The Embodiment of Photorealistic Avatars Influences Female Body Weight Perception in Virtual Reality

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Figure 1: The picture shows the participant's view during the experiment, either only observing (left) or embodying and observing (right) a virtual human. Participants had to guess the body weight of the virtual human.

ABSTRACT

Embodiment and body perception have become important research topics in the field of virtual reality (VR). VR is considered a particularly promising tool to support research and therapy in regard to distorted body weight perception. However, the influence of embodiment on body weight perception has yet to be clarified. To address this gap, we compared body weight perception of 56 female participants of normal weight using a VR application. They either (a) self-embodied a photorealistic, non-personalized virtual human and performed body movements in front of a virtual mirror or (b) only observed the virtual human as other's avatar (or agent) performing the same movements in front of them. Afterward, participants had to estimate the virtual human's body weight. Additionally, we considered the influence of the participants' body mass index (BMI) on the estimations and captured the participants' feelings of presence and embodiment. Participants estimated the body weight of the virtual human as their embodied self-avatars significantly lower compared to participants rating the virtual human as other's avatar. Furthermore, the estimations of body weight were significantly predicted by the participant's BMI with embodiment, but not without. Our results clearly highlight embodiment as an important factor influencing the perception of virtual humans' body weights in VR.

Keywords: Virtual human, presence, virtual body ownership, agency, body image, eating- and body weight disorders

Index Terms: Human-centered computing—Human computer interaction (HCI)—Empirical studies in HCI; Human-centered computing—Human computer interaction (HCI)—Virtual reality

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1 INTRODUCTION

Body weight misperception is an important topic in the domain of body weight disorders [10]. Researchers have shown that patients suffering from anorexia nervosa perceive their body weight to be higher than it actually is [32], while patients suffering from obesity tend to perceive it as lower [31]. However, the occurrence of body weight misperception does not necessarily have to be limited to diseases. Recent research indicates that it seems to be an omnipresent part of human perception and cognition [29]. In recent years, research has started to address body weight misperception using virtual reality (VR) applications with the idea of systematic modulation of body weight perception using virtual humans [13]. By applying improbable modifications to virtual humans used as digital representations of human bodies, the perception of body weight can be explored in entirely new ways [58].

Certain potentially influential factors must be considered when designing VR applications that support the research and therapy of body weight misperception. Such factors include the observation perspective on the virtual human [34, 61], its realism and degree of personalization [39, 59], and the illusion of being embodied in it [24, 34, 67]. Research on the influence of these factors has increased recently, leading to a large body of heterogeneous previous work [67]. Furthermore, it appears that not only the application characteristics themselves, but also their interplay with the body dimensions of the user can influence body weight estimations in VR. Thaler et al. [59] indicated that the body weight estimation of a personalized, non-embodied virtual human observed in VR was affected by the participants' own body mass index (BMI). In our previous work [67], we found a similar effect for female participants embodying a non-personalized virtual human. The lower the participants' BMI, the lower they estimated the embodied virtual humans' body weight and vice versa. We proposed the induced embodiment as an explanation for the revealed effect. However, we have left the comparison of the results to a condition without embodiment to future work.

1.1 Contribution

The present study explores the influence of embodiment on body weight perception of a virtual human while keeping the degree of its personalization constant. We systematically extend previous work by comparing body weight estimations between (a) a newly created no embodiment illusion condition and (b) an embodiment illusion condition adapted from Wolf et al. [67]. In the embodiment illusion condition, participants performed five visuomotor tasks while observing the virtual human moving synchronously with the participant's body movements in a virtual mirror. In the no embodiment illusion condition, the virtual mirror was replaced by a door frame leading to an adjacent room in which an animation-controlled virtual human performed the same movements. Therefore, the virtual human could be observed in both conditions from exactly the same allocentric (or third person) perspective, while the egocentric (or first person) perspective was only available in the embodiment illusion condition. After observation, we asked participants for a body weight estimation of the virtual human as our main dependent variable and we checked the perceived feeling of embodiment. We also assessed other potentially mediating variables such as presence, confounding variables such as simulator sickness, and individual-related variables such as body image disturbance or the participant's BMI.

2 Related Work

VR has become an important tool for the research of body perception in recent years. By using devices such as head-mounted-displays (HMDs) [56], users can encounter the feeling of being in a computer-generated artificial world [6]. A resulting subjective reaction to the provided world is called presence. It describes the feeling of really "being" in that virtual world [51, 53]. A high feeling of presence is known to cause behavioral, cognitive, and emotional reactions to the content of the world that are fundamental for therapeutic scenarios [11, 27].

Virtual humans are often an essential part of virtual worlds. When a virtual human refers to a specific user (e.g., is controlled by the user), it can also be called an avatar [1]. The feeling of being inside an avatar, to own an avatar, and to control an avatar is called illusion of embodiment [26] and emerged from the essential findings of the rubber hand illusion [3, 21, 62]. Slater et al. [55] expanded this finding to full-body illusions in VR. The illusion leads to an attribution of the virtual human to the self and can be accomplished by achieving sensory coherence of the corresponding sensory inputs. An embodiment illusion's quality is composed of the sub-concepts virtual body ownership (VBO), agency, and self-location [26]. By maintaining a high feeling of those factors, the embodiment illusion's credibility increases and leads to a higher acceptance of the virtual body as the own body, and consequently to an increased feeling of presence [22, 26, 30, 54, 57]. The illusion of owning a different virtual body can lead to the Proteus effect. It indicates that the individual's behavior conforms to the expected behaviors and attitudes observed from a virtual (self-)representation [69].

