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Exploring Presence, Avatar Embodiment, and Body Perception with a Holographic Augmented Reality Mirror

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Figure 1: The picture shows a participant embodying a generic avatar and observing it in the holographic mirror. In our evaluation, participants had to perform body movements, answer questions about the experience, and guess the body weight of the avatar.

Abstract

The embodiment of avatars in virtual reality (VR) is a promising tool for enhancing the user's mental health. A great example is the treatment of body image disturbances, where eliciting a full-body illusion can help identify, visualize, and modulate persisting misperceptions. Augmented reality (AR) could complement recent advances in the field by incorporating real elements, such as the therapist or the user's real body, into therapeutic scenarios. However, research on the use of AR in this context is very sparse. Therefore, we present a holographic AR mirror system based on an optical see-through (OST) device and markerless body tracking, collect valuable qualitative feedback regarding its user experience, and compare quantitative results regarding presence, embodiment, and body weight perception to similar systems using video see-through (VST) AR and VR. For our OST AR system, a total of 27 normal-weight female participants provided predominantly positive feedback on display properties (field of view, luminosity, and transparency of virtual objects), body tracking, and the perception of the avatar's appearance and movements. In the quantitative comparison to the VST AR and VR systems, participants reported significantly lower feelings of presence, while they estimated the body weight of the generic avatar significantly higher when using our OST AR system. For virtual body ownership and agency, we found only partially significant differences. In summary, our study shows the general applicability of OST AR in the given context offering huge potential in future therapeutic scenarios. However, the comparative evaluation between OST AR, VST AR, and VR also revealed significant differences in relevant measures. Future work is mandatory to corroborate our findings and to classify the significance in a therapeutic context.

Keywords: Virtual reality, virtual human, virtual body ownership, agency, body image distortion, body weight perception

Index Terms: Human-centered computing—Human computer interaction (HCI)—Empirical studies in HCI; Human-centered computing—Human computer interaction (HCI)—Interaction paradigms—Mixed / augmented reality;

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1 Introduction

The use of embodied avatars (i.e., 3D models of human beings controlled by the user), or so-called full-body illusions, for behavioral manipulation has become a hot topic in virtual reality (VR) research [55]. Since the discovery of the Proteus effect [60], suggesting that an avatar's appearance can influence its user's attitudes and behavior, various works have demonstrated the beneficial capabilities of full-body illusions in general [34], but also for mental health [27]. Great examples are eating and body weight disorders with an underlying body image distortion, where the potential of full-body illusions has recently been confirmed [50]. The general idea of improving body image through modulated embodied avatars can be realized by scenarios helping to reveal and visualize the users' mental body image, improving the motivation for therapy by showing their weight loss successes, or working intensively with their current and desired body weight [13, 35].

However, VR usually shuts out the visual perception of the real environment. By breaking the users' isolation in the virtual environment through augmented reality (AR), they could reference the experience directly to their physical bodies. For example, an exposure would be conceivable in which users can compare their virtual self in a virtual mirror with themselves in a real mirror by only looking in a different direction. AR would also allow for a multimodal interaction between therapists and users, enabling better intervention when necessary. However, while the use of embodied avatars in VR has become widespread, the application in AR is far less common, and the display technology's influence on user experience related factors and potentially relevant treatment effect mediators such as the feeling of presence and embodiment or body weight perception has not been clarified yet [17, 55, 57]. Hence, the question arises whether the potential advantages of AR are accompanied by an unintended impact on the aforementioned factors.

In our work, we have developed a holographic AR mirror system for investigating presence, avatar embodiment, and body weight perception in AR. It is based on a Microsoft HoloLens 2 [28] optical see-through (OST) AR headset and markerless body tracking provided by The Captury [47, 49], allowing users to interact with their physical bodies in an unrestricted way. Within the holographic mirror, they observe a generic photorealistic avatar animated according to their movements, giving them the feeling of embodying it. To evaluate the general quality of our OST AR system, we performed qualitative interviews on the perception of the avatar's appearance and movements, including questions about the perceived accuracy of body tracking and the display properties (e.g., field of view (FOV), luminosity, or resolution). To evaluate the strength of potential effect mediators quantitatively, we captured the feeling of presence and embodiment and asked for estimations of the avatar's body weight. We further controlled self-esteem, body shape concerns, gender, simulator sickness, and the participant's body mass index (BMI) as potential confounds. In an extended statistical analysis, we compared the quantitative results of our OST AR system to the video see-through (VST) AR and VR systems tested in previous work [57].

