Distribution of pointing at self over the body regions. The percentage of trials pointed at each body region for each participant depicted in a heatmap: (Upper left) for regions of the physical body for the VR headset; (Upper right) for regions of the physical body for the Pano-LSID; (Middle left) for regions of the perceived body for the VR headset; (Middle right) for regions of the perceived body for the Pano-LSID; (Bottom) for regions of the body templates.

locations, four participants stated that they had imagined a line extending from the pointer to their body and two participants indicated that they had moved the pointer up and down a bit to get a feeling for where it was pointing. Eight participants stated they had used no specific strategy, although most of them did specify one or more on the next two follow-up questions. On the second question (4 in the questionnaire), on pointing to self, eight participants reported that they had pointed at their eyes, seven at their chest, three at their face or chest and two at their eyes or face. Other body parts were reported, but only once each, and five participants indicated not to have pointed at a specific body part. On the third question (5 in the questionnaire), on pointing to body parts, seventeen participants reported to have felt where their body parts were, two to have imagined a picture of their body, and five to have imagined a line from the pointer to their body. One participant reported feeling and imagining a picture and one reported feeling, imagining a picture, and imagining a line. Only one participant indicated on this question to have used no strategy. Note, that per question each individual participant only occurs once in the total number of reported cases.

4. Summary of results and discussion

4.1. Does pointing to self and body parts differ between an LSID and a VR headset?

For pointing to body parts, there were large differences in accuracy between the VR setups. Namely, while in the Pano-LSID participants were rather accurate with the exception of the top of the head (overshooting) and the feet (undershooting), in the VR headset large errors were found for several body parts, especially the feet, knees, and hips (undershooting) and top of the head (overshooting). Also, the VR-headset had overall undershooting, while the Pano-LSID had overall overshooting of body part locations. Our expectation was therefore supported for body parts: there were significant differences between the VR setups in the error distances for several body part locations.

That pointing to body parts was found to be not fully accurate and to differ between VR setups may be due to the following reasons. Not having visual access to one's own body in the VR headset likely makes both body part and body boundary localizing more difficult. Moreover, having visual access to your body part locations might also improve the accuracy for locating non-visible body parts, such as the top of your head; or it may enhance general body awareness. Not having visual access may therefore partially explain the less accurate pointing to body parts in general, as well as the larger undershooting for the feet, knees, and the hips and the larger overshooting for the top of the head in the VR headset. Finally, instead of promoting pointing to the face, the headset may also have decreased the amount of pointing to the face. This may have resulted from the headset forming a barrier between the pointer and the participant, or from it being experienced as a strange object that is not you.

Egocentric distance perception is known to be inaccurate in both VR headsets and in LSIDs. However, distortions in distance perception, and thereby in the perceived distance of the pointer, may have been larger in the VR headset than in the Pano-LSID in the current study (Piryankova et al., 2013; Young et al., 2014; Creem-Regehr et al., 2015) and this may partially explain the differences in the findings for the two VR setups. Moreover, we chose a distance to the pointer stimuli known to minimize misperception in the Pano-LSID (3.5 m; Piryankova et al., 2013) and used the same distance in the VR headset. If the pointer in the current VR setups appeared closer than it was, this may on average have resulted in extremer pointing angles than actually needed to point to specific bodily locations. This may also partially explain the larger amount of overshooting above the head for self-location for the VR headset compared to the Pano-LSID, as well as the larger amounts of undershooting reflected in pointing below the hips and to the lower torso.

Self-pointing based on the physical body was found to differ between VR setups. Since perceived body part locations also differed between VR setups, it became important to use perceived body regions to see whether the differences in self-pointing were due to differences in body part localization. Overall, after rescaling the self-pointing to the perceived body, there was no interaction between body region and VR condition for self-pointing. Differences in physical vs. perceived body part locations were therefore likely the reason self-location differed between VR setups when considering physical body regions. Our expectation was thus not supported for self-localization: there was no significant difference in self-localization between the VR setups used, when body part localization in each VR setup was taken into account.

After rescaling to the perceived body, the current results look more like the bimodal self-pointing (to the upper torso and the upper face) found previously in a physical setup (Alsmith and Longo, 2014). The results are also somewhat consistent with the predominant pointing to the upper face as found in Van der Veer et al. (2018) where no rescaling to perceived body regions was performed.

This effect of rescaling to the perceived body suggests that, taking into account where people estimate their body parts to be as well as the differential distortions in spatial perception between VR setups, makes it possible to better understand where people locate themselves in VR. Distortions in body perception in VR may therefore be confined to distortions in the localization of body parts, rather than also involving where people ultimately locate themselves as such.

4.2. Is indicated self-location in the body template task outside of VR similar to self-localization in VR?

On the body template task, the mean pointing height (in percentage of total template body height) was lower than the mean pointing height (in percentage of the participants' total **physical** body height) in both VR setups (significantly lower compared to the Pano-LSID only, not compared to the VR headset). In contrast to VR self-pointing, mean pointing per participant in the body template task was most frequently to the upper torso, followed by the upper face. No correlation was found between mean pointing height on the body in the template tasks and mean pointing height on the physical body in either VR setup. These findings confirm our expectations and are in line with those of Van der Veer et al. (2018), but not with the other earlier experiments employing outlines of human bodies as discussed in the introduction (Limanowski and Hecht, 2011; Starmans and Bloom, 2011; Anglin, 2014). These experiments all found the location of the self to be indicated (most often) in the face or related areas, such as the brain or eyes, rather than in the torso.

The difference in our findings for the template task compared to VR could be due to several factors: the perspective on the body; the potentially lower identification with the body outlines as compared to one's own body; and possibly a general tendency to point to the center of an object (or, more precisely, on the medial axis skeleton: Firestone and Scholl, 2014). Moreover, in a perspective-taking study it has been found that people value their own minds more than their bodies, but often fail to realize that others do so as well, assuming others value their own bodies more than their minds (Jordan et al., 2019). As pointing on the template may resemble pointing to someone else (counter to task instructions), this bias may also have promoted the smaller amount of pointing on the template to the (upper) face, where typically the mind is thought to reside. Our findings are nicely in line with Alsmith et al.'s (2017) findings of self-location being distributed between head and torso, with larger contributions for the torso. In this study, self-location was implicated by the part(s) of the body used by participants to indicate the locations of external objects relative to themselves. Thereby it shares with our template task that the performed action was not directed at one's own physical body.