In the context of body weight perception, Normand et al. [36] already showed in 2011 in a HMD-based VR environment that full-body illusion with increased belly size can cause differences in the self-assessment of belly size before and after inducing the feeling of embodiment. Piryankova et al. [40] could confirm and extend these findings by showing a change in body size perception after embodying an avatar from an egocentric perspective using affordance and body size estimation tasks. Both works show the fundamental efficacy of the modification of body perception through embodiment illusions in VR.

2.1 Influences on Body Weight Perception

It is imperative to understand the basic mechanisms of body weight perception inside VR. Notably, most prior work investigating body weight perception with normal weighted participants show a general body weight underestimation of the virtual humans [35, 39, 59–61, 67]. In light of related work, it appears that factors such as the degree of personalization of the virtual human [59], whether a participant was embodied in the virtual human [67], and the observation perspective on the virtual human [61] contribute to an attribution of the user's self-perception to a present virtual human. By analyzing the relationship between the participant's BMI and the body weight perception of their personalized, non-embodied virtual human, Thaler et al. [59] recently found that the participant's BMI serves as a linear predictor for the estimations of the virtual human's body weight. A lower BMI led to an underestimation of the virtual human, while a higher led to an overestimation. For non-personalized avatars, however, the predictive effect of the BMI could not be shown. Interestingly, Wolf et al. [67] found in a comparable experimental setting that participants who embody a non-personalized avatar also estimated their avatar's body weight in proportion to their BMI. The authors attributed the effect to the induced embodiment and stated that it might have led to a self-attribution of the virtual body and thus to an association of the self with the virtual human. However, the authors left it to future work to compare their findings to a condition with no embodiment illusion.

Another factor that contributes to the feeling of embodiment, and which also could potentially influence body weight perception, is the observer's perspective on a virtual human. In general, we distinguish between two different perspectives. An egocentric perspective, as we experience with our body as human beings, shows only an excerpt of the body from the first-person view. In comparison, an allocentric perspective shows a more holistic picture of a body from a third-person view, for example, by using a (virtual) mirror. In a similar experimental setup to ours, Neyret et al. [34] explored the differences in body perception between having an embodied ego- and allocentric perspective and only having an unembodied allocentric perspective. The researchers stated that having only the allocentric perspective allowed the participants to perceive the virtual human without attributing it to themselves. However, the researchers refrained from capturing numeric body weight estimates and from analyzing the influence of the participants' body weight on their measurements. Thaler et al. [61] investigated the differences between an egocentric and an allocentric perspective on the perception of body weight and body dimensions, but did not induce an illusion of embodiment. Their study did not find a significant influence of the perspective on the perception of body weight or body dimensions, but reported descriptively less accurate estimations for the egocentric perspective. The results support the theory that perspective is not necessarily the most relevant factor influencing body weight perception. Consequently, the authors highlighted in their discussion the potential importance of factors such as the personalization of the virtual human or whether one is embodied to it or not.

2.2 Summary

In summary, the aforementioned work suggests that the relationship between the own body and the body of a virtual human is influenced by different self-attribution supporting factors such as the personalization of the virtual human, the illusion of embodiment, or more unlikely the observing perspective. To the best of our knowledge, no previous work has explicitly investigated the influence of embodiment illusions on direct body weight estimations considering the impact of the participant's BMI. Therefore, our work will investigate the influence of an embodiment illusion on the estimation of body weight, while keeping the degree of personalization and the allocentric perspective constant. In doing this, we combine insights of existing work on the effects of embodiment [24, 36, 40] and the more recent findings on the influence of the participant's BMI on the perception of body weight [59, 67]. Our research thus contributes to the understanding of possible application-related influencing factors and their control within therapy supporting applications.

3 Design and Hypothesis

As noted above, we identified missing research regarding the influence of embodiment on body weight perception of virtual humans in VR. This applies in particular to the influence of the estimator's BMI on the perception of the virtual human's body weight. The exploration of those potential influences defines the primary research goal of our current work. Additionally, we aimed to confirm prior results regarding the influence of embodiment on the feeling of presence and to confirm the illusion of embodiment's influence on the corresponding embodiment measurements VBO and agency. To this end, we used a between-subject design to compare our no embodiment illusion condition with the embodiment illusion condition of Wolf et al. [67].

3.1 Body Weight Perception

Based on the existing literature on body weight perception [33, 35, 39, 60] and the potentially existing impact of embodiment on body weight estimations [24, 34, 59, 61, 67], we propose the following hypotheses:

H1.1: Participants in the embodiment illusion condition will estimate the virtual human's body weight lower than in the no embodiment illusion condition.

H1.2: Participants in the no embodiment illusion condition will not misestimate the virtual human's body weight.

H1.3: The BMI of participants in the embodiment illusion condition has a stronger effect on body weight estimation than the BMI of participants in the no embodiment illusion condition.

3.2 Presence

With respect to the existing literature on the effects of the illusion of embodiment on presence [22, 30, 54, 57], we propose the following hypothesis:

H2.1: Participants in the embodiment illusion condition will report a higher feeling of presence than participants in the no embodiment illusion condition.

3.3 Embodiment

Regarding the embodiment measurements used to check for our manipulation strength between the no embodiment and the embodiment illusion condition, we propose the following hypotheses based on the existing literature [26, 46]:

H3.1: Participants in the embodiment illusion condition will report a higher feeling of VBO towards the virtual human than participants in the no embodiment illusion condition.

H3.2: Participants in the embodiment illusion condition will report a higher feeling of agency towards the virtual human than participants in the no embodiment illusion condition.