2 Related Work

Milgram's reality-virtuality continuum states that different display types offer different degrees of virtuality depending on their characteristics (e.g., reality covered by virtual elements (AR) or solely virtual elements (VR)) [29]. These characteristics are often associated with the degree of immersion as introduced by Slater and Wilbur [45], defining the degree of virtual reality on a display's objective properties (e.g., FOV, luminosity, or resolution) [44]. A higher immersion usually provides a higher level of virtuality. In our context, the spectrum ranges from low immersive OST AR displays, over more immersive VST AR displays, to fully immersive VR displays, which all offer different kinds of user experiences [56].

A major concept quantifying the quality of the provided experience is presence, originally defined as the sense of really being in a virtual environment and later divided into place and plausibility illusion [43]. Wienrich et al. [56] recently elaborated the sense of transportation (or spatial presence), known as place illusion and determined by the system's immersion, and the sense of realism, known as plausibility illusion and determined by the experience's coherence, as two major dimensions for quantifying presence across the reality-virtuality continuum. A higher immersion of a display usually results in a higher feeling of presence [8, 12, 52], and consequently to a higher degree of plausibility and credibility of the experience, which has been suggested as a necessary "hygiene factor" for behavior change in mental health using AR or VR [22, 40, 55].

Another important quale of the user's experience in terms of behavioral changes initiated by the Proteus effect is the sense of embodiment. It can be decomposed into the feeling of being inside (self-location), controlling (agency), and having a virtual body (virtual body ownership (VBO)) [21, 38]. Similar to Milgram's reality-virtuality continuum, Genay et al. [17] recently proposed the body avatarization continuum, which encompasses the extent to which a user embodies a virtual representation. It ranges from having a real body, over having a partial virtual body representation, to being fully embodied to a virtual avatar. Similar to the relation of immersion and presence, it can be assumed that the degree of body avatarization, often determined or limited by the used display type and its immersion, impacts the feeling of embodiment [17]. For example, seeing the real body while also having a virtual body can lead to a direct comparison of the bodies and thus might decrease VBO, as observed in other works [52, 61]. A narrowed FOV could also have a negative impact on VBO, as it might break the continuity of the embodiment experience [17]. Particularly when using OST AR displays, the direct visual feedback of the real body movements might impact agency since there is no latency in the view on the real body, increasing the latency between directly observed real motions and the virtual body's motions [17]. Similarly, the direct view on the real body ensures that the visual and proprioceptive information is synchronized [36], but this consequently results in a greater visual and proprioceptive difference between the real and the virtual body. Lastly, virtual content in OST AR is partially transparent and might cause depth perception problems that could negatively affect the embodiment experience [54].

Ratan et al. [34] assume that "the Proteus effect outcomes should be stronger the closer the user feels to the avatar", which might not be the case when the feeling of embodiment decreases due to the use of AR. However, the influence of the display type on the feeling of embodiment has been rarely investigated empirically [17]. Skola et al. [61] examined the feeling of VBO in response to a real-world, AR, and VR condition and found a significant difference between the AR and real-world conditions, but not between AR and VR. Wolf et al. [57] investigated how the type of display (VST AR vs. VR) affects embodiment and presence and found that the influence was rather small. The authors referred to the fairly small difference in immersion as an explanation. Finally, Nimcharoen et al. [31] developed an OST AR embodiment system using 3D point cloud avatars and explored presence and embodiment. They were able to show that participants developed a considerable feeling of VBO and agency towards their avatar but did not include a comparative condition, making interpretation difficult and showing us that comparative conditions are inevitable for our work.

With respect to body image, the user's perception of the virtual avatar's body weight is another aspect to consider. Prior work has already shown that avatar embodiment impacts body weight perception based on the user's BMI [58]. However, the influence of different display types on body weight perception seems unclear. Wolf et al. [57] conducted a narrow review of potential factors influencing body perception in AR and VR and found that existing work is still rare and heterogeneous, preventing them from determining the influence of different display types on body weight perception. In their additionally performed evaluation, they found no significant difference in body weight estimates between VST AR and VR, but observed descriptive differences, based on which they did not rule out an influence of display type on body weight perception.

In summary, the introduced potential benefit of AR, being able to interact with the real world, could be accompanied by a diminished feeling of presence and embodiment, negatively impacting on the users' experience. In addition, it is mainly unclear how different display technologies alter the user's body weight perception concerning body image therapy. Due to only little empirical work on body illusions in AR, a comparison of different display technologies concerning presence, embodiment, and body weight perception seem essential to further explore the use of body illusions in AR, especially with regard to a future use in the field of mental health.

