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The Influence of Visual Perspective on Body Size Estimation in Immersive Virtual Reality

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Figure 1: Left: Participant views the virtual scene in the HTC Vive headset; Middle: Screenshots of the virtual scene, view on the gender-matched avatar with grey and own texture from a third-person perspective; Right: View on the avatar from a first-person perspective and the user interface projected onto the virtual floor.

ABSTRACT

The creation of realistic self-avatars that users identify with is important for many virtual reality applications. However, current approaches for creating biometrically plausible avatars that represent a particular individual require expertise and are time-consuming. We investigated the visual perception of an avatar's body dimensions by asking males and females to estimate their own body weight and shape on a virtual body using a virtual reality avatar creation tool. In a method of adjustment task, the virtual body was presented in an HTC Vive head-mounted display either co-located with (first-person perspective) or facing (third-person perspective) the participants. Participants adjusted the body weight and dimensions of various body parts to match their own body shape and size. Both males and females underestimated their weight by 10-20% in the virtual body, but the estimates of the other body dimensions were relatively accurate and within a range of ±6%. There was a stronger influence of visual perspective on the estimates for males, but this effect was dependent on the amount of control over the shape of the virtual body, indicating that the results might be caused by where in the body the weight changes expressed themselves. These results suggest that this avatar creation tool could be used to allow participants to make a relatively accurate self-avatar in terms of adjusting body part dimensions, but not weight, and that the influence of visual perspective and amount of control needed over the body shape are likely gender-specific.

CCS CONCEPTS

• **General and reference** → *Experimentation*; • **Social and professional topics** → *Gender*; • **Human-centered computing**; • **Applied computing** → *Psychology*;

KEYWORDS

Biometric Avatars, Body Size Estimation, Visual Perspective, Immersive Virtual Reality, Gender Differences

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1 INTRODUCTION

Avatars are becoming increasingly important for networked virtual reality applications such as immersive social media[1], collaborative tasks [Pan and Steed 2017; Schroeder 2012], and telepresence [Fuchs et al. 2014; Kuster et al. 2012], all of which allow users to create a digital self-representation for family, friends, or colleagues. To date, most applications have employed highly stylized characters that cannot fully convey the user's identity in terms of visual appearance. Current approaches for creating biometrically plausible avatars that better represent individual appearance require expertise and are time-consuming in terms of processing and acquisition. Rapid avatar creation tools that allow for manually adjusting the visual appearance of a realistic virtual body, e.g. in terms of the body shape, will become increasingly popular for applications that want to allow users to identify with their self-avatar. Allowing users to adjust the body shape of an avatar to their perceived own body shape is especially relevant for applications that want users to perceive the virtual body as similar to themselves and do not require the avatar to represent the user accurately. These tools will also be relevant for clinical applications, including mirror exposure therapy and therapy progress indicators for individuals with body image disturbance [Keizer et al. 2016; Serino et al. 2016]. The aim of this study was to investigate whether the visual perception of an avatar's body dimensions differs based on the visual perspective (first-person vs. third-person) one has on the virtual body. For assessing the visual perception of a static avatar's body shape, we used a psychophysical paradigm in which participants estimated their own body size and shape when adjusting the body dimensions of a virtual body. We additionally addressed whether estimates depend on the amount of control over body shape, as well as potential gender differences in these estimates by recruiting male and female participants. The results are relevant for research on own body size estimation (BSE) and provide insight into what shape of a virtual body people perceive as similar to their own.

The visual experience of our body is one factor that contributes to the conscious mental representation of our physical appearance, also sometimes called body image. There are two visual perspectives we have on our bodies: 1) viewing our body from a third-person perspective, such as in mirrors or photographs, and 2) viewing our body from a first-person perspective when looking down at ourselves. In daily life, the amount of time spent seeing the body from a third-person perspective is – for most healthy people – relatively limited as compared to the time the body is visually experienced from a first-person perspective. Yet, to get a quantitative measure of how accurately people perceive their own body size, previous studies have employed depictive BSE tasks where participants compared their own body to 2D body templates viewed from a third-person perspective (e.g., Cornelissen et al. 2015, 2016b; Hagman et al. 2015). These studies have used personalized body stimuli created based on depictions of the participants (e.g., Urdapilleta et al. 2007), and non-personalized body stimuli based on the same standard body (e.g., Cornelissen et al. 2015, 2016a,b, 2013). The focus of most studies has been on the accuracy of estimated own body weight, due to its relevance for eating disorder populations [Mölbert et al. 2017] and individuals who may be overweight or obese [Gardner 2014]. In an attempt to simulate changes in weight in body stimuli, many studies have stretched or compressed photographs using image-distortion techniques, which result in unrealistic body deformations and do not allow for quantification of the changes in weight due to the distortion (e.g., Hashimoto and Iriki 2013; Urdapilleta et al. 2007). Recent approaches have addressed these issues by using computer-generated bodies calibrated for body mass index (BMI) based on datasets of biometric data [Cornelissen et al. 2015, 2017]. Because the use of 2D body stimuli has not allowed to examine how people perceive their own body size from a first-person perspective, little is known about whether body size perception differs based on the visual perspective on the body. The two perspectives on one's own body differ in various aspects. The third-person perspective provides a more holistic view on the body and is the same perspective we have on other people's bodies. This perspective might also serve self-other comparisons. The first-person perspective, on the other hand, is the perspective we are visually more familiar with.

Only recently have researchers started to use virtual reality and 3D virtual bodies to investigate body weight perception in ecologically valid scenarios [Corno et al. 2018; Mölbert et al. 2018; Piryankova et al. 2014; Thaler et al. 2018a]. Whereas weight is a bodily aspect that people are often concerned about, it is also the factor of adult bodies that varies the most. Other body dimensions, e.g. height, arm and leg length, remain relatively constant throughout adulthood. Thus, the long-term visual experience of these stable body dimensions could allow for more accurate size estimation of certain body dimensions compared to overall weight estimation. Another important difference between body weight and specific body dimensions (e.g., arm and leg length) is that weight gain or loss will likely change the shape of the whole body, but not necessarily the shape of individual parts as much. Until recently, there has not been a method that allows for realistic and biometrically plausible manipulations of single body parts and weight of a virtual body. *The Virtual Caliper* [Pujades et al. 2019] is the first avatar creation tool that allows for this based on the statistical body model SMPL [Loper et al. 2015a]. It therefore provides the possibility to investigate whether people's perception of an avatar's body dimensions differ based on the visual perspective on the body by asking them to adjust the dimensions to their perceived own body dimensions. This is insofar also important to understand as self-avatars in virtual reality are usually experienced from a first-person perspective, but sometimes also from a third-person perspective using virtual mirrors that allow users to view the reflections of their avatar [Gonzalez-Franco et al. 2010].

