Body Weight Perception of Females using Photorealistic Avatars in Virtual and Augmented Reality

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Figure 1: The figure shows the experimental environment for AR (left) and VR (right) from an observer's perspective. Participants had to guess the body weight of their avatar after performing five different movement tasks.

Abstract

The appearance of avatars can potentially alter changes in their users' perception and behavior. Based on this finding, approaches to support the therapy of body perception disturbances in eating or body weight disorders by mixed reality (MR) systems gain in importance. However, the methodological heterogeneity of previous research has made it difficult to assess the suitability of different MR systems for therapeutic use in these areas. The effects of MR system properties and related psychometric factors on body-related perceptions have so far remained unclear. We developed an interactive virtual mirror embodiment application to investigate the differences between an augmented reality see-through head-mounted-display (HMD) and a virtual reality HMD on the before-mentioned factors. Additionally, we considered the influence of the participant's body-mass-index (BMI) and the BMI difference between participants and their avatars on the estimations. The 54 normal-weight female participants significantly underestimated the weight of their photorealistic, generic avatar in both conditions. Body weight estimations were significantly predicted by the participants' BMI and the BMI difference. We also observed partially significant differences in presence and tendencies for differences in virtual body ownership between the systems. Our results offer new insights into the relationships of body weight perception in different MR environments and provide new perspectives for the development of therapeutic applications.

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1 Introduction

In a wide variety of mixed reality (MR) applications avatars serve as digital representations of individual users [3]. The appearance of these avatars can have a significant impact on the user's experience and self-perception within a virtual environment (VE) [70]. Beyond the impact within the VE, the Proteus effect suggests that "[...] an individual's behavior conforms to their digital self-representation independent of how others perceive them", which in turn can lead to altered perception, attitude, and behavior even after the virtual experience [50, 72]. Those effects are particularly interesting for the development of MR systems to support the therapy of body related misperceptions. Self-perception, or rather misperception, and in particular body weight misperception, are important topics for body weight disorder therapy, as researcher showed that patients who suffer from obesity tend to underestimate their body weight [35] while anorexia nervosa patients tend to overestimate it [41]. The treatment of body weight disorders often includes cognitive-behavioral therapy with the aim to readjust body weight misperceptions. In general, MR has been proven to support, improve, or even replace existing therapy approaches for various mental disorders [40]. Based on the idea that the appearance of avatars can influence body perception, various therapeutic scenarios are imaginable, particularly for distortions of body perception as a symptom of eating disorders. Systematic real-time modulation of photorealistic and personalized avatars of the patient could be used to visualize the achieved therapeutic successes, the existing body image discrepancies, or the consequences of the patient's behavior [14].

An essential prerequisite for such therapeutic MR systems is that the system itself affords a realistic visual perception of the avatar for users. In addition, different MR systems applied in therapeutic settings should afford a comparable degree of precision. However, due to the methodological heterogeneity, recent research on body size and body weight perception does not allow to conclude on the effects of MR system properties and MR-related psychometric factors (e.g., using systems with different degrees of immersion, including different mediating variables), making a suitability assessment of the systems for therapeutic usage difficult. Table 1 presents a summary of related studies and their system parameters and measurements. Consequently, the question arises on how MR systems themselves and their related psychometric factors affect body weight perception.

The present paper aims at answering parts of this question by conducting a systematic comparison of a lower-immersive augmented reality (AR) see-through HMD system and a higher-immersive VR HMD system. Both systems are considered to support body distortion therapy in a research project. Since our work focuses on the effect of system differences on body weight perception, other environmental factors need to be controlled as best as possible. For this purpose, we re-modeled our physical environment as virtual replication to present similar environments in both conditions. In our experiment, normal weighted female participants embodied a photorealistic avatar using one of both systems. In both systems, the avatar could be observed from an allocentric perspective in a virtual mirror and moved synchronously to the subjects' body movements. Thus, the systems differed only in the degree of immersion resulting from the differences between the virtual and real environment observed from the egocentric perspective. As shown in Fig. 1, these differences are also reflected in the body representations (real body vs. avatar). Participants had to perform five visuomotor tasks to induce the feeling of embodiment and were then asked to estimate the body weight of their avatar. According to the importance of the sense of presence and embodiment on self-perception in MR [50], participants answered questions about the feeling of both. Additionally, we controlled for the potentially confounding factors self-esteem, body image disturbance, gender, simulator sickness, the participant's BMI, and the BMI difference between the participant and their avatar [58, 64]. In summary, we investigated the differences in the influence of an AR see-through HMD and a VR HMD on the perception of body weight, presence and embodiment in relation to the BMI of the participants.

2 Related Work

2.1 Immersion and Presence

VEs generated by MR systems provide the user the feeling of being surrounded by a computer-generated artificial virtual world. One indicator of the extent to which a MR system can support natural sensorimotor contingencies for perception is the system's immersion. Immersion is defined as an objective property of a MR system [60]. It includes the response to a visual perceptual action or aspects such as the display's resolution and its field of view. Slater and Wilbur defined immersion as the "[...] extent to which a display system can deliver an inclusive, extensive, surrounding, and vivid illusion of virtual environment to a participant." [62]. This emphasizes that immersion comprises technical aspects of a system and not the subjective reaction of its users. Along Milgram's reality-virtuality continuum [39], a variety of systems with varying degrees of immersion are defined. Fully immersive VR systems include virtual visual perception via HMDs using solely virtual elements. However, there are also less-immersive systems within the broad field of MR. AR systems combine both real and virtual elements. One way to experience AR is realized by video see-through [17]. Here, the HMD augments a camera-based view on the real surroundings by virtual elements. There are also optical see-through devices. However, commercially available devices provide only a narrow field of view and limited computing power [36, 37]. While being close to fully immersive VR HMD systems, AR HMDs might still offer less immersion by a decreased feeling of being surrounded by a virtual world due to their lower inclusivity and potential interference from the real environment. With regard to the reality-virtuality continuum, we compared in our work a lower-immersive camera-based AR see-through HMD with a higher-immersive VR HMD.

While the physical properties of a system define immersion, presence is a subjective response to the provided VE [59]. It describes the feeling of being inside a VE and is therefore rather a perceptual than a cognitive illusion [60]. When instantiating behavioral changes through credible stimuli in therapy-supporting VR systems, a high level of presence has proven to be particularly important [30, 56]. Additionally, a high level of presence has been shown to increase spatial perception and therefore might also influence body weight perception [20, 51]. Even though immersion and presence are clearly distinguished, there is a certain relationship between the two concepts. In a meta-review, Cummings and Bailenson showed that immersion has a medium-sized effect on presence [11]. In a more recent work closely related to the present investigation, Waltemate et al. showed a clear influence of immersion on presence in a virtual embodiment experiment [70]. By following the literature, it is crucial to provide a highly immersive system that offers a high degree of presence to provide a VE that causes changes in the perception of body weight. To test whether the two systems actually induce a different level of presence, our first hypothesis is as follows:

H1: Participants using the AR see-through HMD will report a lower feeling of presence than participants using the VR HMD.