4 Apparatus

The system we used was adapted from Wolf et al. [67] and implemented using Unity 2019.1.10f1 [63]. The following sections will summarize the adopted system parts and describe the applied adaptions. A more detailed description of the whole system architecture as well as the detailed design decisions can be found in the corresponding work. The VR hardware setup consisted of four SteamVR Base Stations 2.0, a HTC Vive Pro HMD, two HTC Vive controllers, and three HTC Vive trackers [20]. It was integrated using SteamVR version 1.13.9 [64] and its corresponding Unity plug-in version 2.5.0. The HTC Vive Pro provides a resolution of 1440×1600 pixels per eye, a field of view of 110 degrees, and a refresh rate of 90 Hz. Software and VR hardware were driven by a modern VR capable gaming PC (Intel Core i7-9700K, Nvidia RTX2080 Ti, 32GB RAM) running Windows 10. The motion-to-photon latency of the setup measured with a Casio EX-ZR200 high-speed camera recording 240 fps averaged 50 ms as determined by frame-counting [18].

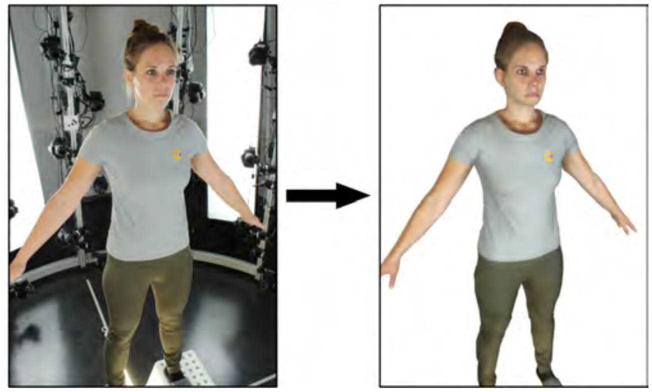

Figure 2: The figure from Wolf et al. [67] shows one of the images taken from the model of the virtual human during the body scan (left) and her generated representation (right).

4.1 Virtual Environment

Using Blender version 2.79b [2], we adopted the already existing realistic looking VE [14, 67] to fit the needs of the no embodiment illusion condition. To this end, we added a door frame leading into a mirrored, adjacent room in which we placed an agent to allow for a similar allocentric perspective on the virtual human as in the embodiment illusion condition. For the embodiment illusion condition, Wolf et al. [67] used a virtual full-body mirror to enable participants to observe their virtual human from an allocentric view [12]. The modifications are depicted in Fig. 1 (left and right).

4.2 Virtual Human

To ensure comparability with Wolf et al. [67], we used the same virtual human created by scanning a female model with a BMI of 22.25, a body height of 1.68 m, and a body weight of 62.8 kg. Following their design, the virtual human was used for all participants and was uniformly scaled to match the participants' body height. The scaling was necessary to assure the virtual human in the embodiment condition matched the participant's body height. Consequently, we also had to scale it in the no embodiment condition to control between conditions. Fig. 2 shows a picture of the model (left) and her generated virtual human (right) from the same perspective.

4.3 No Embodiment Illusion

In the no embodiment illusion condition, participants stood in front of the virtual human within the VE. The virtual human was located behind a virtual door frame, leading to a separate, mirrored room comparable to the one in which the participants were virtually located. A screenshot of the participant's view is shown in Fig. 1 (left). The virtual human could only be observed from an allocentric perspective while it performed pre-recorded body movements completely decoupled from the participant's movements. Thus, the participants in the no embodiment illusion condition had no egocentric perspective on the virtual human. We used the same system as the embodiment illusion condition to capture the movements used to animate the virtual human. A female actor performed all movements according to the description in Sect. 5.3 and the animations were recorded using the animation baker provided by the Unity plug-in FinalIK version 1.9 [44]. We did not perform post-processing on the animations to provide an identical movement quality between the conditions. Animations were played using Unity's animation system and controlled by a custom agent script during the experiment.

4.4 Embodiment Illusion

The embodiment illusion condition was completely adopted from Wolf et al. [67]. In the following, we summarize the implementation. Participants embodied the generated virtual human as an avatar within the VE. The participants' movements were captured by the prior described SteamVR setup. FinalIK version 1.9 [44] was then used to continuously compute a body pose and animate the participants' avatar in real-time to support visuomotor coupling and induce the feeling of embodiment. Participants could observe themselves from an allocentric perspective by looking into a virtual mirror added to the scene. They could also observe their avatars' virtual body from an egocentric perspective. The virtual presentation remained the same distance to the participants in both conditions. A screenshot of the participant's view is shown in Fig. 1 (right).

5 Evaluation

The following section will describe our performed experiment. Measurements, body movements, and the experimental procedure were adopted from Wolf et al. [67] and adapted for our purpose.

5.1 Participants

A total of 56 females participated in our study, 49 of whom were undergraduate students at the University of Würzburg and received course credit for participation. Seven further participants were post-graduates on a voluntary basis. While body weight misperception is subject to gender-specific differences [8, 19, 37], and to increase the comparability to the related work, we used data only from female participants. Prior to our experiment, we defined the following exclusion criteria: (a) participants should have correct or corrected-to-normal vision and hearing; (b) participants should have at least ten years of experience with the local language; (c) participants should not have suffered from any kind of mental or psychosomatic diseases such as eating or body weight disorders; (d) participants should have a BMI above 17 and below 30; and (e) participants should not have a known sensitivity to simulator sickness. Three participants met the exclusion criteria, and another one was excluded due to technical issues, leaving 26 participants in each condition.