4.3. Where do people precisely locate themselves in their bodies?

In two VR setups we found that when asked to point directly at themselves, overall participants pointed to the face most (upper followed by lower), followed by the torso regions and with some pointing to all regions of the body, as well as above the head. This is largely consistent with previous VR findings (Van der Veer et al., 2018), showing predominantly pointing to the upper face in a VR headset, and Alsmith and Longo's (2014) results from a wholly physical setup, where bimodal pointing to the upper torso and upper face was found.

For self-pointing, the predominant pointing to the upper face found in Van der Veer et al. (2018) was interpreted as possibly resulting from wearing a VR headset, i.e., from drawing more attention to the face/eyes (resulting from the pressure and weight of the headset) and from not having visual access to one's own body. However, in the present study, we also found a large amount of pointing to the upper face in the Pano-LSID—where no special emphasis was placed on the head and participants had visual access to their bodies. Interestingly, the slightly larger amount of pointing to the (upper) torso for the self-location pointing in the Pano-LSID as compared to the VR headset is more similar to outside of VR (Alsmith and Longo, 2014)—with which it has visual access to the body in common. Therefore, it seems that people mostly do localize themselves in the face and the torso. This idea gets some further support from the locations participants reported to have pointed to, as stated on the post-questionnaire. For self-locating, out of the 30 participants 10 reported to have pointed to the eyes or face, seven to the chest (upper torso) and three to both the face and the chest.

5. General discussion

The main finding of this study is that the VR setup influences where people point to their body parts, but not to themselves (as long as you take into consideration the perceived body part locations). In particular, we found large differences in body part localization between a VR headset and an LSID. For body parts, we found distortions in body perception as described in non-VR setups [e.g., Linkenauger et al. (2015) and Fuentes et al. (2013)]. Additionally, we found that estimations of the boundaries of the body seem to be heavily distorted in a VR headset and to a lesser extent in an LSID. Body part localization likely differs in these two setups due to at least two factors, differences in distance estimation and differences in access to the visual body. In a follow-up version of the VR headset condition, it could therefore be interesting to connect to current technological possibilities further and to provide the participants with visual cues about their bodies in the form of (partial) (tracked) self-avatars. When switching to a more recent addition to the VR headset hardware market for easier implementation of body tracking, the issue of distance underestimation may be further reduced as well.

When rescaling self-pointing to the perceived body, participants point mostly to the face, as well as to a lesser extent to the torso. Finally, pointing in VR differs from the body template task where pointing to self was found to be primarily to the upper torso. Our results suggest that experimental paradigms using VR as a tool to study aspects of the bodily self and body perception should consider that the technology itself may influence body part localization, and also self-location estimates if inaccuracies in body part localization in the specific VR setup are not taken into into consideration.

The implication for the use of virtual reality technology is primarily that users may be uncertain of where exactly their body parts (especially their bodies' boundaries) are in the virtual world. This implication clearly relates to several of the fundamental challenges for virtual environments as described by Slater (2014). First, since VR is likely moving to the home and being used by large numbers of people, there is a need to understand how VR might influence body part localization and awareness, especially after longer exposure times. Since how you perceive and how you act are tightly connected, it is clear that a different perception of one's own body in VR may result in acting differently in VR. Finally, as Slater points out, virtual reality profits from exploitation of the brain to produce illusions of perception and action. Our results suggest that fundamental properties of body perception can be altered depending on the technology used. In order to exploit these illusions properly, a more complete understanding of the baseline of how human perception works in VR may be needed. Fortunately, pointing to self remains unchanged in the two current VR setups when considering the perceived body, based on body part localizations. This suggests that the sense of self-location is consistent across vastly different VR technologies and is primarily in the face and torso regions.

Ethics statements

All participants gave written informed consent. Procedures were in accordance with the principles of the Declaration of Helsinki and approved by the Ethics Committee of the University Hospital Tübingen.

Author contributions

AvdV: conceptualization, analysis, investigation, methodology, visualization, writing: original draft, writing: review and editing. ML: conceptualization, methodology, writing: review and editing. AA: conceptualization, methodology, writing: review and editing. HW: conceptualization, writing: review and editing. BM: conceptualization, analysis, methodology, visualization, writing: original draft, writing: review and editing.

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Supplementary material

The Supplementary Material for this article can be found https://www.frontiersin.org/articles/10.3389/frobt.2019.00033/full#supplementary-material

Table S1: The merged data from all VR pointing tasks from all participants.

Table S2: The data from the pointing at the body templates for all participants.

Data Sheet 1: Post-questionnaire.

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Conflict of interest statement

BM is a review editor for Frontiers in Robotics and AI: Virtual environments. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Copyright statement

Article 3:

The influence of viewpoint in a self-avatar on body part and self-localization

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Table of contents

The influence of the viewpoint in a self-avatar on body part and self-localization

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.

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 overestimation 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 outlines of 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 behavioral 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 one-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.

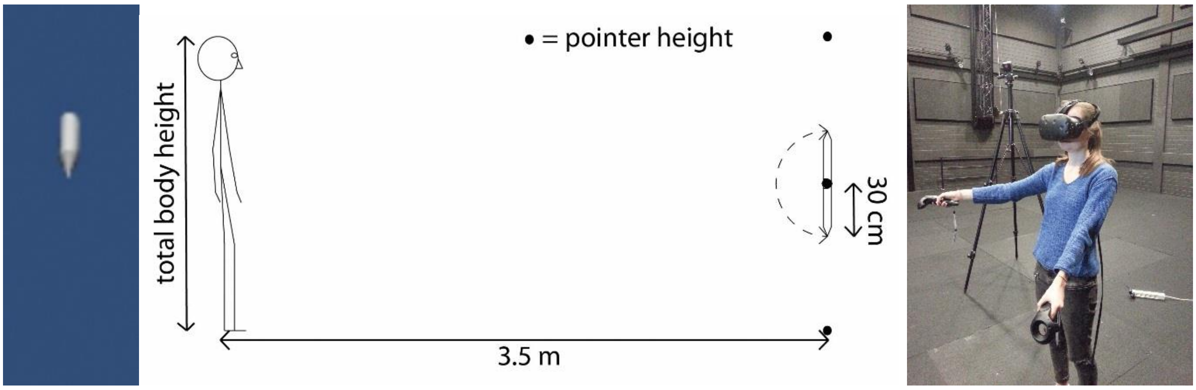

Figure 1. Left: A close-up view of a pointer stimulus. Center: A schematic depiction of the setup during the pointing task. The dotted line indicates the range of possible pointer rotations. The pointer starting direction was either straight up or down. Three pointer heights were spread out across the 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.