2.2 Embodiment

One essential component within a VE is the user's virtual representation, the avatar. To create the illusion of being represented by a virtual avatar, the behavior of the avatar is of crucial importance. Ideally, it should react to the user's control input in real-time and exactly as intended by the user [3]. The feeling of being inside an avatar, to own an avatar, and to control an avatar often is called sense of embodiment [29]. The concept of embodiment dates to the essential findings of the rubber hand illusion and describes the incorporation of external objects into the own body schema through visuotactile coherence [6, 66]. Later research replicated these findings in VR [24], extended it to the incorporation of full-body representations [61], and showed that visuomotor coherence can also achieve the feeling of embodiment [61]. Embodiment can be divided into several sub-concepts. Of particular interest to our work are virtual body ownership (VBO) and agency. While VBO is the subjective experience to self-attribute a virtual body, the concept of agency describes the subjective experience of having control of a body [29]. By maintaining high VBO and agency, the credibility of the embodiment illusion increases and leads to a higher acceptance of the virtual body as one's own body. A high acceptance can then be used to initiate perceptual or attitudinal changes through avatar modification. In an HMD-based VR environment, Normand et al. [45] showed that egocentric embodiment within an avatar with increased belly size can cause differences in the self-assessment of belly size before and after inducing the feeling of embodiment. Additionally, Banakou et al. showed that VBO can have a considerable impact on spatial perception, which might reflect in an impact on the perception of the body dimensions and thus on body weight perception [4].

In turn, various different psychometric factors have been identified to influence embodiment [31, 32, 34, 70, 71]. For example, in a comparison between a HMD VR and a projector-based large stereoscopic AR display, Waltemate et al. [70] found that the higher the degree of immersion, the higher the perceived VBO. In their experiment, agency was also influenced by the immersion of the system. However, we assume that this effect was mainly caused by the different display devices used (VR HMD vs. AR projector).

Table 1: The table shows related work on body dimension perception. It contains information about the display used (*AR projector = projector-based large stereoscopic AR display*), the perspective used (*E = egocentric, A = allocentric*), the embodiment stimulation technique used (*VT = visuotactile, VM = visuomotor*), the avatar personalization (*personalized, non-personalized*), and the sample used (F = female, M = male). It also shows how body dimensions (BD) were assessed (*S = body size, W = body weight*) and whether presence (PR) and embodiment (EM) were captured.

Study	Immersion	Embodiment		Avatar	Sample	Measurements		
	Display	Perspective	Stimulation	Personalization	Gender	BD	PR	EM
Mölbert et al. [42]	AR projector	A	–	✓	F	W	–	–
Piryankova et al. [47]	AR projector	A	–	✓	F	W	–	–
Thaler et al. [65]	AR projector	A	–	✓	F, M	W	–	–
Thaler et al. [64]	AR projector	A	–	✓	F	W	–	–
Nimcharoen et al. [44]	AR optical see-through HMD	E, A	VM	✓	F, M	W	✓	✓
Keizer et al. [26]	VR HMD	E	VT	–	F	S	–	✓
Normand et al. [45]	VR HMD	E	VM, VT	–	M	S	–	✓
Piryankova et al. [48]	VR HMD	E	VT	–	F	S	–	✓

Therefore, we assume that two systems with similar display devices (HMD vs. see-through HMD) do not lead to differences in agency. Based on this, we propose for embodiment the following hypotheses:

- H2.1: Participants using the AR see-through HMD will report a lower feeling of VBO towards their avatar than participants using the VR HMD.
- H2.2: Participants using the AR see-through HMD will perceive a similar feeling of agency towards their avatar than participants using the VR HMD.

2.3 Body Weight Perception

The general findings of embodiment research form the basis for research on body perception in MR. Since MR systems allow for various experimental manipulations that cannot be achieved in reality (e.g., rapid body weight changes), they offer the possibility for further exploration how body weight is perceived. For example, prior research found that avatar personalization and the participant's body weight can have a great impact on the perception of body weight [42, 47, 64, 65] and showed a general body weight underestimation of participants' avatars [44, 47, 64]. Other works showed that participants can develop a considerable sense of embodiment towards avatars with modified belly size and even that body size perception temporarily can be modified [26, 45, 48]. Table 1 summarizes methodologies and measurements of the mentioned works. Thaler et al. [64] recently found that the own body weight serves as a linear predictor for body weight estimation of personalized non-embodied avatars in a female population. Mölbert et al. [42] confirmed these findings for underweight females. The researchers surprisingly could also not replicate the widespread assumption that patients with anorexia overestimate their body weight [41]. This contradicts the results of years of eating disorder research and suggests that a MR system's properties might have an influence on body weight perception. Also with subjects classified as having normal weight, several studies showed a general underestimation of the body weight of personalized and weight-modified avatars [42, 47, 64].

To the best of our knowledge, existing research regarding body weight perception has not systematically explored how different MR systems influence body weight perception in VEs. As can be seen in Table 1, the heterogeneity of previous performed experiments does not allow any comparisons across experiments regarding the influence of the system's parameter on the perception of body weight. However, there are indications that this could be the case. While a system's immersion is expected to influence presence and embodiment, research indicates that latter factors might impact spatial perception [4, 20, 51]. Based on these findings, we consider that spatial perception, in turn, might influence the perception of body weight, leading to the assumption that presence and embodiment could have a mediating function on body weight perception. Our suggested influences on body weight perception are summarized in Fig. 2. Therefore, it seems crucial to clarify which factors influence the perception of body weight in which way. According to our related work, we propose for body weight perception the following hypotheses:

- H3.1: Participants within a healthy BMI range will underestimate the avatar's body weight regardless of the used system.
- H3.2: Participants will estimate the avatar's body weight differently (a) depending on their own BMI and (b) moderated by the usage of the AR see-through HMD compared to the VR HMD.

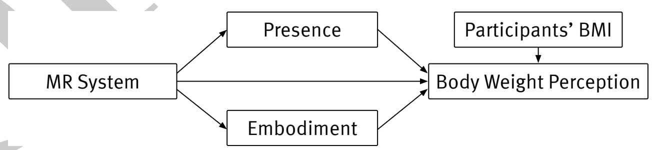

Figure 2: The figure illustrates our assumed influences on body weight perception in VEs.

3 System Description

To test our hypotheses, we developed an interactive system that supports an AR see-through HMD and a VR HMD. Within the VEs provided by the system, the participants embody a generic photorealistic avatar from an egocentric perspective. To induce the feeling of embodiment, the participants' movements are continuously captured and used to animate their avatar in real-time. To support visuomotor coupling, participants can observe themselves from an allocentric perspective by looking into a virtual mirror. We used Unity 2019.1.10f1 [67] to integrate the four components explained in the following. The system architecture is depicted in Fig. 3.