5.2 Measurements

5.2.1 Body Weight Measurements

We used the participants' *body weight misestimation (BWM)* of the virtual human as a dependent variable and the *BMI difference* between participants' BMI and the scaled virtual humans' BMI as a body weight-related control variable. Wolf et al. [67] showed that BMI difference is a major predictor for estimating the virtual human's body weight. For calculating these measurements, we captured the body weight and height of the virtual human's model and of the participants with officially approved and calibrated medical equipment. Additionally, we asked participants to estimate the virtual human's body weight. In the following, we will summarize the calculation of the measurements. A more detailed explanation can also be found in the work of Wolf et al. [67].

BWM is based on the relative difference between the virtual human's BMI, estimated by the participants (E-BMI) and the approximated virtual human's BMI (A-BMI), and is calculated as $(\text{E-BMI} - \text{A-BMI})/\text{A-BMI}$. A negative value of the BWM represents an underestimation of the virtual human's body weight, and a positive value an overestimation. The E-BMI was calculated using its estimated body weight and the virtual human's body height in the standard BMI equation (weight/height^2 $[kg/m^2]$). The A-BMI was approximated by multiplying the previously identified scaling factor of the virtual human with the model's BMI. The scaling factor s was calculated by dividing the participant's body height by the height of the virtual humans' model. The scaling approach we used in our work only approximates the virtual human's BMI and results in smaller participants facing a relatively lighter avatar and larger participants facing a heavier one. Therefore, we included the scaling factor as a control variable in our results. The BMI difference between the participant's BMI (P-BMI) and the virtual human's approximated BMI is calculated as $(\text{P-BMI} - \text{A-BMI})/\text{A-BMI}$. A negative or positive value indicates that the participant was lighter or heavier than the virtual human.

5.2.2 Presence Measurements

We captured presence by a *one-item in virtuo question* [4, 5] and by the *Igroup Presence Questionaire (IPQ)* [48]. The one-item question is considered a rapid and accurate presence measurement and asks participants to state on a scale between 0 and 10 (*10 = highest presence*) how present they currently feel in the virtual environment. Additionally, we used the IPQ to measure presence more conclusively and reliable post-immersion [4]. It captures presence through 14 questions divided into four different dimensions – general presence (GP), spatial presence (SP), involvement (INV), and realism (REAL) – reported on a normalized scale from 0 to 10 (*10 = highest presence*).

5.2.3 Embodiment Measurements

We captured two embodiment sub-categories, virtual body ownership (VBO) and agency (AG), each by *a one-item in virtuo question* [23, 65] and by the *Virtual Embodiment Questionnaire (VEQ)* [46]. In the in virtuo questions, participants had to state on a scale from 0 to 10 (*10 = highest VBO, AG*) to what extent they felt that the virtual human's body was their body and to what extent they felt the virtual body moved as they intended it to move. Additionally, we used the VEQ to measure VBO and AG post-immersion. The questionnaire assesses four items for each dimension, reported on a normalized scale from 0 to 10 (*10 = highest VBO, AG*).

5.2.4 Control Measurements

Body weight misperception is known to have a strong relationship to self-esteem and attitude towards the body [9, 49]. Therefore, we controlled self-esteem and body shape concerns as further potentially confounding factors between conditions. For self-esteem, we used the Rosenberg self-esteem scale (RSES) [17, 45, 47] to capture self-esteem on a scale between 0 and 30 (*30 = high self-esteem*). For body shape concerns, we used the validated shortened form of the body shape questionnaire (BSQ) [9, 15, 41]. The score is captured with 16 different items ranging from 0 to 204 (*204 = highest concerns*). As another potentially confounding factor, we captured the feeling of simulator sickness by use of the simulator sickness questionnaire (SSQ) [25]. It captures the presence and intensity of 32 different symptoms associated with simulator sickness. The total score of the questionnaire ranges from 0 to 2438 (*2438 = strongest simulator sickness*). An increase in the score between a pre- and post-measurement indicates the occurrence of simulator sickness.

5.3 Body Movements

The following five body movements were used either to animate the virtual human in the no embodiment illusion condition or as movement tasks in the embodiment illusion condition. All movements were guided by instructions to either watch or perform the movements carefully.

BM1: Raising the right hand and relaxed waving straight ahead.

BM2: Raising the left hand and relaxed waving straight ahead.

BM3: Walking in place with knees up to the height of the hip.

BM4: Stretching out both arms straight ahead of the body and moving them in a circle.

BM5: Stretching the arms to the left and right and moving the hips alternately to the left and right sides.

Figure 3: The figure shows a participant who is currently performing BM4. The corresponding egocentric view is depicted in Fig. 1 (right).

In the embodiment illusion condition, the following sentence accompanied each body movement instruction to support visuomotor stimulation: "Please look alternately at the movements of your mirror image and your body." In the no embodiment illusion condition, each body movement introduction was followed by the sentence: "Please observe the movements and the posture of the virtual human carefully so that you can repeat them later". Fig. 3 shows a participant currently performing BM4.

5.4 Procedure

Our participants were each tested in individual sessions with an average duration of 35 minutes. For a better understanding, the whole experimental procedure is visualized in Fig. 4. During each session, explicit attention was paid to compliance with local hygiene and safety regulations regarding COVID-19 valid at the time of the experiment (i.e., wearing masks, continuous air circulation, equipment disinfection, keeping distance).