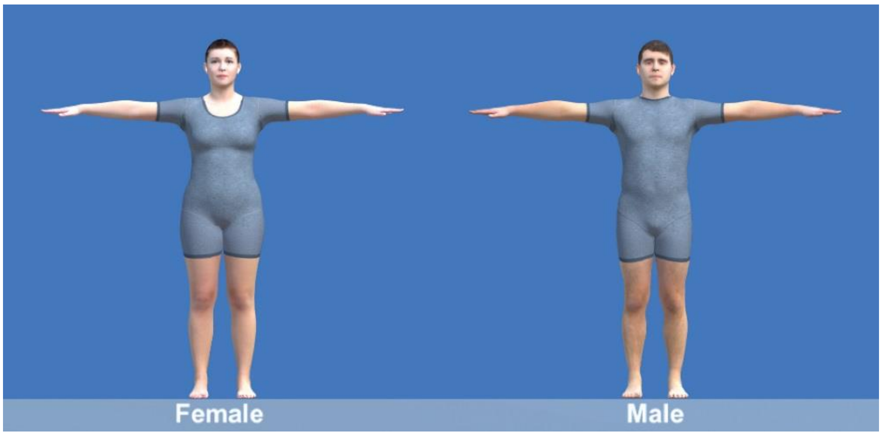

Figure 2. The female and male SMPL avatars used in the experiment.

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.

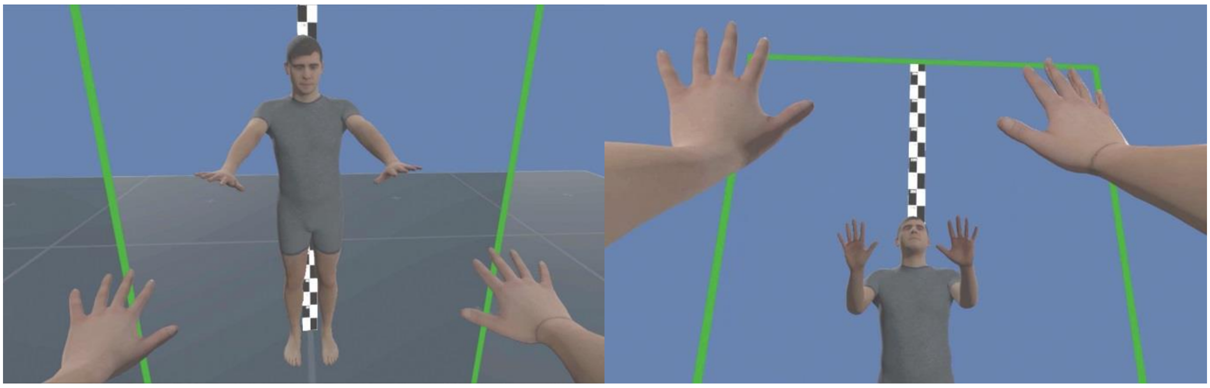

Figure 3. Image of the avatar adaptation phase from the viewpoint at: Left: eye-height, and Right: chest-height.

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 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 sub-scales 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

3.1.1.1. 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.

3.1.1.2. 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, η^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, η^2 = .036) or the interaction between viewpoint and target ($F(2.42, 50.78) = 1.96$, p = .076, η^2 = .063).

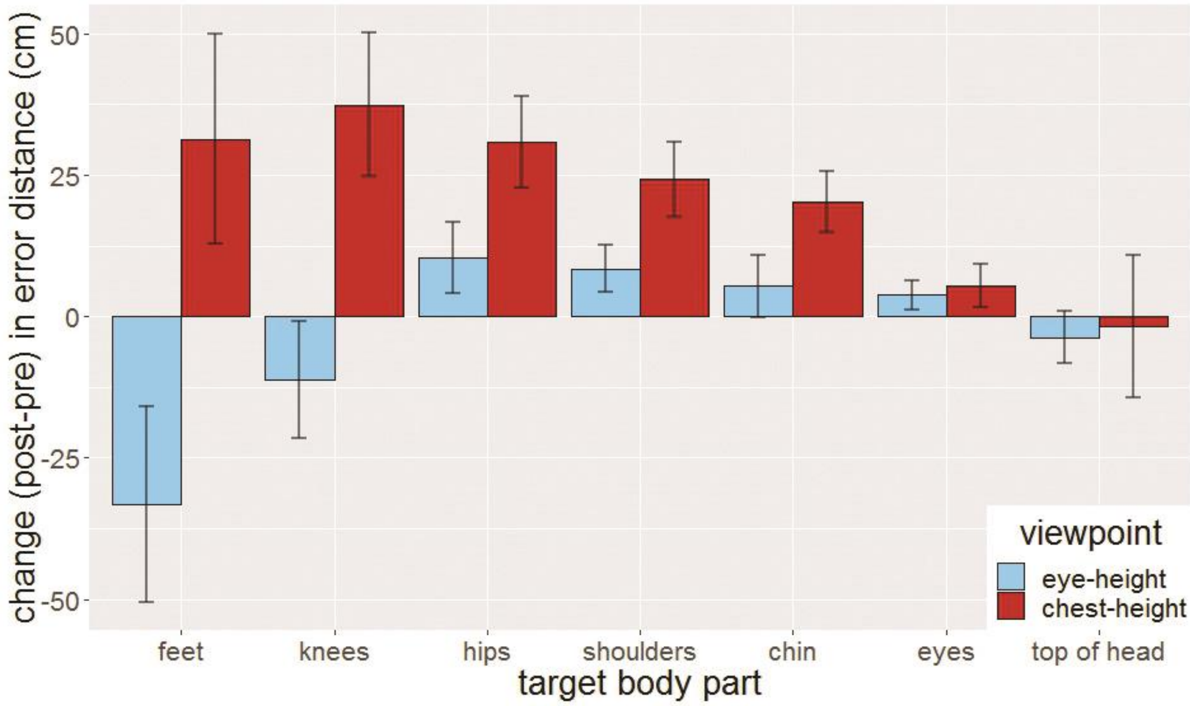

Figure 5. Shift in pointing for body part localization between pre-test and post-test in terms of mean error distance between pointed at and physical body part location, per target body part (N = 23; error bars: ± 1 SE). The shifts are directional, with negative being down and positive being up relative to the pre-test body part localization.