3.1 Tracking Component

A convincing embodiment system requires a robust and rapid tracking of the participant's body pose to transfer the movements to the corresponding avatar continuously. Choosing an appropriate tracking technology is always a compromise between different factors such as the tracking quality, tracking speed, preparation effort, naturalness, precision, and costs in consideration of the intended use case. Different works suggest using a full-body tracking system for retargeting the captured body pose as accurately as possible on the used avatar [63, 70]. However, the retargeting of a full-body tracked source skeleton on a target skeleton with different body proportions cause problems like end-effector position offsets and

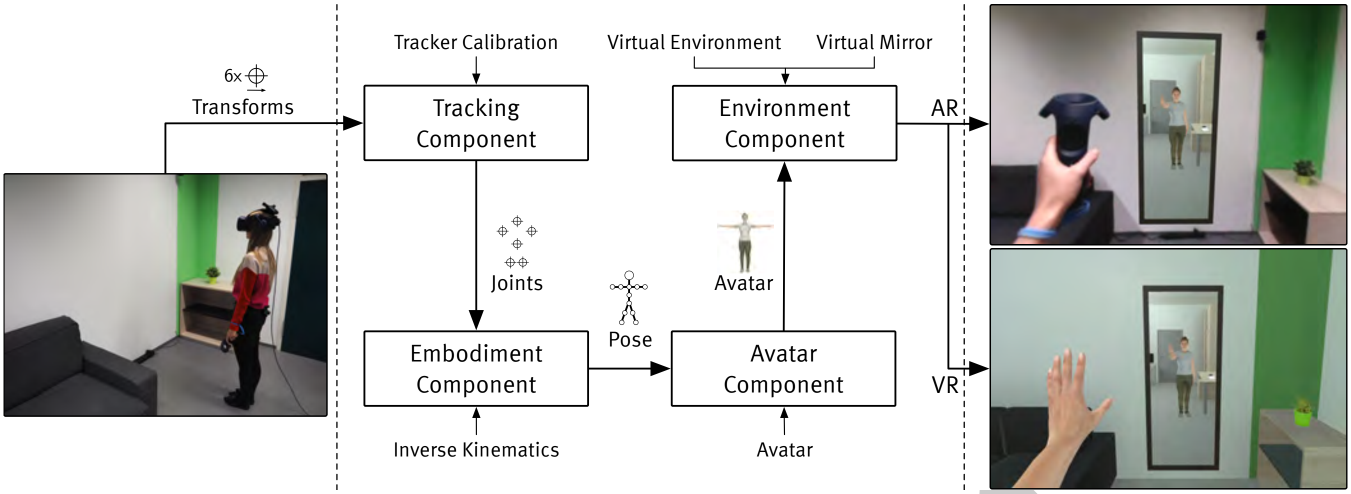

Figure 3: The figure illustrates the system's architecture ranging from the input layer (left) to the output layer (right). The input layer shows a participant located in the real environment wearing the required tracker. Six tracker transforms are passed to the process layer (middle) where the scene is rendered. In the output layer, the resulting virtual and augmented reality is shown from the participant's egocentric perspective.

sliding feet. As a result, a strong discrepancy between the positions of the end-effectors in the VE and the real world could lead to a break in the illusion of embodiment. To avoid these problems, we used the inexpensive, robust, and easy to use SteamVR [68] tracking system in combination with inverse kinematics (IK) [2].

Our setup consisted of four SteamVR Base Stations 2.0, the HTC Vive Pro HMD, two HTC Vive Controllers, and three HTC Vive Trackers [22]. The SteamVR tracking system provides a rapid (22ms) and accurate (within a sub-millimeter range) [43] infrared-based body tracking for the head, left hand, right hand, pelvis, left foot, and right foot with a sampling rate of 1000 Hz. By the use of this setup, head and body tracking are provided by using the same tracking space. Therefore, no alignment of different tracking spaces is required. To stream the tracking positions into our Unity application, we use SteamVR version 1.9.5 [68] and its corresponding Unity plug-in. The plug-in provides transforms (position and orientation) for the six tracking devices in use. To identify the position of the tracker on the body parts, we use a custom calibration algorithm which requires the user to stand in an upright pose and spread out the arms horizontally, called T-pose. The transforms are then assigned to the body parts (also called joints) according to their positions from top to bottom and from left to right (e.g., the first transform belongs to the head). After the calibration is successfully performed and saved, the joint transforms are passed continuously to the embodiment component as long as the user is tracked.

3.2 Embodiment Component

The embodiment component generates a Unity compatible humanoid body pose on the base of the six received joint transforms. As Unity requires 15 joint transforms to generate a valid body pose, the missing nine joints need to be approximated by following the anatomical characteristics of the human body using IK. To this end, we use the Unity plug-in FinalIK version 1.9 [52], which provides a full-body inverse kinematics solver for VR applications. It needs at least the six before-mentioned transforms to create a valid body pose. Further optional elbow and knee tracker could complement the mandatory joint transforms to enable more faithful animations. However, a larger number of trackers also increases the complexity of the system, the vulnerability to malfunction, and leads to higher preparation times. We considered our implemented 6-point body tracking to be sufficient for the intended use case.

3.3 Avatar Component

The avatar component is used to animate a generic photorealistic avatar that was generated during the development process. We decided to use the same non-personalized generic avatar for each participant to allow for a comparison of body weight estimations between our participants. Fully personalized avatars do not allow for body weight estimations since human beings are usually aware of their own body weight. The same task also leads to the restriction that we could not scale the avatar's limbs according to the user's limbs. When scaling the limbs, the body dimensions of the avatar would change, and the estimations would become less accurate. To generate the generic avatar, we used the pipeline for fast generation of photorealistic looking human 3D models introduced by Achenbach et al. [1]. The pipeline is set up in a laboratory of the HCI Group at the University of Würzburg and consists of a circular rig on which 106 DSLR cameras are mounted. For our evaluation, we hired a female model with a normal BMI of 22.25 at a body size of 1.68 m and a body weight of 62.8 kg. The model was scanned by triggering all cameras synchronously to capture pictures from 106 different perspectives. A dense point cloud was then generated from these images, and a fully rigged generic human 3D template was fitted onto the point cloud. After the model generation, a high-quality texture was generated from the model geometry, the corresponding texture layout, and the pictures. The original model, as well as the generated 3D model, are shown in Fig. 4. During our evaluation, the avatar was always uniformly scaled according to the participant's body height. The scaling factor s was calculated as

$$s = \frac{\text{Participant height}}{\text{Model height}}. \quad (1)$$

3.4 Environment Component

The purpose of the environment component is to manage the virtual objects (e.g., avatar, environmental objects, virtual mirror) within the VE and to make it available as AR or VR experience. In both of our conditions, the VE is displayed using a HTC Vive Pro HMD [22], which provides a resolution of 1440×1600 pixels per eye, a field of view of 110 degrees, and a refresh rate of 90 Hz. The motion-to-photon latency of our VR setup measured by a Casio EX-ZR200 high-speed camera was around 50 ms. During our evaluation, the VE was controlled by an evaluation script that modified the VE according to the experimental procedure.

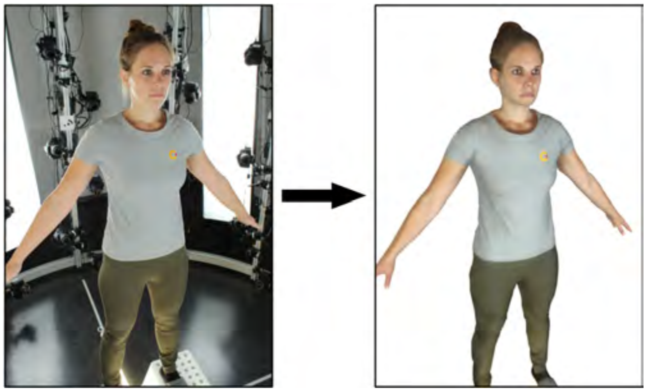

Figure 4: The figure shows one of the 106 pictures taken from the model (left) and the generated avatar (right).