The goal of the current study was to investigate whether the visual perception of a virtual body's dimensions differs based on the visual perspective on a virtual body. To this end, we utilized immersive virtual reality and a head-mounted-display (HMD) and

[1] i.e., Oculus Rooms and Parties [Oculus 2018], Microsoft AltspaceVR [Microsoft 2018], Facebook Spaces [Facebook 2018], Linden Labs Second Life [Labs 2018b], and Linden Labs Sansar [Labs 2018a].

compared estimates of own body weight and shape when viewing and adjusting a life-size and gender-matched virtual body from a third-person perspective to when viewing the body from a first-person perspective. The number of body dimensions that could be adjusted was systematically varied to investigate whether estimates depended on the amount of control over the body shape. We extended previous body size estimation research by asking participants not only to adjust the body weight of the avatar, but also other body dimensions including leg length, arm span, hip width, and shoulder to wrist length. We hypothesized that the greater visibility of the different body parts and their relations from a third-person perspective might allow for more accurate estimates because this perspective provides people with a more holistic sense of the body shape and weight as changes are applied to body dimensions. Estimates might also then become more accurate as more parts can be adjusted together. However, if visual familiarity with the perspective on the body plays a role, then estimates from a first-person perspective should be better. Given differences in the size of bodies overall and the relative differences in size of body parts could vary with gender, we additionally investigated potential gender differences in these estimates. Finally, participants additionally adjusted the virtual body to their ideal body size so that we could get a more objective measure of their body satisfaction.

2 METHOD

2.1 Participants

36 participants (18 females, 18 males), all with normal or corrected-to-normal vision, participated in the experiment. All were naive to the purpose of the experiment. Participants provided written informed consent and were compensated with €8 per hour. The experimental procedure was approved by the ethical committee of the University of Tübingen and was performed in accordance with the Declaration of Helsinki.

2.2 Stimuli and Scene

We used *The Virtual Caliper* avatar creation tool available at https://vc.is.tue.mpg.de. The virtual scene contained a gender-matched avatar standing in a static T-pose in an empty virtual environment. The avatar was placed either at a distance of two meters from the participant (Figure 1, middle) or was placed at the location of the participant in the virtual world, so the avatar's body was visible when looking down (Figure 1, right). The head of the avatar was made invisible in the first-person perspective condition, to prevent participants from accidentally seeing the inside of the avatar's head when moving their own head. The T-pose was chosen over other poses, such as an A-pose or a natural pose, as it allows for changes of body dimensions without changing the angles of the body. For example, changes in body weight and hip width would have affected the distance of the arms to the torso and this might have provided additional cues for estimates across trials and trial types. The advantage of the T-pose is that it exposes most of the surface of the body and has no self-occlusions. The avatar was illuminated with a three-point lighting set-up, and a separate top-light generated a real-time shadow of the avatar on the floor.

On the virtual floor, an interface indicated which dimensions of the virtual body could be adjusted in each trial (Figure 1, right).

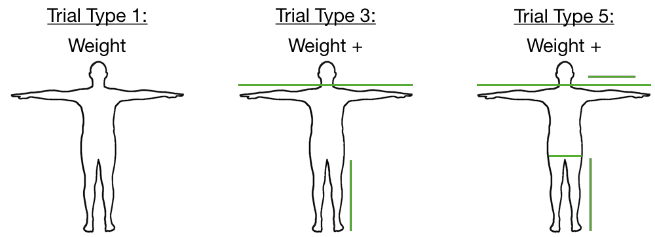

Figure 2: Schematic representation of the dimensions that could be adjusted in the different trial types used in the experiment. Trial Type 1: Weight; Trial Type 3: Weight, leg length, and arm span; Trial Type 5: Weight, leg length, arm span, hip width, and shoulder to wrist length.

The avatar's body could be adjusted based on three regressors. The regressors allowed for the creation of a virtual body with precise body dimensions. In each trial, the avatar's body could either be adjusted for just one dimension (Trial Type 1: weight), three dimensions (Trial Type 3: weight, leg length, and arm span), or five dimensions (Trial Type 5: weight, leg length, arm span, hip width, shoulder to wrist length) (Figure 2). The same slider ranges were used for all trial types and for males and females; Weight: 28−111 kg, arm span: 1.3−2.1 m, leg length: 0.57−1.02 m, hip width: 0.28−0.5 m, and shoulder to wrist length (arm length): 0.4−0.6 m. Across the three different trial types, changes in body dimensions slightly differed as they were constructed with different constraints. This can be seen when visually comparing the heatmaps showing where the changes in body dimensions express themselves (Appendix: Figures 7, 8, and 9).

The arm span, leg length, hip width, and shoulder to wrist length correspond to distances between two vertices on the virtual body. The avatar's weight was estimated based on the volume of the body. For computing this relation between the body volume and weight, the SMPL body model [Loper et al. 2015a] was registered to all female and male subjects in the CAESAR database [Robinette et al. 2002] and the volume of the obtained registrations was computed. The weight measurements of all female and male subjects in the CAESAR dataset have a linear relation to the volume of the SMPL fit, but are slightly different for each gender. A linear regressor was learned separately for females and for males, allowing for prediction of weight from the body volume. The two regressors were trained using iterative re-weighted least squares.

Anthropometric measurements of the participants were used to calculate the dimensions of the initial avatar in each trial to present participants with bodies bigger and smaller than themselves. For all trials, the avatar's height was kept constant to that of the participant. In the trials where only one dimension (weight; Trial Type 1) was adjusted, the starting avatar was set to ±20% of participants' own weight. For the trials where three and five dimensions were adjusted, it was not possible to use the same percent changes for all participants as for some participants and trials this would have resulted in statistically implausible bodies. In those cases, the values were therefore slightly corrected. In the trials where three dimensions could be adjusted (weight, arm span, leg length; Trial Type

3), the smaller and bigger starting avatar was set to a weight of ±20%, an arm span of ±5%, and a leg length of on average -4.65% (SD = 0.13) and +4.76% (SD = 0.01) of participants' actual body dimensions. In the trials where five dimensions could be adjusted (weight, arm span, leg length, hip width, shoulder to wrist length; Trial Type 5), the smaller and bigger starting avatar was set to a weight of ±20%, an average arm span of ±4.94%, a leg length of -4.94% (SD = 0.04) and +4.94% (SD = 0.41), a hip width of -18.85% (SD = 0.03) and +18.85% (SD = 2.68), and a shoulder to wrist length of +2.9% (SD = 3.59) and +14.09% (SD = 2.27) of participants' actual body dimensions. Note that the shoulder to wrist length of the smaller starting avatar was on average bigger than participants' actual shoulder to wrist lengths because for some participants the combination of dimensions would otherwise not have resulted in a statistically plausible body shape.

During the experiment, participants wore the HTC Vive headset and held a HTC Vive controller in their dominant hand. The position of the headset and the controller was tracked using two SteamVR Lighthouse base stations. The system was calibrated using the SteamVR standing-only room calibration procedure. At the start of each experiment, a floor distance calibration was performed to ensure proper eye height above ground. The inter-ocular distance was adjusted for each participant as assessed by a pupillary distance measuring tool. To adjust the different body dimensions, participants pointed to the interface buttons using the controller and confirmed the selection by pressing the trigger button. The pointing position was indicated by a red dot. For the selected dimension, they could then adjust the dimensions by moving a slider bar with the controller. To confirm the responses and proceed to the next trial, participants pointed to the 'Finished' button and pressed the trigger button. The virtual scene was programmed in the Unity game engine.