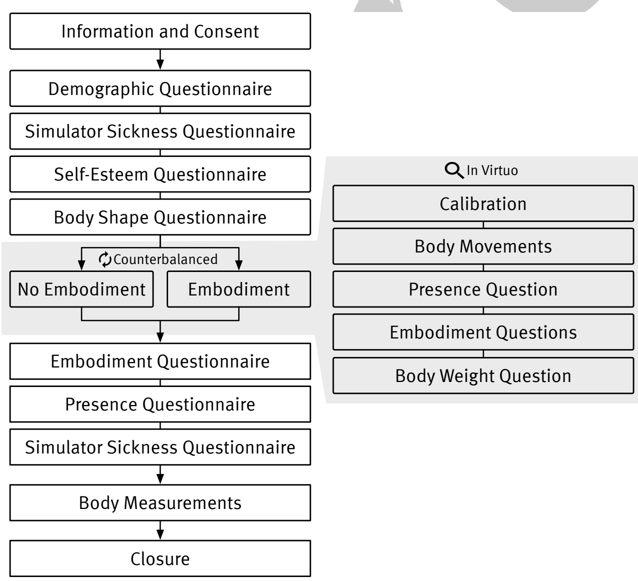

Figure 4: The flowchart visualizes the controlled experimental procedure and gives an overview of the performed measurements.

Information, Consent, and Pre-Survey Participants first had to read the experimental information and gave consent. Afterward, they answered the pre-questionnaires using LimeSurvey 3 [28]. The questionnaires were either translated to German as precisely as possible by us, or were validated, translated versions.

Calibration and Exposure After the pre-questionnaires, the exposure phase in VR followed. The experimenter demonstrated how to fit the equipment using a demonstration device and visually checked that the participant used theirs correctly. For this reason, participants also were asked to adjust the HMD's interpupillary distance and position on the head until they could read a sample text in VR. Subsequently, the exposure phase started following a preprogrammed linear procedure (see Fig. 4, right) that automatically played pre-recorded auditory instructions and displayed text instructions for calibration, body movements, and in virtuo questions. For calibration, participants stood briefly in a T-Pose. Participants were explicitly told that the virtual human they were to face was scaled to their exact body height (for both conditions) and that it either represented another person (for the no embodiment condition) or themselves (for the embodiment condition). In the no embodiment condition, participants were additionally told that the person in the adjacent room performing loosening exercises should be observed carefully. After calibration, participants performed or observed each of the body movements for 34 seconds. The virtual human was only visible to the participants when they had to perform or observe body movements. Otherwise, the mirror or the door-frame was blackened. Finally, participants verbally answered the in virtuo questions regarding presence and embodiment, and estimated the virtual human's body weight (in kg). The experimenter recorded verbal responses within the experimental software. The whole exposure phase in VR lasted on average 7.6 minutes.

Post-Survey and Body Measurements After the exposure phase, participants continued with the questionnaires and the body measurements were performed. For the exposure phase and the body measurements, participants had to take off their shoes to ensure a correct body height measurement.

6 Results

Statistical analysis was performed using the software R for statistical computing [42]. For power analysis, we used G*Power version 3.1.9.7 [16]. The descriptive results of our evaluation are shown in Table 1. For greater comparison between the different measurements, we normalized all variables' values, with the exception of BWM, to a range between 0 and 10. Before we conducted the main analysis, we performed a test of normality and homogeneity of variances for all variables to determine whether the data met the parametric testing requirements. For body weight perception, the BWM data met the criteria for parametric testing. To test our hypotheses on BWM, we calculated a multiple linear regression model. We included the centered BMI difference and the condition as predictors in our regression model. To test whether the deviation between participants' body weight estimations and the virtual humans' actual body weight differed between the two conditions (H1.1), we analyzed the main effect of the condition on BWM within the regression model. To test whether participants misestimated the avatar's weight in the no embodiment illusion condition (H1.2), we included an additional two-sided, one-sample t-test. As we expected no misestimation in this condition, we decided to control the probability of false-positive test results by adjusting the alpha level to $\alpha = .20$. To test the interaction between participants' BMI difference and condition in predicting BWM (H1.3), we analyzed the interaction effect of the regression model. All hypotheses within the linear model were tested against a non-adjusted α of .05. Concerning presence and embodiment, the pre-assumptions for parametric testing were violated in some cases. Thus, we conducted one-sided Mann-Whitney-Wilcoxon tests with effect size r for those measurements (H2.1, H3.1, H3.2). As

Table 1: The table shows the descriptive values for our captured variables normalized from 0 to 10 except BWM.

		No Embodiment	Embodiment
		M (SD)	M (SD)
Body Weight	BWM in %	0.53 (6.00)	−3.25 (8.81)
Presence	IV	7.46 (1.27)	6.69 (1.54)
	IPQ G	2.69 (1.64)	7.05 (2.02)
	IPQ SP	5.23 (1.19)	7.12 (1.18)
	IPQ INV	3.11 (1.58)	4.58 (1.93)
	IPQ REAL	4.09 (0.86)	4.68 (1.39)
	IPQ Total	4.17 (1.27)	5.84 (1.17)
Embodiment	IV VBO	1.73 (2.29)	4.77 (2.12)
	IV AG	2.58 (2.61)	8.04 (1.40)
	VEQ VBO	4.46 (1.73)	5.29 (2.02)
	VEQ AG	5.63 (1.60)	8.28 (0.91)

both measures included several sub-scales resulting in a total of 11 tests, we adjusted the p-values using Bonferroni-Holm correction. The adjusted p-values were tested against an α of .05. In case of non-significant results, we calculated sensitivity analyses using G*Power [16] to support our interpretation.

6.1 Body Weight Perception

In line with our expectations, a significant regression equation was found, $F(3,48) = 8.67, p < .001$, with an R^2 of .31. The prediction followed the equation $\text{BWM} = -3.59 + 0.55 \cdot \text{BMI difference} + 4.17 \cdot \text{condition} - 0.48 \cdot (\text{BMI difference} \cdot \text{condition})$ (For condition: embodiment illusion = 0, no embodiment illusion = 1). As expected (H1.1), within this regression model, the experimental condition had a significant main effect on BWM, $t(48) = 2.35, p = 0.023, \beta = 0.27$. The additional t-test (H1.2) revealed that the participants' estimation in the no embodiment illusion condition did not deviate significantly from the avatar's approximated body weight, $t(25) = 0.45, p = .654, d = 0.089$. A sensitivity analysis revealed that a t-test with the adjusted α of .20 and the sample size of 26 participants would have revealed relatively small effects of $d = 0.423$ or greater with a power of .80 [7]. Thus, we accepted H1.1 as confirmed and did not reject H1.2. The results are shown in Fig. 5.