3.4.1 Virtual Environment

To implement our virtual environment, we used the same virtual objects as Eckstein et al. for their reflected reality experiments [15, 16]. For their work, they rebuilt a physically existing laboratory at the University of Würzburg using the 3D modeling software Blender version 2.79 [5]. The result is a virtual representation of the laboratory that looks very similar to the real one (see Fig. 1 and Fig. 3). We adapted this virtual laboratory for our experiment and added a virtual full-body mirror to enable participants to observe their avatar from an allocentric view [13]. In both cases, the replicated virtual laboratory serves as background for the mirror reflection.

3.4.2 AR See-Through HMD System

In the AR see-through HMD system configuration, participants can observe the real environment and their real body from an egocentric perspective. The perspective is captured by the two see-through front-cameras of the HTC Vive Pro and rendered stereoscopically using Unity and the Vive SRWorks SDK version 0.8.5.0 [23] together with SteamVR. The only virtual object within the presented AR environment is the virtual mirror in front of the participant used to enable participants to observe their virtual representation also from an allocentric perspective. When using the virtual mirror within our AR representation, we use the generated VE only to render the background of the virtual mirror reflection. This is necessary, as the front cameras of the HTC Vive only capture the view of the participant and not what is behind it. A screenshot of the participant's egocentric perspective is shown as upper system output of Fig. 3. Additionally, an allocentric perspective is depicted in Fig. 1 (left). The used see-through cameras provide images with a resolution of 640×480 pixels per eye and a refresh rate of 60 Hz. However, the virtual elements are rendered in the prior described quality of the HTC Vive Pro. Therefore, the quality of AR and VR conditions differed in resolution, illumination, and latency of the environment, but not in the quality of the virtual objects. The motion-to-photon latency of the see-through components was 133 ms on average.

3.4.3 VR HMD System

In the VR system configuration, participants are fully immersed into our VE. They can see the whole VE and their avatar from an egocentric perspective. The perspective is rendered stereoscopically using Unity and SteamVR. Identically to the AR environment, a virtual mirror in front of the participant is used to enable participants to observe their virtual representation from an allocentric perspective. A screenshot of the participant's egocentric perspective is shown as the lower system output of Fig. 3. Additionally, a allocentric perspective is depicted in Fig. 1 (right).

4 Evaluation

4.1 Design

We used a between-subject design with the independent variable being the *used system configuration* and varied between the *AR see-through HMD* and the *VR HMD*. The dependent variables were divided into *presence*, *embodiment*, which were rated both in virtuo (IV) and post-experience, and *body weight misestimation (BWM)* of the avatar's BMI in relation to the avatar's real BMI in virtuo. We controlled BWM using the participant's BMI and the BMI difference between participant and avatar. Additionally, we captured signs for simulator sickness, self-esteem, body image distortion tendencies as well as demographic data of the participants, including their body measurements. A further explanation of the measurements can be found in the next section.

4.2 Measurements

Except the in virtuo questions, all conducted questionnaires were presented through the online survey tool LimeSurvey 3 [33] and answered using an Asus Zenbook UX303L running Windows 10. In virtuo questions were answered orally during immersion. To conduct the questionnaires with German participants, we either used existing validated German versions or translated the questions to the best of our knowledge.

4.2.1 Presence Measurements

Since in virtuo presence measurements are considered as the most accurate measurements of presence [8], we captured presence during immersion with a one-item questionnaire [7]. The following question was answered on a scale between 0 and 10 (*10 = highest presence*) directly after finishing the last experimental task:

Presence: *"On a scale from 0 to 10, to what extent do you feel present in the virtual environment right now? Presence is defined as the subjective impression of really being in the virtual environment."*

As the outcomes of a one-item questionnaire cannot be compared to the outcome of a full presence questionnaire regarding validity and reliability [8], we also used the IPQ [57] to capture presence post-immersion. The IPQ consists of 14 questions divided into four different dimensions, which are the general presence (GP), spatial presence (SP), involvement (INV), and realism (REAL), each rated on scales from 1 to 6 (*6 = highest presence*).

4.2.2 Embodiment Measurements

For measuring embodiment, we follow the definition of Roth & Latoschik [54], dividing the feeling of embodiment into three dimensions: virtual body ownership (VBO), agency (AG), and change (CH). VBO and AG follow our introduced definitions. CH is defined as the degree to which participants feel a difference between their own body and their virtual body. Following Waltemate et al. [70], we chose one question for VBO and one for AG for the in virtuo measurement [25]. In line with the in virtuo presence question, the VPs rated the two in virtuo embodiment questions on a scale from 0 to 10 (*10 = highest VBO, AG*) directly after finishing the presence question as follows:

VBO: *"On a scale from 0 to 10, to what extent do you feel that the virtual body you see in the mirror is your body?"*

AG: *"On a scale from 0 to 10, to what extent do you feel that the virtual body in the mirror moves as you want it to as if it obeys your will?"*

Embodiment was measured post-immersion with the virtual embodiment questionnaire (VEQ) [54]. The participants assessed four items for each of the VEQ's dimensions (VBO, AG and CH) on a scale from 1 to 7 (*7 = highest VBO, AG, CH*).

4.2.3 Body Weight Measurements

For each participant, we captured body weight and body height using the professional scale MPE 250K100HM from Kern [28] and calculated the participant's BMI as

$$\text{Participant BMI} = \frac{\text{Participant weight}}{(\text{Participant height})^2}. \tag{2}$$

Additionally, participants estimated the body weight of their uniformly scaled and height-matched avatar. The estimations were captured as an in virtuo question directly after presence and embodiment questions by using the following phrase:

BWM: *"Can you estimate the body weight of the virtual body in the mirror in front of you?"*

The *estimated* BMI of the scaled avatar was calculated according to Equation 2 from the estimated avatar's weight and the scaled avatar's height. The *true* BMI of the avatar was computed by replacing the estimated weight by the "true weight" of the scaled avatar. Since the height-matched avatar was generated by *uniformly* scaling the scan of the model by a factor s (see Equation 1), the avatar's body volumes scales cubically by s^3. Assuming unchanged mass density distribution, the avatar's weight also scales by s^3. This leads to the simple equation for the scaled avatar's BMI:

$$\begin{aligned} \text{Avatar BMI} &= \frac{\text{Avatar weight}}{(\text{Avatar height})^2} \\ &= \frac{s^3 \cdot \text{Model weight}}{(s \cdot \text{Model height})^2} \\ &= s \cdot \text{Model BMI}. \end{aligned} \tag{3}$$

Our measure for BWM was based on the relative difference between the avatar's estimated and true BMI, and was calculated as

$$\text{BWM} = \frac{\text{Estimated BMI} - \text{Avatar BMI}}{\text{Avatar BMI}}. \tag{4}$$

A negative value states an underestimation, a positive value an overestimation. Furthermore, we calculated the relative difference between the participant's BMI and the avatar's true BMI as

$$\text{BMI Difference} = \frac{\text{Participant BMI} - \text{Avatar BMI}}{\text{Avatar BMI}}. \tag{5}$$

A negative or positive value indicates that the participant was lighter or heavier than the avatar, respectively.

4.2.4 Control Measurements

We captured self-esteem, body shape concerns, and simulator sickness to control potentially interfering factors. Since self-esteem is considered to have a strong relationship with eating and body weight disorders [58], we monitored the participants' self-esteem as potentially confounding factor between conditions. For this purpose, we used the well-established Rosenberg self-esteem scale (RSES) [19, 53, 55]. The score of the questionnaire ranges from 0 to 30. Scores below 15 indicate low self-esteem, scores between 15 and 25 can be considered as normal, and scores above 25 indicate high self-esteem.