2.3 Procedure

The procedure was conducted across two sessions on different days. In the first session, an ISAK certified person [International Society of the Advancement of Kinanthropometry 2018] performed hand measurements of the overall body height, leg length (inseam height), hip width (at inseam level), arm span (from longest fingertip to longest fingertip when standing in a T-pose), and shoulder to wrist length (arm length when standing in a T-pose). Participants' weight was measured using a digital scale. The session took approximately 15 minutes.

Additionally, for a subset of the participants (11 females, 13 males) a body scan was collected using a 3D body scanner (3dMD, Atlanta/GA). The system comprises 22 stereo units, each consisting of two black and white cameras, and a 5-megapixel color camera. For capturing the body geometry, a textured light pattern is projected onto the body by speckle projectors that is then observed by the black and white cameras. The color cameras capture the body texture. The spatial resolution of the scanning system is approximately 1 mm. To get an accurate representation of their body shape, all participants wore tight grey shorts and female participants a grey sports bra during the body scan. Each participant was scanned in a T-pose resulting in a high-polygon mesh that was then registered to the statistical body model SMPL [Loper et al. 2015b]. Based on the pixels from the 22 RGB calibrated images, a texture map was computed for each participant. The texture map was post-processed in Adobe Photoshop (CS6, 13.0.1) to conceal artifacts and standardize the color of the textures across participants. For those participants, the influence of color-information (grey vs. own texture) on body weight and shape estimation was assessed by applying the textures onto the virtual body in an additional block of trials (for an example, see Figure 3, right). The body scans were used to evaluate the body weight calculation used in the experiment.

The second session took place 32.33 days (SD = 12.98) after the first session (females: M = 34.56 days, SD = 14.03; males: M = 30.11 days, SD = 11.82). Before the experiment, participants were instructed that in each trial a varying number of body dimensions (1, 3, or 5) could be manipulated and their task was to adjust the body weight and shape so it best corresponded to their own body given the trial-specific restrictions. They could go back and fourth between the dimensions as often as they wanted with no time limit. Participants were not allowed to touch their own physical bodies during the experiment either with their own hands or the HTC Vive controller. They were, however, allowed to hold up the arm of their non-dominant hand (the hand not holding the controller) and move their fingers to help them get a sense of their arm length and arm span. They were instructed to remain standing at the same location throughout the experiment. This was especially important when the avatar was viewed from the first-person perspective as the avatar was not animated, so was fixed at the participant's standing location. When participants adjusted body dimensions from the first-person perspective, they were encouraged to move their head and torso (lean slightly forward) such that they could somewhat compensate for the restricted field of view of the head-mounted display, and get a good view on all body dimensions.

To familiarize participants with the task, they started with three practice trials in which they first manipulated one dimension (Trial Type 1: weight), then three dimensions (Trial Type 3: weight, inseam height, arm span), and finally five dimensions (Trial Type 5: weight, inseam height, arm span, hip width, and shoulder to wrist length) of a gender-matched avatar with a uniform grey texture. For these practice trials, the same average-sized starting avatars with a fixed height (1.65 m for the female avatar, and 1.78 m for the male avatar) were shown to all participants. Participants viewed the avatar from a third-person perspective because deviations in height between the participant and the avatar would have resulted in an unrealistic first-person perspective on the body. Participants were encouraged to explore how adjustments of the body dimensions influenced the avatar's body shape.

After the practice block, participants completed one block of trials in which they adjusted the gender-matched avatar's body with a grey texture to match their actual body dimensions, followed by one block where they adjusted the body to match their desired (ideal) body dimensions. The starting dimensions of the avatar were personalized and calculated based on the anthropometric measurements of the participant. Between the blocks, participants had a short break. To match each participant's body height to the avatar's height based on the anthropometric measurements, they were asked to take off their shoes during the experiment. Participants were told that the avatar's height was set to their own body height and should serve as a reference when adjusting the other dimensions. Even though participants were not able to adjust the height of the avatar, statistically implausible combinations of the other body dimensions resulted in a slight change in height in the trials where three and five dimensions of the body could be adjusted. Participants were therefore instructed to make sure to stay within the range of body dimensions that would not cause changes in the avatar's height.

In the block where participants adjusted the body dimensions to match their actual body size, they completed six trials when viewing the avatar from a third-person perspective, and six trials when viewing the avatar from a first-person perspective (two trials for each trial type respectively, with the initial avatar smaller and bigger than their own body for each trial type). The different trial types (1, 3, and 5) were presented in random order to prevent training effects. For all participants, the avatar was shown with a grey texture. Half of the males and females started with the first-person perspective, the other half with the third-person perspective. The participants who had their body scanned, completed one block of trials where the uniform grey texture was applied to the body and one additional block of trials where the participant's own texture was applied to the body (Figure 3). The order of texture presentation was counterbalanced across those participants. In the block where participants adjusted the body to match their desired (ideal) body, the avatar with the grey texture was shown. Participants completed three trials when adjusting ideal body size, one for each trial type, from a first- and third-person perspective, respectively.

Following the experiment, participants completed the Rosenberg Self-Esteem Questionnaire [Rosenberg 1965], the Body Image Questionnaire [Clement and Löwe 1996], the Body Comparison Scale [Fisher et al. 2002] (for the results, see Table 1), and a post-questionnaire. In the post-questionnaire participants rated 1) How difficult they found it to adjust the avatar's body in the different trial types (1, 3, and 5) on a 7-point Likert scale from 1 (extremely difficult) to 7 (extremely easy), 2) How satisfied they were with the adjusted body on a 7-point Likert scale from 1 (not at all) to 7 (very), and 3) How similar the avatar was to themselves in terms of the overall appearance, the face, the arms, the torso, and the legs, on a 7-point Likert scale from 1 (not at all) to 7 (very) when the grey (and for the subset of participants, their own texture) was shown.

To control for weight changes between the two sessions, participants' actual body weight was measured using the same digital scale as in session 1, and used for calculating the accuracy of BSE in the experiment. The difference in weight between the sessions was minimal for both genders (1.53%, SE = 0.35 for females, and 1.45%, SE = 0.6 for males). The whole experimental session took approximately 60 minutes.

3 RESULTS

3.1 Participants

Independent t-tests with Bonferroni-corrections revealed that male and female participants significantly differed in weight and height, but not in body mass index (BMI). According to the international classification of BMI [World Health Organization 1995], 1 male and 2 females are classified as underweight (BMI < 18.5), 14 males and 14 females as normal weight (BMI 18.5–24.9), and 1 male and 2 females as overweight (BMI 25–29.9). Males scored significantly higher than

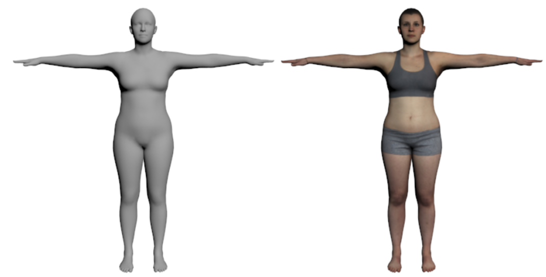

Figure 3: Example female body with grey (left) and own texture based on a body scan (right).

females on the muscularity subscale of the Body Comparison Scale (Table 1), indicating that they more often compare this aspect of their body to other individuals of the same gender.