3.1.2. Self-localization pointing results

3.1.2.1. Self-localization regions for pre-test trials

Before the self-avatar adaptation phase, there was no significant difference between the 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, η^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, η^2 = .14).

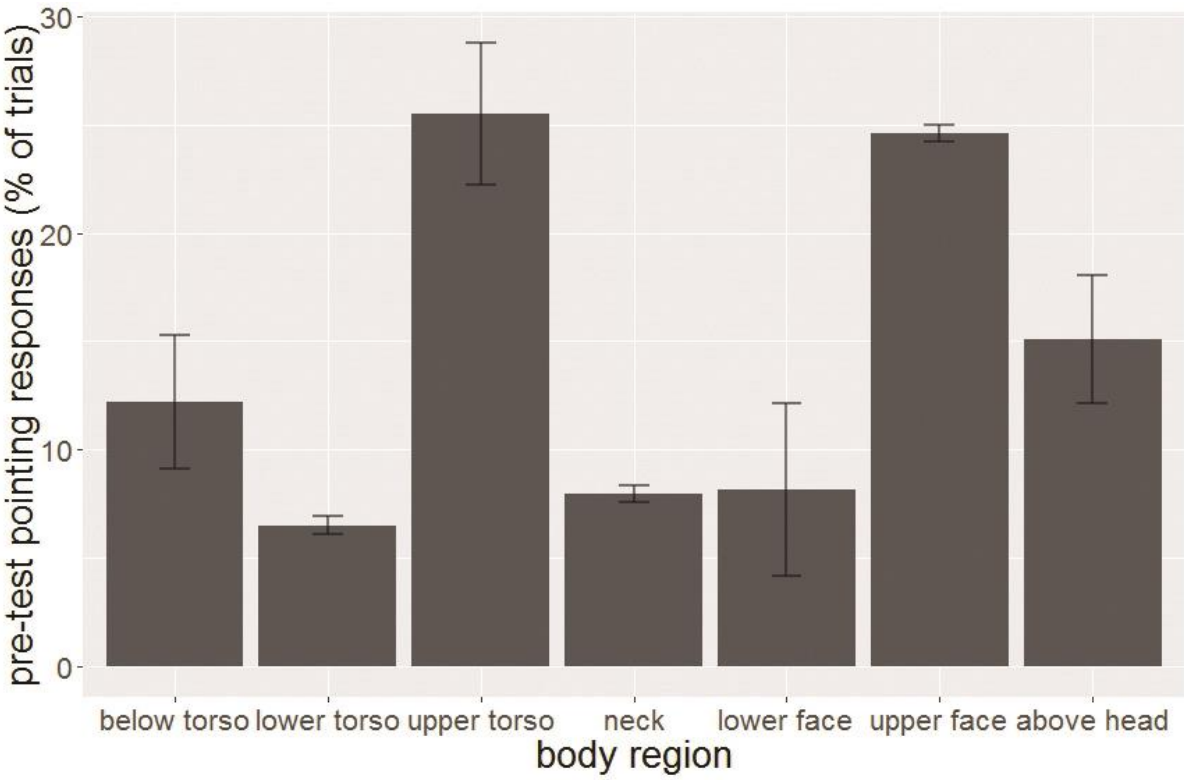

Figure 6. Pre-test (before the avatar adaptation phase) self-localization in terms of percentages of trials pointed at the different body regions (N = 23; error bars: ± 1 SE). Data was collapsed over viewpoint groups, as they showed no significant differences.

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 ($p < .05$).

3.1.2.2. 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.

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 $p < .001$).