Additionally to the main effect of the condition, the regression model revealed a significant impact of the participants' BMI, $t(48) = 4.56, p < .001, \beta = 0.50$ on the BWM. In line with our expectations (H1.3), we found a significant interaction between BMI difference and condition, $t(48) = -3.18, p = .003, \beta = 0.39$. Thus, the slope of the regression of BMI difference on BWM was affected significantly by the condition. The resulting interaction is depicted in Fig. 6. While in the condition with full body illusion the BWM is related to the BMI difference, in the condition without body illusion, the relationship between BMI difference and BWM is negligible. Thus, H1.3 was confirmed.

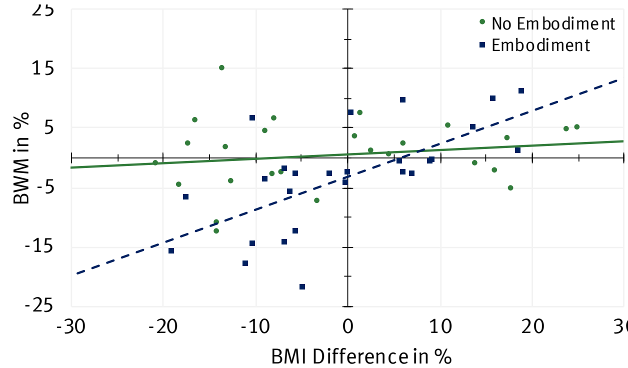

Figure 6: The chart shows the BWM for each of our conditions depending on the BMI difference between the participants' BMI and the virtual humans' BMI.

6.2 Presence

Contrary to our hypothesis H2.1, the in virtuo presence question did not differ significantly between the two conditions, $U(26,26) = 229.5, p_{adj.} = .980$. However, the post-experience presence score revealed a significant difference between the conditions with medium to large effect sizes. Participants reported a higher general presence experience (IPQ G), $U(26,26) = 627.5, p_{adj.} < .001, r = 0.76$, a higher level of involvement (IPQ INV), $U(26,26) = 486.5, p_{adj.} = .016, r = 0.38$, and a higher level of spatial presence (IPQ SP), $U(26,26) = 583.5, p_{adj.} < .001, r = 0.62$, in the embodiment illusion condition compared to the no embodiment illusion condition. In line with these results, the total presence score was higher in the condition with embodiment illusion (IPQ Total), $U(26,26) = 560.5, p_{adj.} < .001, r = 0.57$. The rating of the environment's realism (IPQ REAL) did not differ significantly between the conditions, $U(26,26) = 418.5, p_{adj.} = .070$. A sensitivity analysis revealed that on an α-level of .05, a one-sided Mann-Whitney-Wilcoxon test with a group size of $n = 26$ would only have detected medium effects [7] with an effect size of $r = 0.34$ and more with a power of .80. Consequently, we cannot completely discard a small effect of the condition on the perceived realism. The results are depicted in Fig. 7. We accepted H2.1 as mainly confirmed.

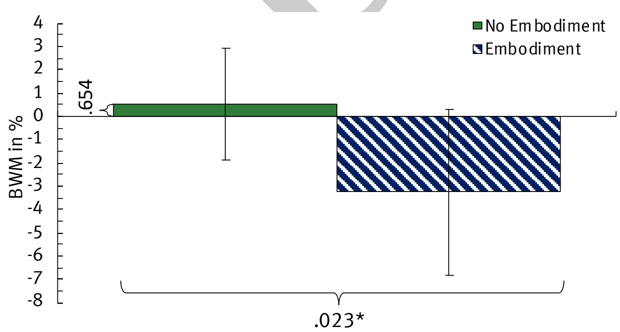

Figure 5: The chart shows the BWM for the no embodiment and embodiment illusion conditions together with the corresponding p-values. Error bars represent 95 % confidence intervals. Asterisks indicate significant p-values.

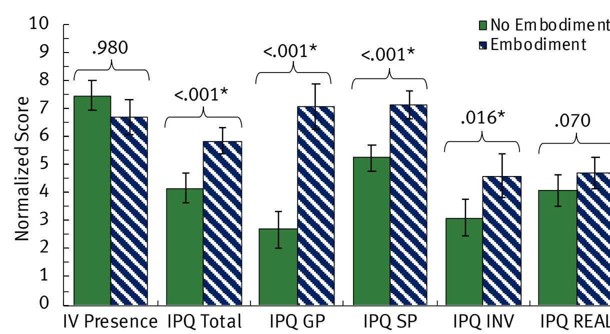

Figure 7: The chart shows the average normalized presence scores for the no embodiment and the embodiment illusion condition together with the corresponding p-values. Error bars represent 95 % confidence intervals. Asterisks indicate significant p-values.

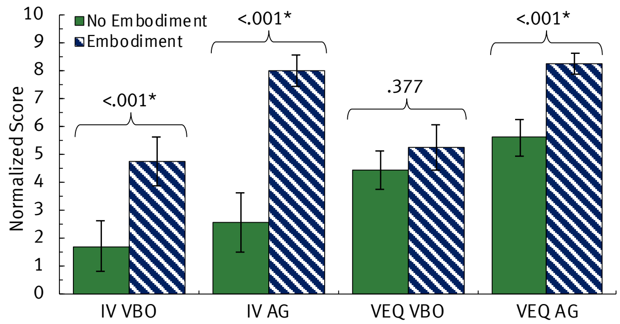

Figure 8: The chart shows the average normalized embodiment scores for the no embodiment illusion and the embodiment illusion condition together with the corresponding p-values. Error bars represent 95 % confidence intervals. Asterisks indicate significant p-values.