Table 1: Descriptive statistics of the participants and gender comparisons (independent t-tests and effect size Cohen's d).

	Females (N = 18)		Males (N = 18)			
	Range	Mean (SD)	Range	Mean (SD)	Sig.	d
Height (m)	1.47–1.72	1.64 (0.06)	1.63–1.93	1.82 (0.08)	$p < .001^*$	2.43
Weight (kg)	48.5–74.3	57.9 (6.83)	62.75–92.9	75.21 (9.15)	$p < .001^*$	2.14
BMI (kg/m^2)	17.22–26.33	21.59 (2.46)	18.45–27.21	22.8 (2.06)	n.s.	0.54
Age (y)	21–35	26.39 (3.53)	18–38	27.94 (4.78)	n.s.	0.35
RSE	14–30	24.9 (4.27)	13–29	23.83 (3.99)	n.s.	0.26
BIQ-VBD	27–44	36.28 (4.78)	27–41	35.22 (4.02)	n.s.	0.3
BIQ-NBE	11–37	19.89 (7.77)	16–46	22.11 (6.94)	n.s.	0.24
BCS-GA	11–29	19.78 (5.3)	11–33	19.72 (5.69)	n.s.	0.01
BCS-M	7–20	13.67 (4.28)	10–25	17.78 (4.25)	$p = .04^*$	0.96
BCS-W	6–20	13.61 (4.41)	5–20	12.00 (4.06)	n.s.	0.38
BCS-MS	7–21	15.33 (3.51)	11–24	15.94 (3.47)	n.s.	0.17

RSE = Rosenberg Self-Esteem Scale; BIQ-VBD = Body Image Questionnaire: Subscale Vital Body Dynamics; BIQ-NBE = Body Image Questionnaire: Subscale Negative Body Evaluation; BCS-GA = Body Comparison Scale: Subscale General Appearance; BCS-M = Body Comparison Scale: Subscale Muscularity; BCS-W = Body Comparison Scale: Subscale Weight; BCS-MS = Body Comparison Scale: Subscale Overall Muscle Tone and Shape; *after Bonferroni correction; n.s. = not significant (p > .05).

3.2 Virtual BMI evaluation

The virtual body's weight was calculated based on the body volume, as described in section *Stimuli and Scene*. Although Pujades et al. [2019] showed that there is a gender-specific linear relationship between the hand measured weight and the volume of bodies in the CAESAR database [Robinette et al. 2002], there will likely be deviations between the calculated weight based on the body volume and the hand measured weight for a given individual. To evaluate this deviation, for the subset of participants that got a body scan, we compared the virtual weight of their body scan, calculated based on the volume, to their actual hand measured weight. The virtual BMI of the scan was then calculated using the virtual weight and the hand measured body height, and was statistically compared to participants' actual BMI. The hand measured height was used for the calculation of the virtual BMI instead of the virtual height to control for potential differences in posture that could affect body height. The virtual BMI of participants' scans was on average higher than participants' actual hand measured BMI (Figure 4). One-sample t-tests revealed that this difference from 0 (participants' actual hand measured BMI) was significant both for females (t(10)

= 6.19, p < .001; M = 3.26%, SE = 0.53, range: 0.45% to 6.21%), and for males (t(12) = 8.56, p < .001; M = 2.9%, SE = 0.34, range: 1.4% to 5.51%). However, an independent t-test showed that there was no significant difference between males and females in terms of the deviation of the virtual BMI from the actual BMI, t(17.5) = 0.57, p = .57.

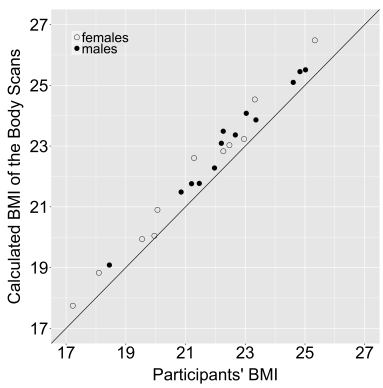

Figure 4: BMI of the registered body scans based on the calculated virtual weight and the hand measured height of each participant as a function of participants' actual hand measured BMI in Session 1. The black line indicates corresponding virtual and actual BMI.

3.3 Does Visual Perspective Influence Body Weight Estimation?

Because previous research has focused on body weight estimation, we first analyzed the body weight estimation results of all participants in the three different trial types when the avatar was shown with the grey texture. To get a measure of the accuracy of the body weight estimation, for each participant and trial, a body perception index (BPI) was calculated according to the formula: BPI = (estimated weight / actual weight) x 100 [Slade and Russell 1973]. The actual body weight was participants' weight measured in the second session. A repeated-measures analysis of variance (ANOVA) was conducted on the BPI with perspective (first-person, third-person) and trial type (1, 3, and 5) as within-subject factors and participant gender (male, female) as a between-subjects factor. t-tests were used for planned comparisons. Effect sizes of the planned comparisons are reported as Cohen's d. The results are shown in Figure 5.

The analysis revealed a main effect of perspective, $F(1, 34)$ = 21.49, p < .001, η_p^2 = .08. One sample t-tests showed that participants significantly underestimated their weight from both perspectives (third-person: t(35) = -7.07, p < .001, d = 1.18; first-person: t(35) = -9.9, p < .001, d = 1.65), but they underestimated significantly less from the third-person perspective (BPI: M = 91.11%, SE = 1.41) as compared to the first-person perspective (BPI: M = 86.04%, SE = 1.26). The interaction of participant gender by perspective was marginally significant, $F(1, 34)$ = 3.79, p = .06, η_p^2 = .03. There was a larger difference in BPI between the two perspectives for males

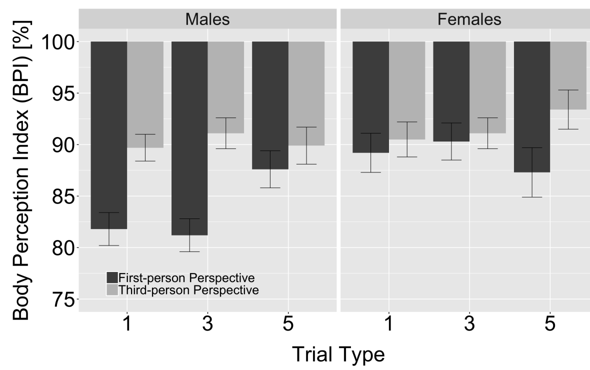

Figure 5: Body Perception Index for the estimated own body weight for male and female participants when the avatar was shown with the grey texture. Error bars represent one standard error from the mean.