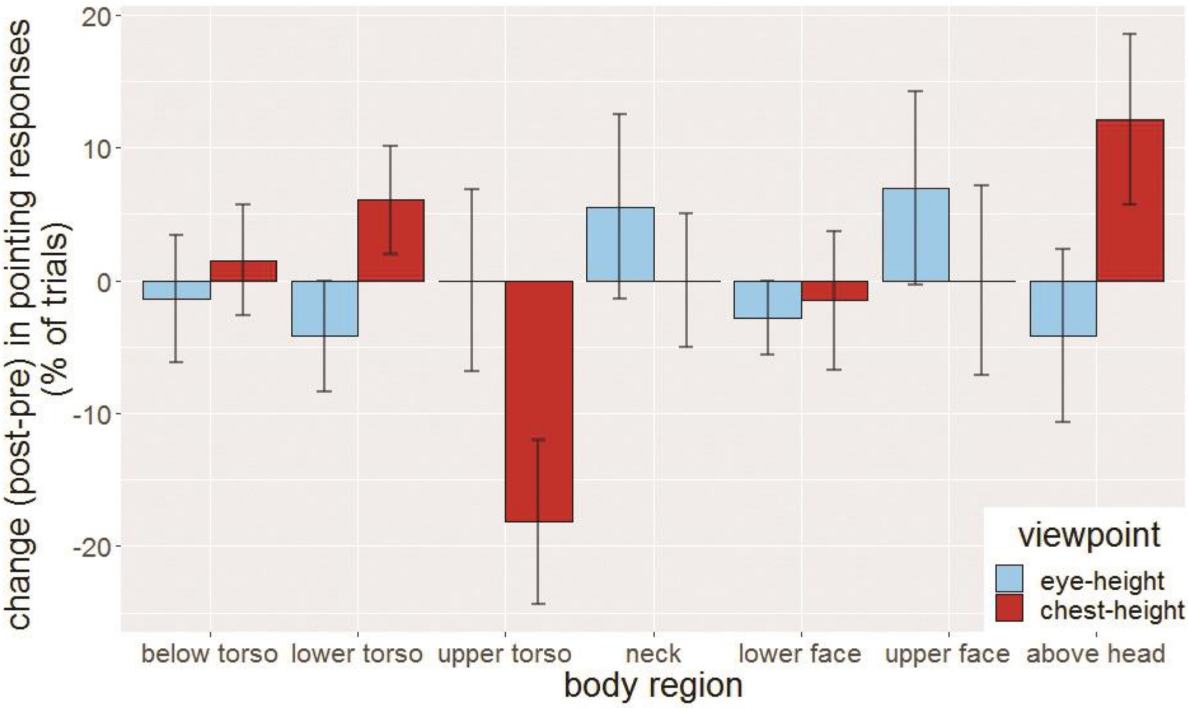

Figure 7. Shift in pointing for self-localization between pre-test and post-test in terms of percentages of trials pointed at the different body regions (N = 23; error bars: ± 1 SE). The changes are directional, with negative being less and positive being more pointing to the participant's physical body regions.

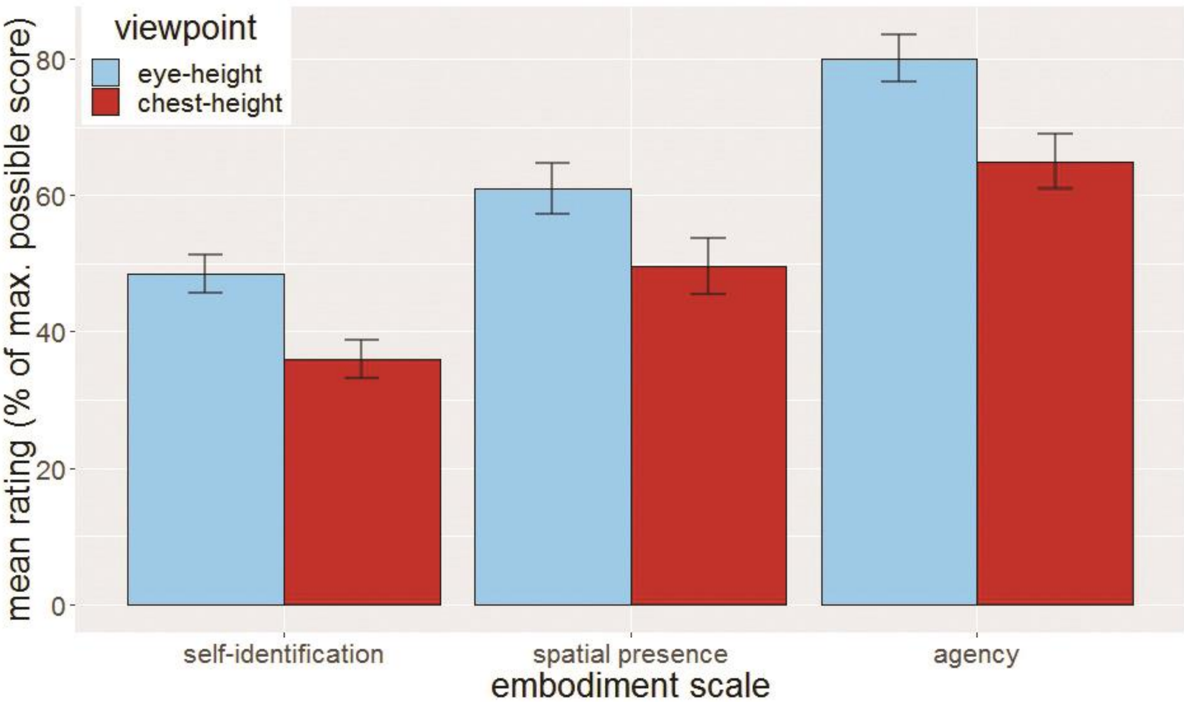

Figure 8. Mean percentage of the maximum score for the three components of the Conscious Full-body Self-perception Questionnaire per viewpoint (N = 23; error bars: ± 1 SE).

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 and 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 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-avatar 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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Supplement 1

Post-questionnaire of study 1

doi:10.1371/journal.pone.0204358.s001

Post-questionnaire

Please circle the relevant answers, give number ratings where asked, and fill out the open questions.

Participant nr.: ____

Date:____

Time:____

1. Did you understand the tasks? yes no
2. Were the tasks clear and easy to understand? yes no

If not, what was unclear or difficult? ____

____

____

3. Did you use a specific strategy for deciding where the balls were relative to you? yes no

If so, what did you do? ____

____

____

4. Did you use a specific strategy for deciding where to direct the pointer to? yes no

If so, what did you do? ____

____

____

5. Did you feel some tasks within one (or more) part(s) of the study were more difficult than others in the same part? yes no

If so, which were more difficult? ____

____

____

6. Do you have any ideas on what the research questions may be? ___________________

____

____

7. Do you have anything else on your mind related to the experiment? ________________

____

____

8. What is your age? _________________
9. What is your gender? _______________
10. What is your handedness? right left

11. Do you play sport? yes no

If so, how many hours per week on average? ________________

12. Do you do yoga, Pilates, or something similar? yes no

If so, how many hours per week on average? ________________

13. Do you meditate? yes no

If so, how many hours per week on average? ________________

14. What is your profession/occupation?

15. What percentage of your waking hours do you on average spend

- seated: ____________________
- standing: ___________________
- walking: ____________________
- doing physical labour: _______________

16. At what time did you eat your last meal? ____________________

17. How many hours ago did you eat your last meal?

18. Are you religious? yes no

If so, how many hours per week do you perform specific religious practice on average? ________