3 System Description

Our holographic AR mirror system was developed using Unity 2020.3.11f1 LTS [51]. It renders a virtual mirror hologram on a wall in front of the user, showing a generic avatar as the user's mirror image being animated by the user's captured movements in real-time (see Fig. 1). At the same time, the user can observe the real environment and the own physical body. The laboratory where the user was located during our evaluation was recreated as a 3D model to render a plausible background in the holographic AR mirror. As an AR display, we used the Microsoft HoloLens 2 [28], providing the user a resolution of 1440×936 pixels with a FOV in horizontal of 43° and in vertical of 29° and a refresh rate of 60 Hz. In our evaluation, the HoloLens 2 was connected via 100 MBit/s ethernet to a high-end PC composed of an Intel Core i7-9700K, an Nvidia RTX2080 TI, and 32 GB RAM running Windows 10 and used to render the content via Holographic Remoting. In the following, we will explain how the user's movements are captured in order to animate the avatar as the user's virtual mirror image. A video showing the running application is provided in the supplementary material.

3.1 Motion Tracking and Avatar Animation

For motion tracking, we use the markerless tracking system Captury Live [47,49]. Eight FLIR Blackfly S BFS-PGE-16S2C RGB cameras mounted on the ceiling of our laboratory running at a capturing rate of 100 Hz assure that the user can be tracked in the whole laboratory in real-time (see Fig. 2). The cameras are connected via two 4-port 1 GBit/s ethernet frame-grabber to a powerful PC composed of an Intel Core i7-9700K, an Nvidia RTX2080 TI, and 32 GB RAM running Ubuntu 18 and Captury Live. The system delivers a stable body pose via ethernet that can be streamed directly into Unity using The Captury's Unity plug-in. The body pose is then calibrated in a way that the head always follows the HoloLens 2 on the horizontal axes without drifting. A huge drawback of the current version of the tracking system is the provided quality of the hand tracking, which is in rotation restricted to only two degrees of freedom. Therefore, we decided to use the built-in hand tracking of the HoloLens 2 in addition. The hand movements are tracked with sufficient accuracy (considering the distance to the mirror) [46], on all six degrees of freedom, and in real-time as soon as a hand is held into the sensory field of the device (see Fig. 3).

The body pose received from Captury Live is continuously retargeted to the avatar shown in the mirror, which is automatically scaled to the user's body height. The potentially occurring discrepancies between the received skeleton and the generic skeleton of the displayed avatar (e.g., different limb lengths) reflected in inaccuracies

Figure 2: The screenshot of Captury Live's tracking view shows the user from Fig. 1 inside our laboratory currently waving to her holographic reflection while her pose is tracked in real-time.

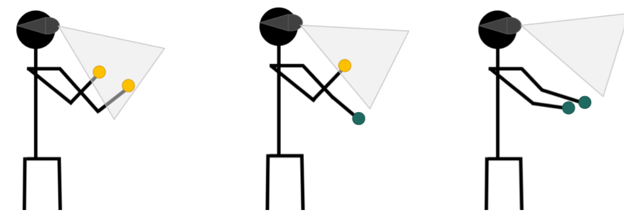

Figure 3: The pictures sketches the principles of our hand tracking. The light gray area in front of the head visualizes the sensory field of the HoloLens 2. As soon as a hand is in the field, the position and orientation is taken from the HoloLens 2 hand tracking (yellow dot), otherwise, it is captured via Captury Live (green dot).

in the alignment of the pose or the end-effectors (hands and feet) are compensated by an IK-supported pose optimization step, where the end-effectors of the avatar are aligned with the end-effectors of the tracked user. This leads to high positional conformity between the user's body and the embodied avatar and avoids sliding feet due to the retargeting process. The end-effector adaptions are also used to integrate the hand pose of the HoloLens 2 hand tracking into the avatar's pose. As soon as a hand is recognized in the sensory field of the HoloLens 2 hand tracking, the corresponding hand of the avatar interpolates from the Captury to the HoloLens 2 hand tracking and vice versa. The interpolation time was empirically determined to 100 ms, providing a smooth transition between the two tracking systems and avoiding choppy hand movements.

In a further step, we used frame-counting [18] to determine the motion-to-photon latency of our virtual mirror image. For this purpose, a high-speed camera of an iPhone 12 was used to record the user's motions and the corresponding reactions of the avatar through the see-through display at 240 fps. The motion-to-photon latency for the whole body pose from Captury averaged 162.4 ms ($SD = 30.39$ ms). For the HoloLens 2 hand tracking, the latency averaged 126.5 ms ($SD = 18.94$ ms). We attribute the generally high latency to the use of Holographic Remoting, which unfortunately was unavoidable for performing our evaluation. However, for future prototypes, a reduction of latency seems feasible.