(third-person: M = 90.14%, SE = 1.65, first-person: M = 82.93%, SE = 1.5) as compared to females (third-person: M = 92.09%, SE = 1.92; first-person: M = 89.15%, SE = 2.19). The effect of participant gender and perspective was dependent on the trial type as indicated by the significant three-way interaction, $F(1, 68)$ = 6.42, p = .003, η_p^2 = .02. Planned comparisons using paired t-tests showed that there was a significant difference in BPI between the two perspectives for males in all trial types (Trial Type 1: t(17) = 4.85, p < .001, d = 0.94; Trial Type 3: t(17) = 5.47, p < .001, d = 1.43; and Trial Type 5: t(17) = 2.31, p = .03, d = 0.42). For females, there was no difference in BPI for Trial Type 1 (t(17) = 0.62, p = .54, d = 0.12) and 3 (t(17) = 0.49, p = .63, d = 0.12), but a marginally significant difference in Trial Type 5 (t(17) = 2.04, p = .06, d = 0.61). None of the other main effects and interactions were significant (all p-values > .09). These results indicate that the amount of control over the body shape in the different trial types influenced the weight estimates differently for males and females when viewing the body from a first- and third-person perspective.

The adjusted bodies averaged across all trials, separately for the different trial types and the two visual perspectives, for male and female participants are shown in the Appendix Figures 10 and 11. The shape differences between the bodies are visualized in the heatmaps in Figure 6.

3.4 Does Texture Influence Body Weight Estimation?

A second analysis was run on the body weight estimates (BPI scores) of only participants who had a body scan (11 females, 13 males), as this subset of participants also completed one block of trials where their own texture was applied to the virtual body. To control for the bias in the virtual BMI calculation as described in section *Virtual BMI evaluation*, in this analysis the BMI of the adjusted avatar was compared to the virtual BMI of each participant's scan because both were calculated based on the body volume. A repeated-measures ANOVA was conducted on the BPI with perspective (first-person, third-person), trial type (1, 3, and 5), and texture (own, grey) as

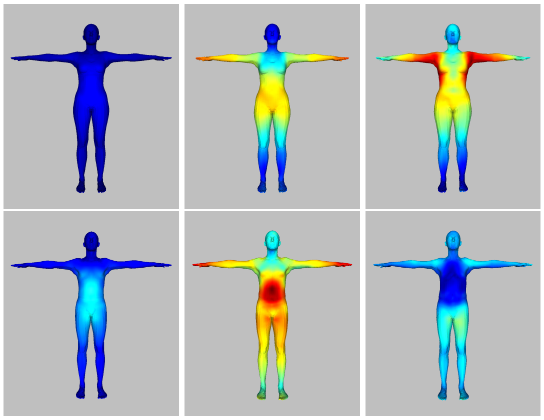

Figure 6: Heatmaps showing the differences between the adjusted body (averaged across all trials and participants) from the two visual perspectives for females (top) and males (bottom) for Trial Type 1 (left), 3 (middle), and 5 (right). Dark blue indicates no difference, red indicates a 2 cm difference for females and a 4 cm difference for males.

within-subject factors and participant gender (male, female) as a between-subjects factor.

The results of the analysis were in line with the results of the analysis on all participants. There was a main effect of perspective (F(1, 22) = 14.39, p < .001, η_p^2 = .06; third-person: M = 88.08%, SE = 1.39, first-person: M = 83.6%, SE = 1.72), and a significant interaction of participant gender by perspective by trial type (F(1, 44) = 10.33, p < .001, η_p^2 = .02). Further, there was a main effect of texture (F(1, 22) = 6.49, p = .02, η_p^2 = .02). Body weight was underestimated more when participants' own textures were shown on the avatar (BPI: M = 84.78%, SE = 1.6), as compared to the grey texture (BPI: M = 86.94%, SE = 1.45). Importantly, even when accounting for the bias in virtual weight calculation, participants significantly underestimated their own weight. This means that the underestimation found in section *3.3* is not due to how the weight of the virtual body is calculated. None of the other main effects and interactions were significant (all p-values > .09).

3.5 Does Visual Perspective Influence Body Part Size Estimation?

To get a measure of the accuracy of the body part size estimation, for each participant and trial, a body perception index (BPI) was calculated according to the formula: BPI = (estimated size / actual size) x 100 [Slade and Russell 1973]. The actual size was participants' hand measured body dimensions in the first session. Pujades et al. [2019] found body-part specific measurement variability between 0.5–2% for the body dimensions adjusted in the present experiment, so the absolute accuracy of body part adjustments should therefore be considered with caution. For the sake of completeness, the results of the weight estimation and the desired body dimensions are presented together with the results of the body part size estimation in Table **??**. A repeated-measures ANOVA was conducted on the BPI scores with body part as a within-subject factor and participant gender (male, female) as a between-subjects factor, separately for Trial Type 3 and Trial Type 5. Only trials where participants estimated their actual body dimensions and where the grey texture was shown were analyzed.

For Trial Type 3, the ANOVA revealed a main effect of body part (leg length, arm span), F(1, 34) = 9.51, p = .004, η_p^2 = .07, and a significant interaction of body part by perspective (F(1, 34) = 19.54, p < .001, η_p^2 = .09). Planned comparisons showed that there was a significant difference in BPI for leg length between the two perspectives (t(35) = 3.14, p = .003, d = 0.56), and a significant difference in BPI for the arm span (t(35) = -4.01, p < .001, d = 0.7). None of the other main effects and interactions were significant (all p-values > .16). For Trial Type 5, the ANOVA revealed a main effect of body part (leg length, arm span, hip width, shoulder to wrist length), F(3, 102) = 186.74, p < .001, η_p^2 = .73, and a significant interaction of body part by perspective (F(3, 102) = 9.72, p < .001, η_p^2 = .05). Planned comparisons showed that there was a significant difference in BPI between the two perspectives for leg length (t(35) = 2.81, p = .008, d = 0.41), arm span (t(35) = -4.01, p < .001, d = 0.7), hip width (t(35) = 3.33, p = .002, d = 0.57) and a marginal difference for leg length (t(35) = -2.02, p = .05, d = 0.35).

These results indicate that males and females did not differ in terms of the accuracy of estimating own body part dimensions, however the estimates differed based on the visual perspective on the virtual body. Overall, the accuracy of the estimated body dimensions lies within a range of ± 6% from the hand measurements, with most of the estimates being relatively accurate (Table **??**).

3.6 Post-Questionnaires

Participants rated Q1) How difficult they found it to adjust the avatar's body in the different trial types and Q2) How satisfied they were with the adjusted body (Appendix, Table 4). Adjusting the body dimensions in Trial Type 5 was perceived to be more difficult, but this did not have an effect on how satisfied participants were with the resulting body. Overall, participants were relatively satisfied with the adjusted body across all trial types.

Participants additionally rated how similar the virtual body was to themselves in terms of the overall appearance, the face, the arms, the torso, and the legs, on a 7-point Likert scale from 1 (not at all) to 7 (very) when the grey and their own texture was shown. The results are reported in Table 3. Median scores are reported because non-parametric tests were used for the analysis. To test whether the similarity ratings of the overall appearance differed depending on the texture that was applied to the bodies, the results of the subset of participants who saw both textures were statistically compared. Non-parametric Wilcoxon signed-rank tests was used because the data were not normally distributed. There was a significant difference in similarity ratings depending on the texture, W = 5, p < .001. Participants rated the avatar's overall appearance to be more similar to themselves when their own texture was shown (Mdn = 5.5) as compared to when the grey texture was shown (Mdn = 4). When visually comparing the scores for the different body parts between males and females and across textures, the largest difference was reported in the similarity ratings for the face. In females, similarity ratings for the face were similarly high for the grey and their own

Table 2: Absolute accuracy of the mean (SE) size estimation in percent deviation from the hand measurements for estimated own and desired body size for the different trial types when the avatar was shown with the grey texture.