19. What is your nationality? ___________________

20. In which country(-ies) did you grow up? ____________________

21. What is your relationship status? ___________________

22. Do you have children? yes no

23. What is the highest level of education you have finished?

24. Do you currently have any pain? yes no

If so, where are you experiencing pain? _____________________

25. Have you experienced virtual reality before? yes no

If so, how many hours in total? ______________

26. Do you play video games? yes no

If so, how many hours per week on average? ________________

27. Did you experience any unpleasant feelings during the experience? yes no

If so, what were they? _______________

28. What do you think was the purpose of the experiment? ___________________________

____

____

1. Please rate your self-confidence (1 (lowest) – 100 (highest)): ________________
2. Please rate your overall stress level (1-100): ________________
3. Please rate your overall happiness (1-100): _________________
4. Please rate yourself on an introversion-extraversion scale (1 (most introvert) – 100 (most extravert)): ________________
5. Please rate how healthy you currently feel (1-100): _________________
6. Please rate how rested you currently feel (1-100): __________________
7. How many hours have you slept last night? _________________
8. Please rate how energetic you currently feel (1-100): ________________
9. Please rate how much you enjoyed the experiments (1-100): ________________
10. To what extent did you feel you were doing your best (1-100)? ______________
11. To what extent did the experiments hold your attention (1-100)? ___________________
12. To what extent were you focused on the experiments (1-100)? ______________
13. To what extent were you aware of yourself in your environment (1-100)? ____________
14. To what extent were you aware of your body (1-100)? _______________
15. To what extent did you want to stop the experiment (1-100)? ________________
16. To what extent did you feel separated from your real-world environment (1-100)? _____

Supplement 2

Awareness scale of the Body Perception Questionnaire

(Porges, 1993)

BODY PERCEPTION QUESTIONNAIRE
I: AWARENESS
Stephen W. Porges, Ph.D.

Each of the 45 items in this questionnaire are to be answered on the 5-point scoring scale described below. Read the instructions for the test and designate your answers for each of the 45 items on the provided answer sheet.

I: AWARENESS
Image how aware you are of your body processes. Select the answer that most accurately describes you. Rate your awareness on each of the characteristics described below using the following 5-point scale:

a) Never b) Occasionally c) Sometimes d) Usually e) Always

During most situations I am aware of:

1. Swallowing frequently
2. A ringing in my ears
3. An urge to cough to clear my throat
4. My body swaying when I am standing
5. My mouth being dry
6. How fast I am breathing
7. Watering or tearing of my eyes
8. My skin itching
9. Noises associated with my digestion
10. Eye fatigue or pain
11. Muscle tension in my back and neck
12. A swelling of my body or parts of my body
13. An urge to urinate
14. Tremor in my hands
15. An urge to defecate
16. Muscle tension in my arms and legs
17. A bloated feeling because of water retention
18. Muscle tension in my face
19. Goose bumps
20. Facial twitches
21. Being exhausted
22. Stomach and gut pains
23. Rolling or fluttering my eyes
24. Stomach distension or bloatedness
25. Palms sweating
26. Sweat on my forehead
27. Clumsiness or bumping into people
28. Tremor in my lips
29. Sweat in my armpits
30. Sensations of prickling, tingling, or numbness in my body
31. The temperature of my face (especially my ears)
32. Grinding my teeth
33. General jitteriness
34. Muscle pain
35. Joint pain
36. Fullness of my bladder
37. My eye movements

38. Back pain
39. My nose itching
40. The hair on the back of my neck "standing up"
41. Needing to rest
42. Difficulty in focusing
43. An urge to swallow
44. How hard my heart is beating
45. Feeling constipated

Supplement 3

Bewusstseinsskala vom Fragebogen zur Körperwahrnehmung

(Porges, 1993)

FRAGEBOGEN ZUR KÖRPERWAHRNEHMUNG
I: BEWUSSTSEIN
Dr. Stephen W. Porges

Jede der 45 Fragen dieses Fragebogens sollte anhand einer fünfteiligen Skala beantwortet werden. Lesen Sie die Instruktionen für den Test und tragen Sie Ihre Antworten für jede der 45 Fragen auf dem separaten Antwortbogen ein.

I: BEWUSSTSEIN
Stellen Sie sich vor, wie bewusst Sie Ihre Körperprozesse wahrnehmen. Wählen Sie diejenige Antwort aus, die Sie am treffendsten beschreibt. Teilen Sie Ihr Bewusstsein für jede der unten beschriebenen Eigenschaften anhand der folgenden fünfteiligen Skala ein:

a) Nie b) Gelegentlich c) Manchmal d) Normalerweise e) Immer

Während der meisten Situation bin ich mir der folgenden Prozesse bewusst:

1. Häufiges Schlucken
2. Ein klingendes Geräusch in meinen Ohren
3. Der Drang zu husten, um einen freien Hals zu bekommen.
4. Das Schwanken meines Körpers, wenn ich stehe.
5. Dass mein Mund trocken ist.
6. Wie schnell ich atme.
7. Dass meine Augen feucht werden oder tränen.
8. Dass meine Haut juckt.
9. Geräusche, die mit meiner Verdauung zu tun haben.
10. Müde oder schmerzhafte Augen.
11. Verspannte Muskeln in Rücken und Nacken.
12. Ein Anschwellen meines Körpers oder einzelner Körperteile
13. Harndrang
14. Zittern der Hände
15. Stuhldrang
16. Gespannte Muskeln in Armen und Beinen.
17. Ein Aufgedunsenen Gefühl infolge Rückhalten von Wasser
18. Gespannte Muskeln im Gesicht
19. Hühnerhaut
20. Gesichtszuckungen
21. Erschöpft sein
22. Magen- und Bauchschmerzen
23. Rollen oder unruhiges Zucken der Augen
24. Geblähter oder aufgedunsener Magen
25. Schwitzende Hände
26. Schweiss auf der Stirne
27. Ungeschicktes Bewegen oder unabsichtlich mit Leuten zusammenstossen
28. Zittern der Lippen
29. Schweiss in den Achselhöhlen
30. Ein Gefühl von Ameisenlaufen oder Kitzeln oder Einschlafen (gefühllos) im Körper
31. Die Temperatur meines Gesichter (speziell der Ohren)
32. Zähneknirschen
33. Allgemeine Nervosität
34. Muskelschmerzen
35. Gelenkschmerzen
36. Volle Blase
37. Meine Augenbewegungen

38. Rückenschmerzen
39. Juckende Nase
40. Die Nackenhaare stellen sich auf
41. Das Bedürfnis auszuruhen
42. Konzentrationsschwierigkeiten
43. Ein Drang zu schlucken
44. Wie stark mein Herz schlägt
45. Das Gefühl, verstopft zu sein

Supplement 4

Post-questionnaire of study 2

https://www.frontiersin.org/articles/10.3389/frobt.2019.00033/full#supplementary-material

Post-questionnaire

Please circle the relevant answers, give number ratings where asked, and fill out the open questions.