4 Evaluation

We tested our holographic AR mirror system in a structured evaluation using several qualitative questions and quantitative measurements. Our experimental setup followed our previous work [57] in order to enable the most valid comparison possible between the newly collected data of the OST AR condition and the already existing data of the VST AR and VR conditions from the previous work. The used avatar was originally created using the generation pipeline of Achenbach et al. [1].

4.1 Participants

We included 27 female-only BA students from the University of Würzburg in our evaluation that fulfilled the following participation requirements: (1) they had to have good or corrected to normal vision and hearing; (2) they had to have at least ten years of experience with the German language; (3) they should currently not suffer from a diagnosed mental, psychosomatic, or body weight disorder; (4) they should not have a known sensitivity to simulator sickness; (5) and they should not have participated in the study of the previous work. Since body weight perception might differ between gender, we followed Wolf et al. and only tested females [10,57]. One additional participant was excluded due to technical issues. Descriptive values and statistical analysis regarding relevant demographic data and control measurements will be provided in Sect. 5.

4.2 Design and Hypothesis

We employed an experimental design that combines the data collected in this evaluation (OST AR) with the data previously collected (VST AR and VR) [57]. Consequently, a 3×1 between-design with the *display type* being the independent variable was used. The display type could either be our OST AR display or their VST AR or VR display. The dependent variables were divided into the perceived feeling of *presence* and *embodiment* and *body weight misestimation* (BWM) of the avatar's BMI in relation to the avatar's real BMI. To support the post-hoc interpretation of the collected quantitative data, we additionally conducted supplemental interviews with focus on the system properties of our OST VR system.

Based on our introduced related work, we propose the following hypotheses regarding our dependent variables. Since the results of our previous work have already been published [57], we always formulate the hypotheses from the perspective of our OST AR condition with respect to the VST AR and VR conditions. All hypotheses are backed up by a brief summary of the relevant related work.

Due to the system properties of the OST AR display (i.e., narrow FOV, lower resolution and luminance, direct visibility of the real environment, virtual objects occlusion), we assume that our OST AR potentially provides a lower degree of immersion, which is known to impact negatively on presence [8, 12, 42, 52]. Therefore, we formulate the hypothesis regarding presence as follows:

H1: Participants using OST AR will report a lower feeling of presence than participants using VST AR or VR.

As comprehensively summarized by Genay et al. [17], the implementation of avatar embodiment in AR can negatively impact the feeling of embodiment. The physical body's presence can lead to a direct comparison with the virtual replica and thus might decrease VBO, as already observed in other works [52, 61]. The direct availability of the physical body in OST AR can also influence agency, since there is no motion-to-photon latency in the view on the own physical body, which in turn increases the latency between directly observed physical motion and virtual motion observed in the mirror [17]. Hence, we propose the following hypotheses:

H2.1: Participants using the the OST AR will report a lower feeling of VBO towards their avatar than participants using the VST AR or VR.

H2.2: Participants using the OST AR will perceive a lower feeling of agency towards their avatar than participants using the VST AR or VR.

Based on the narrow review on body weight perception influencing factors performed by Wolf et al. [57] and the results of their evaluation, we expect that body weight estimations could be influenced when using OST AR. However, since previous work is still rare and heterogeneous, we have refrained from formulating a directed hypothesis and decided to explore body weight estimations further. Our undirected hypothesis is as follows:

H3: Participants using OST AR will estimate the avatar's body weight differently than participants using VST AR or VR.

4.3 Measurements

In the following, we summarize the questionnaires used to operationalize our variables, explain how body weight estimates were calculated, and describe the interview conducted.

4.3.1 Questionnaires

Table 1 summarizes all questionnaires used in our evaluation, including their different dimensions and original score ranges used for statistical analysis. The table further contains references to used validated German versions when available. Otherwise, we translated the questions to the best of our knowledge using back and forth translations. The time a questionnaire was conducted is depicted in Fig. 4. For a comprehensive explanation of the measurements, we refer to corresponding publications. To allow for a comparison between different measurements, the values for presence and embodiment are presented in a normalized range from 0 to 10. For measuring presence, the participants received the additional information that virtual objects, such as the mirror, including its background, are counted as the virtual environment.

Table 1: Summary of all questionnaires used in our evaluation.