Another potential confounding factor between conditions is the attitude towards the own body. We measured participants' tendencies for body shape concerns by the use of the validated shortened form of the body shape questionnaire (BSQ) [10, 18, 49]. The score is captured with 16 different items ranging from 0 to 204 (*204 = highest concerns*).

As a last potentially confounding factor, we captured the feeling of simulator sickness by use of the simulator sickness questionnaire (SSQ) [27]. It captures the presence and intensity of 32 different symptoms associated with simulator sickness and is carried-out as pre- and post-measurement. An increase in the calculated total score between pre and post-measurement indicates the occurrence of simulator sickness. The total score of the questionnaire ranges from 0 to 2438 (*2438 = strongest simulator sickness*).

4.3 Tasks

Five simple motor tasks, similar to the ones of Waltemate et al. [70], were used to induce embodiment by synchronous visuomotor stimulations. All tasks were performed in the VE while seeing the allocentric view of the avatar in the virtual mirror. To control the execution of the tasks, all tasks were guided by the use of visual and auditory instructions in virtuo. The virtual mirror in front of the avatar was only turned on when the tasks should be performed. The tasks were instructed as follows:

T1: "Please raise your dominant hand and wave in a relaxed manner towards your reflection."

T2: "Please raise your non-dominant hand and wave in a relaxed manner towards your reflection."

T3: "Please walk in place. Raise your knees up to the height of your hips again and again."

T4: "Please stretch out both arms straight in front of your body and move them in a circle."

T5: "Please stretch your arms to the left and right and move your hips alternately to the left and right side."

The following sentence accompanied each task instruction: "Please look alternately at the movements of your mirror image and your body."

4.4 Participants

We recruited 58 female BA students of human-computer-interaction or media communication of the University of Würzburg, who received course credit for participation. Since the perception of body weight is subject to gender-specific differences and seems to be more common among females, we decided to examine females first [9, 21, 46]. Additionally, we wanted to increase comparability with prior work (c.f. Table 1). Prior to our experiment, we defined the following exclusion criteria: (1) participants had to have correct or corrected to normal vision and hearing; (2) participants should have at least ten years of experience with the German language; (3) participants should not have suffered from any kind of mental or psychosomatic disease, or from body weight disorders; and (4) participants should not have a known sensitivity to simulator sickness. Three participants were excluded because they met the exclusion criteria, and another one was excluded for technical reasons, leaving 54 participants. The participants were randomly assigned either to the AR or to the VR condition, having 27 participants in each group. None of the participants in both conditions used VR applications for more than 20 times before. For analyzing the body weight perception, we had to exclude one more participant from each group, as they exceeded a BMI of 30 and were therefore considered as obese (see Table 2 for descriptive statistics). None of the participants had to be excluded due to rising simulator sickness during the experiment.

Table 2: Statistics of the participants used for the body weight perception analysis.

	AR ($n = 26$)		VR ($n = 26$)		
	Range	M (SD)	Range	M (SD)	p
Age	18–29	20.4 (2.4)	18–22	19.7 (1.1)	.187
BMI	17.2–26.5	21.8 (2.6)	17.2–27.2	22 (1.7)	.741
RSES	9–29	22 (4.5)	9–30	23.1 (4.7)	.418
BSQ	40.4–125.4	80 (26.4)	40.4–148.8	79.5 (26.8)	.939

4.5 Procedure

Participants were tested in individual sessions following a controlled experimental procedure visualized in Fig. 5. After participants arrived, they read the experimental information, gave consent, and started-up with a first questionnaire phase. Afterwards, the exposure phase followed. The experimenter demonstrated each participant how to fit the HTC Vive HMD and the tracking devices and made sure the participant wore it correctly. The exposure followed a pre-programmed logic that automatically played and displayed the instructions of the calibration, tasks, and questions. For calibration of the system, the virtual mirror was turned off. After calibration, participants were told explicitly that the avatar was scaled to their exact body height. The mirror was always turned on as soon as instructions for a task started to play and was turned off when the participant had to stop the task. After the exposure, participants continued with questionnaires and body measurements were performed. The whole procedure took around 35 minutes per participant. The average exposure time in the virtual environment was 7.78 minutes. For the exposure phase and for the body measurements, participants had to take off their shoes.

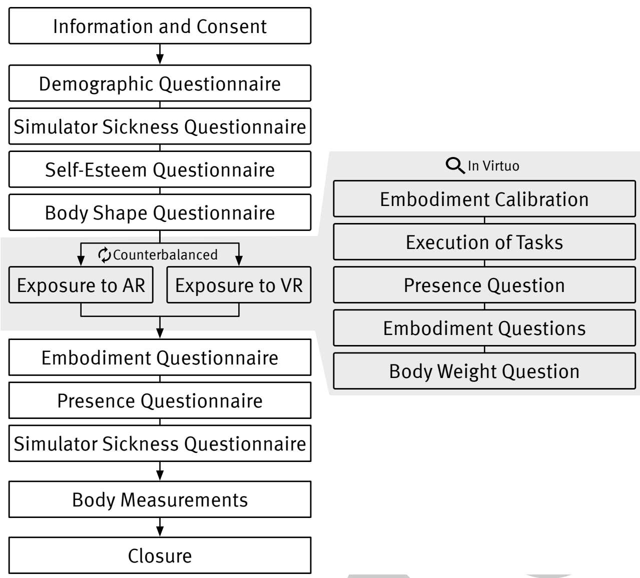

Figure 5: Flowchart for visualizing the controlled experimental procedure and giving an overview of the performed measurements.

5 Results

The descriptive results of our evaluation are shown in Table 3. Before we conducted the main analyses, we performed a test of normality and homogeneity of variances for all variables to determine whether the data met the requirements for parametric testing. Concerning presence and embodiment, the pre-assumptions for parametric testing were violated in some cases. Thus, we conducted one-sided (H1, H2.1) and two-sided (H2.2) Mann-Whitney-Wilcoxon tests with effect size r for those measurements. To test whether the participants' estimations differed from the avatars' actual body weight (H3.1), we tested two one-sided one-sample t-tests, as the data on BWM met the criteria for parametric testing. To test the last hypothesis (H3.2), we calculated a multiple linear regression to predict BWM based on the centered participants' BMI and the condition (AR HMD vs. VR HMD). The model met all criteria for parametric testing. For H2.2, we expected a similar result for the two conditions and therefore, the alpha level was adjusted to α = .20 to have better control for the probability of false-positive test results. The other variables were tested against a non-adjusted α of .05.

Table 3: The table shows the descriptive values for the results.