Participant number: ____

Date: ____

Time: ____

1. Did you understand the tasks? yes no
2. Were the tasks clear and easy to understand? yes no

If not, what was unclear or difficult? ____

____

____

3. Did you use a specific strategy for deciding where to direct the pointer to? yes no

If so, what did you do? ____

____

____

4. When pointing directly at you, did you point at a specific body part? yes no

If so, which one? ____

5. When pointing directly at body parts, did you use one of the following specific strategies? Feeling where your body parts are? Imagining a picture of your body?

Other? ____

Don't know.

6. Can you indicate how far away from you the pointer was located (in centimetres)?

On the large screen: ____ In the head-mounted display: ____

7. Over the course of the experiment did you …

… become tired? ____

… lose interest? ____

8. Did you feel some tasks within one (or more) part(s) of the study were more difficult than others in the same part? yes no

If so, which were more difficult? ____

____

____

9. Can you rate the confidence you have in your responses (1 (lowest) – 100 (highest)), for each part of the experiment (not necessarily listed in the order you have done them)?

a. Pointing at self, head-mounted display: ____ b. Pointing at self, large screen: ____

c. Pointing at body parts, head-mounted display: ____ d. Pointing at body parts, large screen: ____

10. Do you have any ideas on what the research questions may be? ________________________

____

____

11. Do you have anything else on your mind related to the experiment? ____________________

____

____

12. What is your age? ___________

13. What is your gender? ___________

14. What is your handedness? right left

15. Do you play sport? yes no

If so, how many hours per week on average? ___________

16. Do you do yoga, Pilates, or something similar? yes no

If so, how many hours per week on average? ___________

17. Do you meditate? yes no

If so, how many hours per week on average? ___________

18. What is your profession/occupation? ___________

19. What percentage of your waking hours do you on average spend

- seated: ___________
- standing: ___________
- walking: ___________
- doing physical labour: ___________

20. At what time did you eat your last meal? ___________

21. How many hours ago did you eat your last meal? ___________

22. Are you religious? yes no

If so, how many hours per week do you perform specific religious practice on average? ___________

23. What is your nationality? ___________

24. In which country(-ies) did you grow up? ___________

25. Do you have children? yes no

26. What is the highest level of education you have finished? ___________

27. Do you currently have any pain? yes no

If so, where are you experiencing pain? ___________

28. Have you experienced virtual reality before? yes no

If so, how many hours in total? ___________

29. Do you play video games? yes no

If so, how many hours per week on average? ___________

30. Did you experience any unpleasant feelings during the experience? yes no

If so, what were they? ___________

31. What do you think was the purpose of the experiment? ______________________________

____

____

32. Do you wear glasses? yes no 33. If so, today? yes no

34. Do you wear lenses? yes no 35. If so, today? yes no

1. Please rate your self-confidence (1 (lowest) – 100 (highest)): ___________
2. Please rate your overall stress level (1-100): ___________
3. Please rate your overall happiness (1-100): ___________
4. Please rate yourself on an introversion-extraversion scale (1 (most introvert) – 100 (most extravert)): ___________
5. Please rate how healthy you currently feel (1-100): ___________
6. Please rate how rested you currently feel (1-100): ___________
7. How many hours have you slept last night? ___________
8. Please rate how energetic you currently feel (1-100): ___________
9. Please rate how much you enjoyed the experiments (1-100): ___________
10. To what extent did you feel you were doing your best (1-100)? ___________
11. To what extent did the experiments hold your attention (1-100)? ___________
12. To what extent were you focused on the experiments (1-100)? ___________
13. To what extent were you aware of yourself in your environment (1-100)? ___________
14. To what extent were you aware of your body (1-100)? ___________
15. To what extent did you want to stop the experiment (1-100)? ___________
16. To what extent did you feel separated from your real-world environment (1-100)? ________

Supplement 5

Conscious Full-body Self-perception Questionnaire (English)

Administered in digital form.

(adapted from Dobricky & De la Rosa (2013))

Self-report statements used for the assessment of conscious full-body self-perception, English version (from: Dobricki & De la Rosa, 2013; doi:10.1371/journal.pone.0083840.t001).

Response format: visual analog scale (minimum = not at all; maximum = very much).

1 It seemed as if I might have more than one body.
2 It felt like I could have moved the head of the virtual body, if I had wanted.
3 I felt somehow connected with the virtual body.
4 I experienced the virtual body as a part of myself.
5 Sometimes, I had the feeling that I was looking at myself.
6 Sometimes, I had the feeling of standing in the place of the virtual body.
7 It felt like I was in control of the virtual body.
8 Sometimes, it felt like I and the virtual body were one.
9 It felt like the virtual body was my body.
10 It felt like I could have moved the virtual body, if I had wanted.
11 It felt like the virtual body belonged to me.
12 Sometimes, I felt like I was inside the virtual body.
13 I had the feeling that I was standing in front of myself.
14 I experienced myself as part of the presented environment.
15 I felt like I was actually there in the presented environment.
16 It was as though my true location had shifted into the presented environment.
17 It seemed as though I was present in the environment.
18 I felt as though I was physically located in the presented environment.
19 It felt like I could have moved the arms of the virtual body, if I had wanted.
20 It seemed like my body was in the location where the virtual body was.

Supplement 6

Conscious Full-body Self-perception Questionnaire (German)

Administered in digital form.

(adapted from Dobricky & De la Rosa (2013))

Self-report statements used for the assessment of conscious full-body self-perception, German version (from: Dobricki & De la Rosa, 2013; doi:10.1371/journal.pone.0083840.t001).

Antwortformat: visuelle Analogskala (minimum = gar nicht; maximum = sehr).