6.3 Embodiment

In line with H3.1, the in virtuo measure of VBO revealed a significant difference between the conditions, $U(26,26) = 568, p_{adj.} < .001, r = 0.59$, with participants reporting a higher feeling of VBO in the embodiment illusion condition compared to the no embodiment illusion condition. However, the post-experience ratings on VBO (VEQ VBO) did not differ significantly between the conditions, $U(26,26) = 401, p_{adj.} = .377$. Again, on an α-level of .05, a one-sided Mann-Whitney-Wilcoxon test with a group size of $n = 26$ would have detected medium effects of at least $r = 0.34$ with a power of .8. The ratings of agency (H3.2) within and after the virtual experience revealed a clear effect. Both in virtuo, $U(26,26) = 659.5, p_{adj.} < .001, r = 0.83$, and post-experience (VEQ AG), $U(26,26) = 623.5, p_{adj.} < .001, r = 0.73$, the embodiment illusion condition led to a significantly higher reported feeling of agency than the no embodiment illusion condition. Thus, H3.1 was only confirmed partially, while we accepted H3.2 as fully confirmed. The results are depicted in Fig. 8.

6.4 Controls

No participants were excluded due to rising simulator sickness during the experiment. An overview of the participants' demographic data and control variables can be found in Table 2.

To test whether the scaling factor s influenced our results on body weight perception, we performed a moderation analysis including BMI difference and condition as predictor variables and the scaling factor as a moderator variable. The scaling factor had a significant impact on the BWM $t(45) = -2.5, p = .016$. However, neither the interaction between the scaling factor and the BMI difference, $t(45) = 0.88, p = .400$, nor the interaction between the scaling factor and the condition, $t(45) = -0.10, p = .919$, was found to be significant. These results identify the scaling factor as a non-moderator of the relationship between the BMI difference, the embodiment illusion condition, and BWM.

Table 2: The table shows the results of the control variables scaling factor (s), BMI, self-esteem (RSES), and body shape concerns (BSQ).

	No Embodiment		Embodiment		
	Range	*M* (*SD*)	Range	*M* (*SD*)	*p*
Scale *s*	0.94–1.05	0.99 (0.03)	0.93–1.10	0.99 (0.04)	.921
BMI	17.4–27	21.8 (3)	17.2–27.2	22 (2.2)	.757
RSES	13–29	22.5 (5)	9–30	23.1 (4.7)	.650
BSQ	36–157	91.1 (33.5)	40–148	79.5 (26.8)	.174

7 Discussion

The purpose of this work was to investigate the influence of self-embodying a virtual human in VR on the perception of the body weight of a photorealistic virtual human, the participants' feeling of presence, and the participants' feeling of embodiment. However, the latter was primarily recorded to verify our successful manipulation between our no embodiment illusion and the embodiment illusion condition of Wolf et al. [67]. Additionally, we considered the BMI difference between the participants' BMI and the virtual humans' BMI on body weight estimations as a potentially major moderating factor. In general, our results show that having an embodiment illusion has a significant influence on body weight estimation, including the moderating influence of the BMI difference, on the feeling of presence, and on the feeling of embodiment.

7.1 Body Weight Perception

Among other potential factors, we identified the presence or absence of an embodied virtual human as potential influencing factor on body weight perception. Prior work suggested that embodiment might contribute to an attribution of one's own body weight to the perception of a virtual human's body weight and would lead to the underestimation of the virtual human by a sample within a healthy BMI range. Therefore, we hypothesized that body weight estimations of the virtual human in the embodiment illusion condition will be significantly lower than in the no embodiment illusion condition (H1.1), which we could confirm with our results. Additionally, we did not reject our hypothesis that body weight estimations in the no embodiment illusion condition would not significantly differ from the virtual human's body weight (H1.2). We further hypothesized that our condition would moderate the effect of BMI difference between the participants' BMI and the virtual humans' BMI on body weight estimations (H1.3). We confirmed this hypothesis, as we observed no significant predictive influence of BMI difference on BWM in the no embodiment illusion condition, while in the embodiment illusion condition, body weight estimations were highly significant predicted by the BMI difference.

Our results on body weight perception are in line with the presented related work and with our hypotheses. The confirmation clearly highlights the role of embodiment and one's own body weight in the perception of a virtual human's body weight. Our results indicate that (a) the body weight of our non-personalized virtual human is more realistically perceived when observed without the embodiment illusion. Thus, we claim that the body weight perception of the virtual human was not influenced by the VR system itself. We further showed that (b) the embodiment illusion impacts the perception of non-personalized humanoid virtual humans' body weight. We were also able to show (c) that embodying the virtual human impacts the relationship between one's own BMI and the weight perception of the virtual human, leading to a more biased estimation with an increased difference between one's own and the virtual human's BMI.

The results of our work and of prior related work [59, 67] suggest that embodiment and the degree of personalization are factors contributing to an attribution or projection of one's own body perception to the perception of a virtual human. However, with our experimental design, we could only show that the feeling of embodiment influences the body weight perception of virtual humans. We suggest performing an additional experiment considering the impact of embodiment on BWM with regard to the degree of personalization in order to further explore those factors. Moreover, it seems necessary to explore other potential factors that could moderate virtual humans' body weight perception (e.g., avatar appearance [68] or situational cues [38]). It also raises the question of whether other body or mental properties exist that moderate the perception of a virtual human when feeling related to it (e.g., self-similarity).