		AR		VR	
		n	M (SD)	n	M (SD)
Presence	IV	27	6.22 (1.8)	27	6.74 (1.53)
	IPQ G	27	3.74 (1.48)	27	4.26 (1.20)
	IPQ SP	27	3.78 (1.22)	27	4.32 (0.74)
	IPQ INV	27	2.19 (1.01)	27	2.78 (1.15)
	IPQ REAL	27	2.74 (0.84)	27	2.83 (0.83)
	IPQ total	27	3.16 (1.01)	27	3.53 (0.71)
Embodiment	IV VBO	27	4.52 (2.49)	27	4.93 (2.23)
	IV AG	27	7.7 (1.75)	27	8.0 (1.39)
	VEQ VBO	27	3.89 (1.39)	27	4.2 (1.2)
	VEQ AG	27	5.95 (0.79)	27	5.94 (0.54)
	VEQ CH	27	3.55 (1.56)	27	3.72 (1.48)
Body Weight	BWM	26	-6.84 (11.7)	26	-3.25 (8.81)

5.1 Presence

Contrary to our hypothesis H1, neither the in virtuo presence question, $U(27,27) = 320, p = .22$, nor the IPQ general presence score, $U(27,27) = 286.5, p = .08$, differed significantly between the two conditions. Spatial presence and involvement showed small effects that were in line with our expectations (see Fig. 6). The participants reported a lower spatial presence (IPQ SP) when using the AR HMD compared to using the VR HMD, $U(27,27) = 267, p < 0.05, r = 0.23$. Further, the participants reported a lower feeling of involvement (IPQ INV) when using the AR HMD compared to the VR HMD, $U(27,27) = 245, p < 0.05, r = 0.28$. Additionally, participants using the AR HMD did not report a significantly lower feeling of realism (IPQ REAL) compared to the VR HMD, $U(27,27) = 367, p = .52$. Thus, H1 was only partially confirmed. A post-hoc power analysis revealed that on an α-level of .05, a one-sided Mann-Whitney-Wilcoxon test with a group size of $n = 27$ would have detected medium effects with an effect size of $r = 0.33$ and more with a power of .8. Consequently, we assume that possible influences of the conditions on general presence or realism would be rather small.

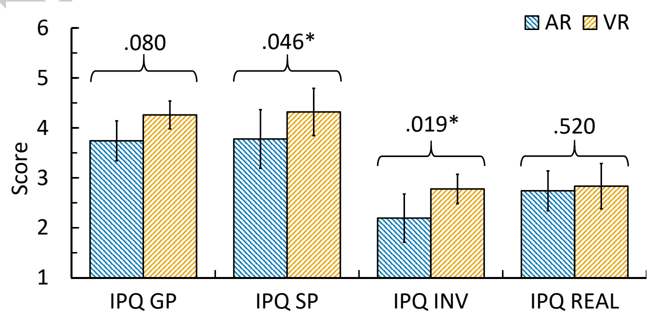

Figure 6: The chart shows the average scores for AR and VR and the corresponding p-value for the IPQ dimensions GP, SP, INV, and REAL. Error bars represent 95 % confidence intervals. Asterisks indicate significant p-values.

5.2 Embodiment

In contrast to our expectations (H2.1), participants using the AR HMD did not report a significantly lower feeling of VBO in comparison to the VR HMD, neither in virtuo, $U(27,27) = 335, p = .31$, nor in the VEQ, $U(27,27) = 309.5, p = .17$. Thus, H2.1 was not confirmed. The results are shown in Fig. 7, left. In line with our expectations (H2.2), the participants did not rate their feeling of agency differently when using the AR HMD compared to the VR

HMD. Neither in virtuo, $U(27,27) = 338.5, p = 0.65$, nor post-experience, $U(27,27) = 404, p = 0.49$ was significant on the adjusted α-level of $\alpha = .2$. Thus, H2.2 was confirmed. The results are shown in Fig. 7, middle. The exploratory tested third embodiment factor change did not reveal a significant difference between the two conditions, $U(27,27) = 335, p = .62$. The results are shown in Fig. 7, right. A post-hoc power analysis revealed that with a power of .8, a two-sided Mann-Whitney-Wilcoxon test with a group size of $n = 27$ would have detected medium effects with an effect size of $r = 0.36$ or more on an α-level of $\alpha = .05$ and effects with an effect size of $r = 0.28$ or more on an α-level of $\alpha = .20$. Consequently, we assume that possible differences between AR HMD and VR HMD in terms of perceived VBO, agency, and change would be rather small.

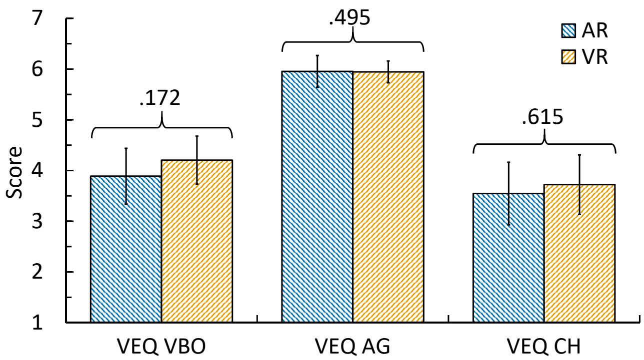

Figure 7: The chart shows the average scores of the VEQ for the dimensions VBO, AG, and CH between the AR and VR condition together with the corresponding p-value. Error bars represent 95 % confidence intervals.

5.3 Body Weight Estimation

In line with our expectations (H3.1), we showed that the participants underestimated the avatars' body weight significantly when using the AR HMD, $t(25) = -2.99, p < .01, d = 0.59$, and when using the VR HMD, $t(25) = -1.88, p < .05, d = 0.37$. Thus, H3.1 was confirmed. The results are shown in Fig. 8.

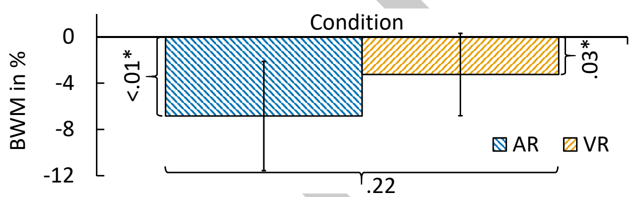

Figure 8: The chart shows the average BWM deviation between the AR and VR condition together with the corresponding p-value. Error bars represent 95 % confidence intervals.

Concerning H3.2, a significant regression equation was found, $F(3,48) = 6.07, p < .01$, with a R^2 of .23. The prediction followed the equation BWM $= -3.47 + 1.89 \cdot$ Participant BMI $- 3.12 \cdot$ Condition (VR = 0, AR = 1) $+ 0.42 \cdot$ (Participant BMI $\cdot$ Condition). In line with our expectations, the results revealed a significant impact of the participants' BMI on BWM, $t(48) = 2.25, p < .05, f^2 = .09$. The resulting slope is depicted in Fig. 9. Within the linear model, the condition did not impact significantly the BWM, $t(48) = -1.23, p = .22$. Additionally, the regression model did not reveal a significant interaction between participant BMI and condition, $t(48) = .38, p = .70$. Thus, the slope of the BWM was not affected significantly by the condition. With a power of .8 and a sample size of $n = 52$ the regression model would have detected medium effects of $f^2 = .16$ or more on an α-level of $\alpha = .05$. We accepted H3.2 as only partially confirmed. As mentioned above, the independent variable condition (AR HMD vs. VR HMD) was not related to the criterion BWM. Therefore, we decided not to perform an additional analysis of a mediating effect of the variables of presence that have been shown to be influenced by the condition (IPQ SP and IPQ INV).