		Males (*N* = 18)				Females (*N* = 18)			
		current		desired		current		desired	
		1st pp	3rd pp	1st pp	3rd pp	1st pp	3rd pp	1st pp	3st pp
TT 1	Weight	-18.2 (2.1)	-10.3 (1.7)	-17.3 (3.7)	-14.1 (2.1)	-10.8 (2.7)	-9.5 (2.3)	-18.5 (3.1)	-18.3 (2.3)
TT 3	Weight	-18.4 (2.0)	-8.8 (1.7)	-18.6 (3.1)	-13.5 (2.4)	-9.6 (2.0)	-8.8 (1.9)	-19.1 (2.3)	-18.7 (1.9)
TT 3	Leg Length	1.6 (1.6)	-1.9 (0.9)	3.2 (1.1)	-0.8 (1.4)	-0.5 (0.9)	-2.4 (0.8)	-0.2 (1.2)	-0.3 (0.8)
TT 3	Arm Span	-5.2 (1.1)	-0.74 (0.6)	-1.3 (1.1)	0.6 (0.8)	-4.9 (1.3)	-2.8 (1.1)	-5.0 (1.0)	-1.9 (0.9)
TT 5	Weight	-12.3 (1.8)	-10.0 (2.1)	-8.9 (3.6)	-10.5 (2.4)	-12.6 (2.8)	-6.5 (2.0)	-18.1 (3.5)	-15.6 (2.4)
TT 5	Leg Length	0.4 (1.4)	-2.2 (1.2)	2.0 (1.6)	-2.8 (1.8)	0.2 (1.3)	-2.0 (1.0)	0.4 (1.3)	0.2 (0.8)
TT 5	Arm Span	-3.6 (0.8)	-1.7 (0.6)	-3.9 (1.2)	-1.1 (0.9)	-1.9 (0.7)	-0.5 (0.5)	-3.1 (1.2)	-0.1 (0.9)
TT 5	Hip Width	5.5 (1.8)	0.2 (1.4)	9.5 (3.1)	2.2 (1.4)	0.7 (1.2)	-0.8 (1.5)	0.1 (1.9)	-2.8 (1.9)
TT 5	Shoulder to Wrist Length	-6.0 (1.0)	-3.9 (0.8)	-7.6 (1.3)	-5.8 (1.2)	0.1 (0.9)	0.7 (0.7)	-1.6 (1.7)	1.5 (1.3)

texture, whereas the face received much higher rating scores for their own texture in males. This result suggests that applying one's own texture to an average face does not seem sufficient for females for self-identification, but seems to be sufficient for males, possibly due to more identity-specific features in the face, such as a beard.

Table 3: Median scores of the similarity ratings (1 – not at all, 7 – very) for all participants for the grey texture and separately for the subset of participants that also saw their own texture (13 Males and 11 Females).

	All participants		Subset of the participants			
	Grey		Grey		Own	
	F	M	F	M	F	M
Overall appearance	4	4	4	4	6	5
Face	2	2	2	2	2	5
Torso	4	4	4	4	6	5
Arms	4	4	4	4	5	5
Legs	4	5	4	4	5	5

4 GENERAL DISCUSSION

The aim of the current study was to investigate whether own body weight and shape are estimated for a virtual body differently based on the visual perspective on that body. In a method of adjustment task, participants adjusted the body weight and a varying number of body part dimensions of a gender-matched virtual body that was presented in an HMD-based immersive virtual environment and viewed from a first-person or third-person perspective. We had two somewhat alternative hypotheses: 1) that a third-person perspective on the body would allow participants to more holistically process the changes in body dimensions as they relate to each other and overall body shape and weight or 2) that a first-person perspective might be easier to adjust the body shape given that is a more familiar perspective on one's own body. Overall, our results generally did not support the second hypothesis. We did not find a significant difference in body weight estimates between the two perspectives for all trial types, but when we did observe differences, the estimates from the first-person perspective were less accurate. We got into discussion of the results in more detail for gender, trial type, and perspective below.

The results show that males and females underestimated their body weight on a virtual body viewed from a third-person perspective by 7–10%. This underestimation is greater than what previous studies found in a method of adjustment task with life-size avatars [Mölbert et al. 2018; Thaler et al. 2018b]. Those studies found that females and males underestimated their weight by only around 2–3%. There are several differences in the current study that could explain the greater underestimation. In Mölbert et al. [2018] and Thaler et al. [2018b], the avatars were personalized in shape and appearance based on 3D body scans, and their weight could only be manipulated within a range of ±20% of participants' actual BMI. An important factor to consider in future research is the influence of identity cues in the body and body shape details on weight estimation. *The Virtual Caliper* avatar creation tool produces smooth body shapes, details in the body shape such as fat pads or protruding bones (e.g., at the shoulders) might be important cues for body weight perception and the lack of these cues might make it difficult to estimate a virtual body's weight.

For males, weight underestimation was greater when viewing the avatar from the first-person perspective (12–18%) as compared to the third-person perspective (9–10%). Interestingly, the difference in weight estimates between the two perspectives was dependent on the number of body dimensions that could be adjusted in the different trial types. Although participants were allowed to lean forward to get a better view on the avatar's body in the first-person perspective condition, the restricted field of view of the HMD does not allow one to fully view the upper torso of the avatar. The results might have been related to how the weight changes were depicted in the male avatar, or the degree of similarity between males' own body shape and the avatar's body shape. Some support for this claim comes from the finding that the effect of visual perspective on weight estimates got smaller in Trial Type 5 when more control over the body shape was given.

For females, the opposite pattern was observed. Visual perspective on the body only affected body weight estimates in Trial Type 5, where compared to the other trial types, underestimation seemed to get slightly larger from the first-person perspective and slightly smaller from the third-person perspective. Similar to the results for males, this indicates that the amount of control over the body shape and the difference in visibility of the body parts that could be adjusted seemed to have an influence of the perception of the avatar's body weight.

There was no gender difference in the accuracy of estimated body part dimensions; however, estimates differed based on the visual perspective on the virtual body. The absolute accuracy of the estimates as compared to the hand measurements were within a range of ±6%, with most of the estimates being relatively accurate. This finding shows that people seem to be much more accurate in estimating their own body dimensions when visual feedback is available in a body, as compared to when estimating on a spatial measure where typically large overestimations are found [Mölbert et al. 2017].