1 Es schien, als hätte ich mehr als einen Körper.
2 Es fühlte sich an, als hätte ich den Kopf des virtuellen Körpers bewegen können, wenn ich gewollt hätte.
3 Ich fühlte mich irgendwie mit dem virtuellen Körper verbunden.
4 Ich erlebte den virtuellen Körper als Teil meiner Selbst.
5 Manchmal hatte ich das Gefühl, mich selbst anzusehen.
6 Manchmal hatte ich das Gefühl, an Stelle des virtuellen Körpers zu stehen.
7 Es fühlte sich an, als hätte ich Kontrolle über den virtuellen Körper gehabt.
8 Manchmal fühlte es sich an, als wären ich und der virtuelle Körper eins.
9 Es fühlte sich an, als wäre der virtuelle Körper mein Körper.
10 Es fühlte sich an, als hätte ich den virtuellen Körper bewegen können, wenn ich gewollt hätte.
11 Es fühlte sich an, als hätte der virtuelle Körper zu mir gehört.
12 Manchmal fühlte es sich an, als wäre ich in dem virtuellen Körper.
13 Ich hatte das Gefühl, vor mir selbst zu stehen.
14 Ich erlebte mich selbst als Teil der präsentierten Umgebung.
15 Ich hatte das Gefühl, tatsächlich in der präsentierten Umgebung zu sein.
16 Es war, als wäre mein echter Standort in die präsentierte Umgebung hinein versetzt.
17 Es schien, als wäre ich in der Umgebung präsent.
18 Es fühlte sich an, als hätte ich mich physisch in der präsentierten Umgebung befunden.
19 Es fühlte sich an, als hätte ich die Arme des virtuellen Körpers bewegen können, wenn ich gewollt hätte.
20 Es schien, als wäre mein Körper an der Stelle, an der der virtuelle Körper war.

Supplement 7

Post-questionnaire of study 3 (English)

Post-questionnaire

Please circle the relevant answers, give number ratings where asked, and fill out the open questions.

Participant number: ____

Date: ____

Time: ____

1. Were the tasks clear and easy to understand? O yes O no

If not, what was unclear or difficult? ____

____

____

2. Did you use a specific strategy for deciding where to direct the pointer to? O yes O no

If so, what did you do? ____

____

____

3. When pointing directly at you, did you point at a specific body part? O yes O no

If so, which one? ____

4. When pointing directly at body parts, did you use one of the following specific strategies?

O Feeling where your body parts are? O Imagining a picture of your body? O Remembering the virtual body? O Don't know. Other? ____

____

____

5. Did you notice anything in particular about the sizes or proportions of the virtual body?

____

____

6. Did any of the activities you did with the virtual body change your sense of your location, or of the sizes of your body parts? Which of the activities did and how? ____________________

____

____

7. Did you point differently after the part with the virtual body? If so, how?

A. For pointing directly at you: ____

B. For pointing at your body parts: ____

8. How similar to you was the virtual body?

	not at all						**very**
total impression	O	O	O	O	O	O	O
figure	O	O	O	O	O	O	O
looks	O	O	O	O	O	O	O
arms	O	O	O	O	O	O	O
legs	O	O	O	O	O	O	O
torso	O	O	O	O	O	O	O
face	O	O	O	O	O	O	O

9. Did you have the impression that the virtual body represented you in the virtual environment?

O yes O no

10. Did the avatar or parts of it appear strange or creepy to you? If so, which body part does this concern the most?

O Arms O Legs O Upper body O Eyes O Mouth O Nose O None O Whole body O else, namely:

____

11. What do you think we had expected you would do for:

A. Pointing to "you"? ____

B. Pointing to your body parts? ____

12. Do you have any ideas on what the research questions may be? ______________________

____

____

13. Do you have anything else on your mind related to the experiment? __________________

____

____

Supplement 8

Post-Fragebogen of Study3 (German)

Post-Fragebogen

Bitte umkreisen Sie die zutreffenden Antworten, geben Sie Zahlenbewertungen, wo gefragt, und füllen Sie die offenen Fragen aus.

Teilnehmernummer: ____

Datum: ____

Zeit: ____

1. Waren die Aufgabenstellungen klar und einfach zu verstehen? O ja O nein

Falls nein, was war unklar oder schwierig? ____

____

____

2. Haben Sie eine bestimmte Strategie für die Entscheidung, worauf der Zeiger ausgerichtet werden soll, verwendet? O ja O nein

Falls ja, was haben Sie getan? ____

____

____

3. Als Sie direkt auf sich gezeigt haben, haben Sie auf einen bestimmten Körperteil gezeigt?

O ja O nein

Falls ja, auf welchen? ____

4. Als Sie direkt auf Körperteile gezeigt haben, haben Sie eine der folgenden Strategien verwendet?

O Fühlen, wo Ihre Körperteile sind? O Vorstellen eines Bildes Ihres Körpers? O Erinnern des virtuellen Körpers? O Ich weiß nicht. Andere? ____

____

____

5. Ist Ihnen etwas Bestimmtes bei den Größen oder Proportionen des virtuellen Körpers aufgefallen? ____

____

____

6. Haben irgendwelche der Aktivitäten, die Sie mit dem virtuellen Körper getätigt haben, Ihr Gefühl Ihres Standorts, oder der Größe Ihrer Körperteile verändert? Welche Aktivitäten und wie?

____

____

7. Haben Sie nach dem Teil mit dem virtuellen Körper anders gezeigt? Falls ja, wie?

A. Beim Zeigen direkt auf Sie: ____

B. Beim Zeigen auf Körperteile: ____

8. Wie ähnlich war Ihnen der Avatar?

	gar nicht						**sehr**
Gesamteindruck	O	O	O	O	O	O	O
Figur	O	O	O	O	O	O	O
Aussehen	O	O	O	O	O	O	O
Arme	O	O	O	O	O	O	O
Beine	O	O	O	O	O	O	O
Torso	O	O	O	O	O	O	O
Gesicht	O	O	O	O	O	O	O

9. Hatten Sie den Eindruck, der Avatar repräsentiert Sie selbst in einer virtuellen Umgebung?

O ja O nein

10. Wirkte der Avatar oder Teile davon seltsam oder unheimlich auf Sie? Wenn ja, welchen Körperteil betrifft das am stärksten?

O Arme O Beine O Oberkörper O Augen O Mund O Nase O andere, und zwar: ____

11. Was meinen Sie, was wir erwartet haben dass Sie tun würden für:

A. Auf "Sie" zeigen? ____

B. Auf Ihre Körperteile zeigen? ____

12. Haben Sie eine Idee, worauf sich die Forschungsfragen beziehen könnten?_________________

____

____

13. Möchten Sie noch etwas auf das Experiment bezogen sagen?_____________________________

____

____

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