It has yet to be clarified by which factors the aforementioned attribution or projection is exactly influenced. The effect discovered, however, raises the question of whether our perception can also be influenced reciprocally by a virtual human displaying high identity conformity with the user, through, for example, personalization or by an embodiment illusion. Corresponding studies without the use of photorealistic virtual humans and accurate body weight estimations [24, 34, 36, 40], as well as research on the Proteus effect [43, 69], support the assumption that the user's body weight perception can be affected by the virtual humans appearance. Therefore, future work should further focus on investigating the interplay between one's own body weight perception and the suggested properties of virtual humans. For this purpose, it seems reasonable to compare the perception of one's own body size before and after the exposure [24] and to put these results in relation to the perception of the virtual human. A clear limitation regarding the absolute body weight perception concerns the approach of uniform virtual human scaling, which was mainly used in our work to maintain comparability with Wolf et al. [67]. We could show that the scaling of the virtual human influenced the estimation of body weight in our two conditions but did not differ between them. Although the absolute estimates were slightly affected by the approximation of the virtual human's BMI, it had no effect on the comparisons between the conditions nor on the effects discovered. Nevertheless, future research should aim to use more realistic scaling approaches, for example, by using statistically trained mesh deformation models [39], which could also be used to modify the body weight of the virtual humans. Such models also provide the basis for research on body weight perception of personalized virtual humans and allow multiple estimations based on only one repeatedly modified virtual human.

7.2 Presence and Embodiment

Regarding presence, we hypothesized that participants in the embodiment illusion condition will report a significantly higher feeling of presence than participants in the no embodiment illusion condition (H2.1). While the scores of the IPQ significantly supported our assumption, the in virtuo presence did not differ significantly between the two conditions. Therefore, we mainly confirm our hypothesis. When looking at our results, the reliability and validity of single-item measurements for presence might be questioned in order to explain the inconsistency within the results. A single-item measure does not address all the different subtleties of presence as noticed already by other researchers [66] and suggests using full questionnaires in virtuo as recommended by recent research [50]. Our results also show the difficulties of presence's subjective assessment and underline the importance of more objective measurements in research [52].

For embodiment, we measured VBO and agency with two in vitro embodiment questions and the VEQ to assess the strength of our experimental manipulation between conditions. Consequently, we expected higher values in VBO (H3.1) and agency (H3.2) in the embodiment illusion condition compared to the no embodiment illusion condition. For VBO, we could show significantly higher scores in the in virtuo question but no significant difference for VBO in the VEQ. Regarding agency, we positively support our hypothesis (H3.2) as participants reported a significantly higher agency in both measurements. In general, we consider our embodiment manipulation to be successful.

As mentioned above, our manipulation of the embodiment illusion significantly impacted body weight perception and partially impacted the measurements of the feelings of presence and embodiment. Therefore, we decided to explore the potentially mediating effects of presence, VBO, and agency on the relationship between condition and body weight perception. However, the mediator analysis did not show a significant indirect effect of those measurements on body weight perception. Therefore, further exploration of potentially mediating factors is suggested for future work.

7.3 Limitations and Future Work

Our work provides interesting new insights into the influences of an embodiment illusion on body weight perception in VR. However, we have also identified some limitations and directions for further research. First, we assume in our work a self-attribution of the virtual body and thus an association of the self with the virtual human triggered by different moderators, such as the feeling of embodiment or avatar personalization. However, no psychometric factors mediating the association have been identified to date. Future research should (a) systematically test the identified, potentially moderating factors and (b) in addition to our factors, explore potential mediators such as self-identification, emotional connectedness, and perceived similarity.

Second, our study was limited to body weight estimations of a single, non-personalized, virtual human scaled to the participants' body height. However, estimations for a single virtual human strongly depend on its appearance and its model. We used a person of average weight wearing simple clothing without additional accessories. Nevertheless, when using non-personalized avatars, it suggests performing estimations multiple times with uniquely generated or body weight-modified virtual humans. Additionally, the uniform scaling we performed introduced the bias of showing taller participants avatars with higher BMI and vice versa. Future experiments should consider more realistic scaling approaches and body weight self-assessment through modified, personalized avatars.

Third, in our no embodiment illusion condition, participants had no virtual body at all. This led to two inconsistencies between conditions: (a) Participants having no embodiment illusion did not have an egocentric perspective on their body and therefore (b) could not alternately look at their virtual bodies directly and via the mirror. Future work should therefore add another condition, in which participants have a virtual body but still need to estimate the body weight of a other virtual human.

Fourth, we conducted our experiment with a relatively small sample of young and healthy female participants. Future research should consider extended samples, including participants suffering from eating- and body weight disorders within the full range of age groups and also male participants.

8 Contribution and Conclusion

To the best of our knowledge, our work is the first to investigate the influence of the embodiment of photorealistic, non-personalized avatars on female body weight perception in VR, considering the impact of the participant's BMI. Contrary to prior work, we used body weight estimations of photorealistic virtual humans with known BMI as an explicit measurement quantifying the differences in body weight perception between conditions and to determine the influence of participant's BMI on the estimations. Using this approach, we could show that an illusion of embodiment highly impacts the perception of non-personalized virtual humans. Our results also indicate that more research is necessary to explore the numerous possible technology-related factors that could affect one's body weight perception when using VR systems, to ensure safe and accurate use in supporting the therapy of body weight misperception, and to further explore body weight perception. The knowledge gained contributes principally to the understanding of our human body weight perception and particularly to the understanding of the perception of virtual humans within VR.

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