Given previous work found greater weight underestimation when a checkerboard texture was applied to an avatar personalized in body shape as compared to own texture [Piryankova et al. 2014; Thaler et al. 2018b], we tested whether body weight estimates were similarly influenced by whether a solid grey or participants' own textures were shown on the avatar. Body weight was underestimated more when participants' own texture was shown. The real body textures may have contained some lighting information from the body scan that provided additional shape cues. While shape from shading cues might allow for a more accurate weight estimation when the underlying body shape is matched [Piryankova et al. 2014; Thaler et al. 2018b], they might lead to less accurate estimates for a different underlying body shape due to inconsistent shape cues. Body weight estimates could also be influenced by how much participants identified with the body. The results of the post-questionnaires showed that the avatar with own texture was perceived to be more similar to participants' own appearance, as compared to the avatar with grey texture. This finding is in line with previous research showing that females rated the avatar's appearance with their own underlying body shape as significantly more similar to their own body for their own texture as compared to a texture of another person [Mölbert et al. 2018; Thaler et al. 2018a], or a checkerboard texture [Piryankova et al. 2014]. Own texture also received higher similarity ratings as compared to a checkerboard texture when the texture was shown on a body with underlying average body shape but matched in weight and height to each participant, both for females [Piryankova et al. 2014] and males [Thaler et al. 2018b]. Interestingly, our results show that similarity ratings for the face were equally low for own and grey texture for females, but much higher for the own texture for males. This finding is in line with a previous study suggesting that own shape might be more important for females, whereas own texture might be more important for males for higher similarity ratings [Thaler et al. 2018b]. This is probably due to more identity-specific skin particularities in the face for males (e.g., beard) than for females, thereby increasing the identification with the face for males even when the underlying face shape is average.

Females desired a lower than their estimated weight across all trial types and perspectives (replicating prior research, Allaz et al. [1998]; Tiggemann et al. [2000]) , whereas for males desired weight estimates depended on control over body shape and perspective. Males desired a lower body weight when viewing the body from a third-person perspective, but this effect disappeared when males could adjust more dimensions of the virtual body. Such a finding indicates that other aspects of the virtual body, e.g. muscularity, are likely more important for males' desired weights [Blond 2008]. The importance of muscularity for males was also apparent in the results of the questionnaires showing that males significantly more often compared their muscularity to others than females. This gender difference "muscles vs. weight" reflects the Western cultural body ideal and is also reflected in people's choices of self-avatars for video games [Ducheneaut et al. 2009; Dunn and Guadagno 2012].

Finally, our study has some limitations, including that only a limited number of body dimensions could be adjusted. It would be desirable to extend control over body shape to other body parts, especially to those that males and females might be concerned about, such as arm and thigh width, waist width, and chest and bust girth. To avoid the need for re-scaling of the estimated body dimensions, the avatar's height was always set to each participant's own height. Because cultural body ideals for both females and males are rather tall, it would be interesting to investigate the role of body height for the desired body. The T-pose used in our experiment is not a very ecological body pose, but it presents certain advantages over other poses in that it has no self-occlusions and allows for changes in body shape without affecting the angle of the body parts. Previous research suggests that body pose and shape can influence how powerful a virtual character is perceived [Wellerdiek et al. 2015]. Little is known about whether there is an influence of body pose on the perception of a virtual body's weight. Further, the restricted field of view of the head-mounted display poses some difficulties for assessing body size from a first-person perspective, as some body parts, especially the shoulder and chest area, are difficult to see.

It is important to consider that the first- and third-person perspective might also have differed in terms of the sense of ownership over the avatar in our study. Previous research has suggested that a body ownership illusion can be introduced by synchronous visuo-tactile stimulation [Petkova and Ehrsson 2008], and also with head tracking [Slater et al. 2010], or seeing a body from a first-person perspective [Petkova et al. 2011; Slater et al. 2010]. Participants may have felt more ownership over the virtual body when viewing it from the first-person perspective. Future research should investigate the role of visual perspective in body size estimation in a more ecological situation with real-time tracking of the participant's motion. This synchronous sensory-motor stimulation could introduce a sense of body ownership both when viewing the avatar from a first- and third-person perspective.

5 CONCLUSIONS

The study has important strengths. We used *The Virtual Caliper* avatar creation tool to investigate the influence of visual perspective on the perception of an avatar's body weight and shape in males and females. This tool made it possible to realistically and independently manipulate body weight and the dimensions of body parts. This methodology provides major advantages over previous depictive body size estimation methods. This avatar creation and adjustment tool could potentially be used for clinical applications, such as virtual mirror exposure therapy for individuals with body image disturbances and patients with anorexia or bulimia nervosa.

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7 APPENDICES

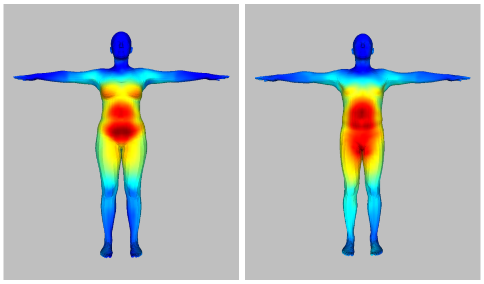

Figure 7: Heatmaps showing where the changes in weight express themselves in the female and male avatar in Trial Type 1 where only weight could be adjusted. Red indicates the area that changes most, blue indicates the area that changes least. All red elements are normalized equally, red is 1 cm displacement in both heatmaps.

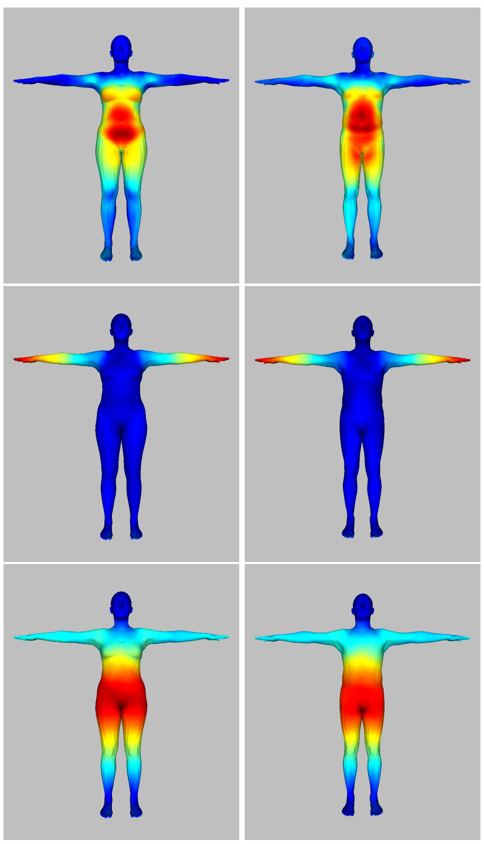

Figure 8: Heatmaps showing where the dimension changes express themselves in the female and male avatar in Trial Type 3 where weight, arm span, and leg length (from top to bottom) could be adjusted. Red indicates the area that changes most, blue indicates the area that changes least. All red elements are normalized equally, red is 1 cm displacement in all heatmaps.