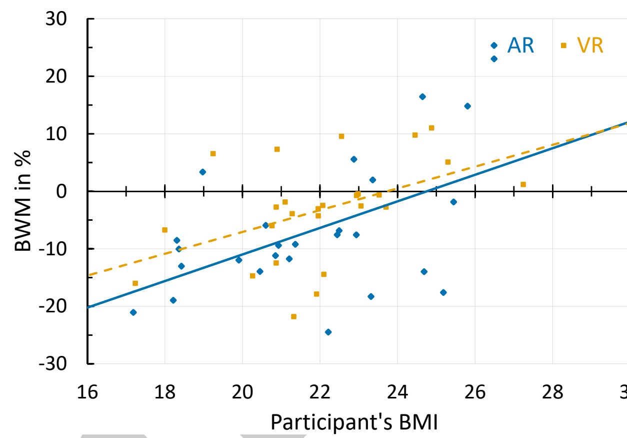

Figure 9: The chart shows the deviation of the BWM depending on the participants' BMI.

On an exploratory basis, we additionally evaluated whether it was rather the BMI difference between participant and avatar than the participants' BMI that could have caused differences in BWM. We extended the regression model by including the BMI difference as an additional predictor. The result was a significant regression equation, $F(4,47) = 28.78, p < .001$, with a R^2 of .69. The prediction followed the equation BWM $= -3.82 - 5.04 \cdot$ Participant BMI $-$ $2.54 \cdot$ Condition (VR = 0, AR = 1) $+ 1.56 \cdot$ BMI difference $- 0.85 \cdot$ (Participant BMI $\cdot$ Condition). Both participant BMI, $t(47)$ = -5.11, $p < .001$, and BMI difference, $t(47) = 8.40, p < .001$, impacted significantly on BWM. We conducted an ANOVA, to test whether the model, including BMI difference, explains significantly more variability than the model without BMI difference. The result revealed a significantly improved model fit, $F(1,47) = 70.53, p < .001$. Thus, we assumed the BMI difference had an impact on BWM in addition the participants' BMI.

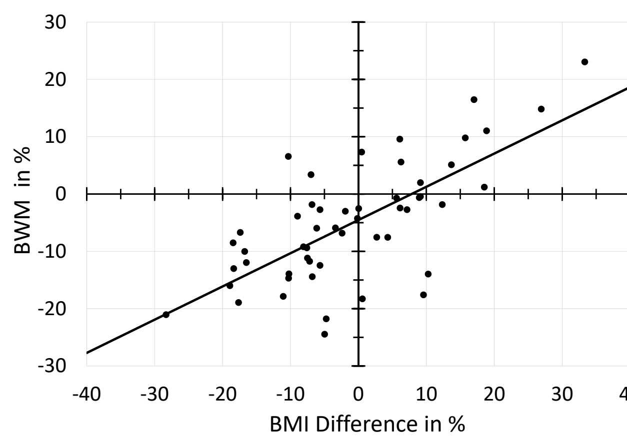

Figure 10: The chart shows the BWM depending on the difference between the participants' BMI and the avatars' BMI.

6 Discussion

The purpose of this work was to investigate the differences between an AR see-through HMD and a VR HMD in terms of body weight perception, presence, and embodiment. As expected, participants in both conditions underestimated the weight of their avatar. However, the influence of the used system configuration was rather small with a descriptive stronger underestimation of the avatar weight when using the AR HMD and no influencing effect of presence and embodiment. We could confirm a significant influence of the participants' BMI on the body weight estimations. Additionally, we explored the influence of the BMI difference between participant and avatar as predictor of the body weight estimations and could show a significant influence. The higher the participant's BMI, the more decreased the tendency to underestimate the avatar. Contrary to our expectations, the subjects only partially reported a significantly lower presence and no difference in embodiment when using the AR see-through HMD in comparison to the VR HMD.

As introduced, immersion is defined by the inclusiveness, extensiveness, vividness, and surrounding of a system [62]. Usually, inclusiveness is a factor that separates virtual reality from augmented reality. By cutting out stimuli from the physical environment, the virtual environment is clearly brought to attention. However, we aimed for the highest possible congruence between AR and VR environment, since we wanted to investigate the differences in body rather than environmental perception caused by the properties of the systems. With the AR see-through HMD, the physical environment can only be experienced indirectly via a video stream. Thus, it closely resembles the inclusiveness of a VR HMD, since the displayed environment might be perceived as separate from the external environment. In addition, we used a virtual environment designed to be as congruent as possible to physical reality, which would lead to an additional reduction of the effect of blocking out the physical surroundings. As our two systems use the same display and the same control devices, they additionally are very similar in terms of extensiveness and surrounding. Nevertheless, there were differences between the systems in terms of vividness, as the resolution, illumination and latency of the systems were different, and partly in terms of inclusiveness, as the egocentric perspective of one's own body differed between the systems (real body in AR vs. avatar in VR).

In detail, we hypothesized that participants using the AR HMD would perceive lower presence as participants using the VR HMD (H1). However, we could not completely confirm this hypothesis. All of our measurements showed descriptive tendencies towards our assumptions, but significance could only be confirmed for the dimensions SP and INV of the IPQ. Comparing our results to Waltemate et al. [70], who also assessed the same presence measurements, we can observe similar in virtuo presence scores for our VR HMD condition ($M = 6.64$) and their equivalent HMD condition ($M = 6.77$). For our AR HMD system, we can observe descriptively higher presence scores ($M = 6.22$) compared to their AR condition ($M = 4.56$). The contrast of these results supports our classification of the systems' immersiveness along Milgram's reality-virtuality continuum [39]. Since our two display configurations represent two closely situated points on the continuum, the small differences in the resulting presence are not surprising. Analyzing the presence results further, we were able to observe only a very small tendency towards our VR condition for the REAL dimension of the IPQ. The used items highly focus on the degree of realism a participant perceives (e.g., "How real did the virtual world seem to you?"). However, AR does not aim to entirely shut-out the real world, which by nature already has the highest possible degree of reality. The here observed results can probably be attributed to the front-cameras of the used HMD, which decreased the realism of the real world by decreasing its resolution. To get more valid results for presence, REAL items could be excluded from the usage or modified to better fit into the context (e.g., "How real did the virtual objects in the environment seem to you?").

For embodiment, we hypothesized that participants using the AR HMD would perceive lower VBO and similar degree agency compared to participants using the VR HMD (H2). However, we could not confirm these hypotheses. We assume that the AR see-through technology decreased the credibility of seeing the own real body instead of a virtual body from an egocentric perspective. Another explanation could be that an allocentric perspective is a more dominant perspective for developing VBO towards a virtual body. We provided the same allocentric perspective in both conditions and manipulated only the egocentric perspective. Debara et al. [12] already disproved the assumption that the egocentric perspective causes a higher level of embodiment and showed similar results for egocentric and allocentric perspectives. However, the question of which of the two perspectives dominates when presented simultaneously in a mirror scenario was not addressed and leaves space for future investigations. A potential factor that can influence agency is latency. However, our measured average latency of 133 ms for the egocentric view was only very slightly above the determined threshold of 125 ms [71], where the agency usually becomes affected. For the allocentric view, it was with 50 ms even far below. Therefore, we could not show an impact on agency. With our system and by using the same measurements, we could observe similar agency scores as Waltemate et al. [70]. This interesting result suggests that IK supported tracking can potentially compete with full-body tracking solutions in embodiment scenarios.