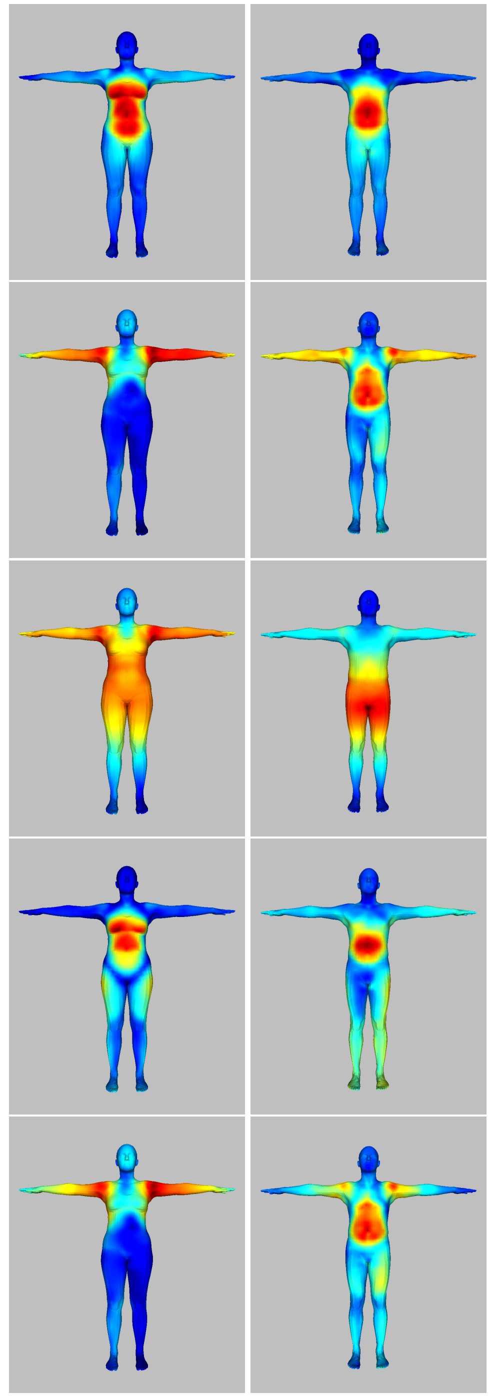

Figure 9: Heatmaps showing where the dimension changes express themselves in the female and male avatar in Trial Type 5 where weight, arm span, leg length, hip width, and shoulder to wrist length (from top to bottom) could be adjusted. Red indicates the area that changes most, blue indicates the area that changes least. All red elements are normalized equally, red is 1 cm displacement in all heatmaps.

Table 4: Median scores of the post-questionnaires. Q1: How difficult did you find it to adjust the avatar's body in the different trial types (TT 1, 3, and 5) (1 – extremely difficult, 7 – extremely easy)?, Q2: How satisfied were you with the adjusted body (1 – not at all, 7 – very) in the different trial types (TT 1, 3, and 5)?

		TT1		TT3		TT5	
		1st	3rd	1st	3rd	1st	3rd
Females	Q1	5	5	5	5	4	3
	Q2	5	5	5	5	5	4
Males	Q1	5	6	4	5	4	3
	Q2	5	5	5	5	5	5

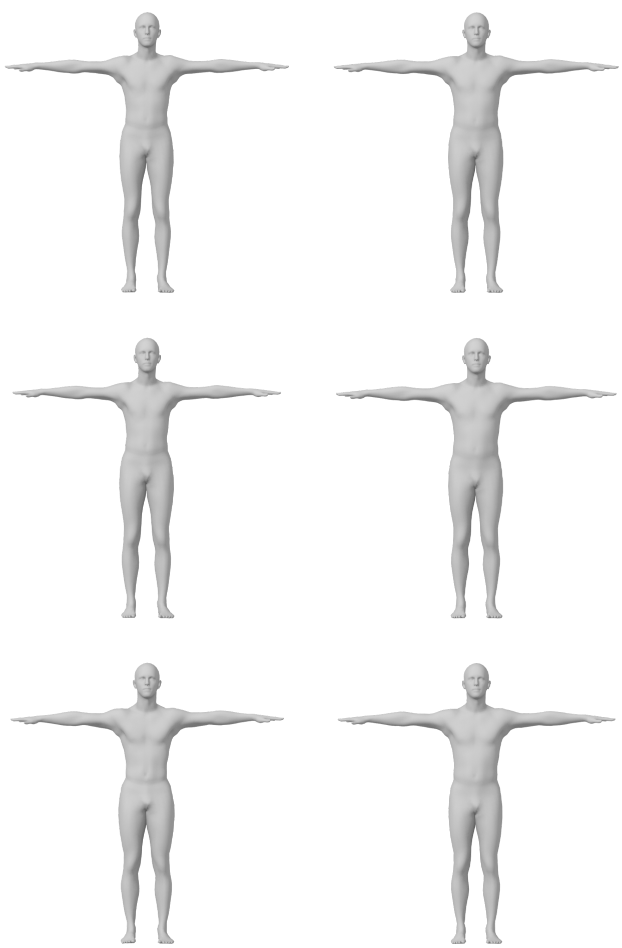

Figure 10: Adjusted body averaged across all trials and male participants when viewing the body from a first-person perspective (left column) and from a third-person perspective (right column) for trial type 1 (top), trial type 3 (middle), and trial type 5 (bottom).

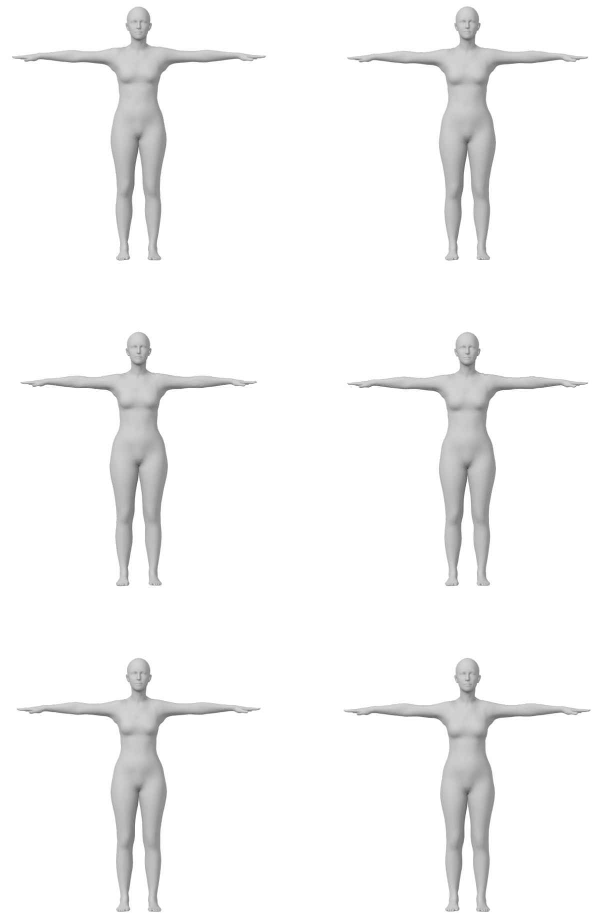

Figure 11: Adjusted body averaged across all trials and female participants when viewing the body from a first-person perspective (left column) and from a third-person perspective (right column) for trial type 1 (top), trial type 3 (middle), and trial type 5 (bottom).

A DISCLOSURE

All of the work for this paper performed by Betty J. Mohler was done prior to her employment with Amazon. Michael J. Black has received research gift funds from Intel, NVIDIA, Adobe, Facebook, and Amazon. While MJB is a part-time employee of Amazon, all research for this project was performed solely at, and funded solely by, MPI.