For body weight perception, we hypothesized that healthy participants would underestimate the avatar's body weight regardless of the used system (H3.1). Additionally, we expected differences in the estimations between participants using the AR HMD and the VR HMD and depending on the participants' BMI (H3.2). As already observed in other works on body weight perception before [47, 64], we also could show that our female sample within a BMI range of 17.2 and 27.2 underestimated the weight of their avatar. As assumed, the body weight estimations were significantly predicted by the participants' BMI. In a further exploratory analysis, we also could show that the individual BMI difference between the participants and their avatars highly influenced body weight estimations. While participants with a lower BMI mostly underestimated the avatar weight, participants with higher BMI rated rather correctly or even overestimated the avatar weight. The question arises whether this is a general issue of body weight perception in MR or whether it was caused by our used avatar scaling approach. Scaling of the avatar according to the participants' height led to a proportional change of the avatar's weight and thus also of the BMI. Consequently, estimates were performed on avatars with different BMI but with the same body shape. Although BMI changes were taken into account when calculating the BWM (c.f. Equation 4), the mentioned differences might have had an influence on estimations. It also remains unclear whether our found regression lines also apply to persons who suffer from eating and body weight disorders, as this would contradict previous findings of in vivo research [35, 41]. In contrast to the results of Thaler et al. [64], where an influence of the BMI on body weight estimations was only observed for personalized avatars, we could find these effects also for completely non-personalized avatars. The discrepancy between studies could indicate that embodiment can potentially trigger self-identification with non-personalized avatars similar to personalization. Therefore, the question of whether embodiment influences body weight perception needs to be investigated in future research. Our performed exploratory mediator analysis of presence and embodiment on body weight perception did not reveal any influence. However, this is not surprising, as we (1) could not show a significant influence of our modification of the used system on presence and embodiment, and we (2) could not show a significant influence of our modification of the used system on body weight perception. Based on our results, we would not preclude an influence of presence and embodiment on body weight perception.

6.1 Implications

In both of our tested system configurations, we could maintain high levels of presence and embodiment while having only little differences between conditions. We also could not show significant differences in the body weight estimations. Additionally, we showed that the participants' BMI profoundly influences the body weight perception of the participants' embodied avatar, even when the avatar is not personalized. This partially confirms and extends the work of Thaler et al. [64], who reported the same effect for estimations of not embodied personalized virtual representations, but not for unpersonalized ones. We attribute the differences to the induced embodiment in our study, which might have led to a self-attribution of the virtual body and thus to an association of the self-identity with the avatar. This is, in turn, in line with the results of Thaler et al. for the evaluation of a personalized virtual bodies. By extending previous findings, our work highlighted that the BMI difference between participants and their avatar also contributes significantly to the misestimation of the avatars' body weight.

Our findings are of particular interest for the research and development of eating and body weight disorder therapy supporting MR systems, since system- and user-related deviations in perception must be systematically differentiated and taken into account in order to avoid system-related influences on therapy. Especially when using immersive technologies in therapeutic contexts, caution seems to be required as long as it is not clear how exactly the body is perceived and which effects can be triggered. The research on Proteus effect has shown that highly immersive technologies can have a great influence on behavior, cognition, and perception. Especially for instantiating behavioral changes through exposure to a trigger stimulus, such as a modulated avatar, it seems necessary to aim for a high degree of presence and embodiment [30]. Even when different haptic or proprioceptive stimuli are missing, the perceptual coupling in connection with the visuomotor interaction between visual stimuli and the performed movements as well as the strong feeling of really being in the VE create the feeling of really being exposed to the trigger stimulus [56]. Our findings could allow for entirely new therapy scenarios, especially regarding the interaction of the patients with their real environment. The contact between patient and therapist does not necessarily have to be limited to an instructing voice or a virtual therapist, as the see-through technology also allows the integration of whole unimmersed persons. Especially in the case of body perception, the use of AR can also enable a comparison between the real and the virtual body. Discrepancies between both perceptions can therefore be revealed more clearly. However, the suggestions regarding the application of our findings need to be investigated further in future work.

6.2 Limitations and Future Work

Our work provides interesting new insights into body weight perception in VEs. However, we have also identified some limitations and directions for further research. First, the differences in the immersion between our AR and VR systems and the resulting differences in presence were relatively small. Although this resulted in interesting conclusions regarding possible therapy scenarios, it does not fully reveal the potential influences of the systems' setup on presence, body weight perception, or a mediating relationship between both. Therefore, future work should aim to test additional system setups, such as AR mirrors [70], high-quality camera see-through HMDs [69], or optical see-through alternatives [38]. Future work should also evaluate the differences between AR and VR by a stepwise manipulation of quality-related parameters such as field of view, illumination or resolution. Second, our manipulation of the system did not lead to differences in VBO. Consequently, it was difficult to capture the mediating influences of VBO on body weight perception. Future work should therefore aim to perform an active manipulation of VBO influencing factors like avatar realism, personalization, or latency [32, 70, 71]. This could also help to examine the differences in the results between our work and Thaler et al. [64]. Third, our study was limited to body weight estimations of a single avatar always scaled to participants' body height. This estimation strongly depends on the appearance of the avatar model and the quality of the generated avatar. We used an average-weighted person wearing simple clothing without additional accessories. Nevertheless, when using non-personalized avatars, it suggests performing estimations multiple times with different models. Additionally, our performed uniform scaling introduced the bias of showing taller participants avatars with higher BMI and vice versa. Future experiments should consider more realistic scaling approaches [47]. Apart from this, future studies should also consider body weight self-assessment through the use of modified personalized avatars. Thus, a third-party assessment of the body weight could be compared to a self-assessment. Fourth, our study was limited to the estimation of avatars within VEs. To conclude on the comparability of body weight estimations of real persons, it seems necessary to compare virtual and real estimations by the use of a control group performing in vivo estimations. Finally, we conducted our experiment with a sample of female university students within a very narrow range of age and with normal BMI. Future research should therefore consider an extended sample with a broader range of BMI, in a wider range of age, with different occupations, and also with male participants.

7 Conclusion

This work investigated the influences of two different MR systems on presence, embodiment, and body weight perception within VEs. The goal was to contribute to the research of therapy-supporting systems for the treatment of distorted body perception as often present in eating and body weight disorders. We motivated our approach from various related work, identified currently existing gaps in the research of supportive MR systems in our context, and performed an evaluation to fill these gaps. Our work has two main contributions. First, we found that our performed modification of the systems only partly influenced the perceived presence, and did not lead to differences in VBO and BWMs. The findings indicate that MR systems with a potentially lower immersion, such as our used AR see-through HMD, can provide a similar environment for the treatment of body perception disorders as fully immersive VR HMD systems. It suggests to extend already existing and novel therapy support paradigms to the interaction with real-world objects, such as the patient's body or the real therapist. Second, we found that body weight perception of embodied avatars is influenced by the user's own BMI and the BMI difference between participant and avatar. Participants with a higher BMI overestimated the avatar's body weight, while participants with a lower BMI underestimated it. Future research needs to show to what extent our findings can be transferred to systems with other properties, like a even lower immersion, or different embodiment implementations. In summury, our results provide further insights on body perception within VEs and help to fill the still existing gaps about the interrelationships between the various underlying psychometric factors. The knowledge gained contributes to the quality of existing and future therapeutic systems for body perception disorders and opens up new questions for future work.

Acknowledgments

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