	Questionnaire	Range	Measurement
Presence	One-item [5, 6]	[0 – 10]	General presence (GP)
	IPQ [41]	[0 – 6]	General presence (GP)
		[0 – 6]	Spatial presence (SP)
		[0 – 6]	Involvement (INV)
		[0 – 6]	Realism (REAL)
Embodiment	One-item [19, 52]	[0 – 10]	Virtual body ownership (VBO)
		[0 – 10]	Agency (AG)
	VEQ [38]	[1 – 7]	Virtual body ownership (VBO)
		[1 – 7]	Agency (AG)
Control	SSQ [3, 20]	[0 – 235.62]	Simulator sickness
	BSQ [11, 14, 32]	[0 – 204]	Body shape concerns
	RSES [16, 37, 39]	[0 – 30]	Self-esteem

4.3.2 Body Weight Estimation

For each participant, body weight and height were captured using calibrated medical equipment. Subsequently, the participant's BMI was calculated as $\frac{\text{Body Weight in kg}}{(\text{Body Height in m})^2}$ [59]. Additionally, participants estimated the body weight of their uniformly scaled and height-matched avatar, from which we calculated the avatars' estimated BMI (E-BMI). We further calculated the avatars' approximated BMI (A-BMI) by multiplying the scaling factor s, which was calculated by dividing the participant's body height by the height of unscaled avatar, with the avatars original BMI. Body weight misestimation (BWM) further was calculated as $\frac{(\text{E-BMI}-\text{A-BMI})}{\text{A-BMI}}$. A negative value of BWM represents an underestimation of the avatar's body weight, and a positive value an overestimation. A detailed explanation of the calculations can be found in Wolf et al. (see Section 4.2.3) [57].

4.3.3 Interview

A semi-structured interview with predefined questions was conducted to obtain information about the system's perceived quality and the AR experience itself. Especially the perception of the avatar's appearance and movement was in focus, including questions about the perceived accuracy of body tracking. However, possibly as negative interpretable display properties of the HoloLens 2, such as the perceived FOV or the perceived luminosity and transparency of the virtual objects, were also queried. A list of all questions can be found in the supplementary material of this work.

4.4 Procedure

Fig. 4 illustrates the procedure of an evaluation session that averaged 36 minutes per participant and took place in a quiet laboratory at the University of Würzburg. Before the evaluation, participants were required to read the COVID-19 regulations, privacy policy, and study information and to give explicit consent to participate. All questionnaires outside the AR exposure had to be completed on a separate computer in the laboratory using LimeSurvey 4 [26].

The subsequent AR exposure phase followed a pre-programmed logic, and participants automatically received all information via pre-recorded audio and visual text instructions. For calibration of the AR exposure, participants first had to walk a short distance in

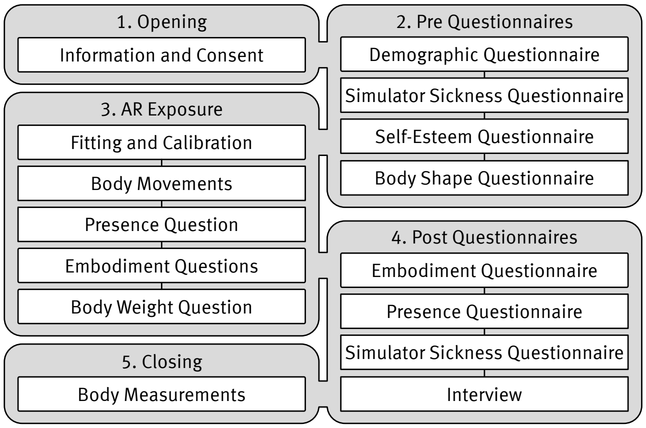

Figure 4: The figure shows the evaluation's procedure arranged in a meandering pattern including all questionnaires carried out.

the laboratory to set up and optimize the markerless body tracking. Then, they put on the prepared and calibrated HoloLens 2 and had to remain standing for a brief moment to set up the avatar embodiment. At the end of the preparation, the experimenter verified that the system worked correctly. After the calibration, the virtual mirror appeared, and participants could see their virtual self. Subsequently, participants had to perform five movement tasks (i.e., waving towards the mirror image with left and right hand each, walking in place, circling the arms in front of the body, and performing hip movements while stretching the arms to both sides) while seeing their virtual representation in the mirror to strengthen the feeling of embodiment towards their avatar. This was followed by the one-item questions for presence and embodiment and the avatar's body weight. The AR exposure duration averaged 7.5 minutes.

After exposure, the participants completed the remaining questionnaires and the experimenter conducted the interview to collect the qualitative feedback. The interview duration averaged 6 minutes. Finally, the participants' weight and height were measured.

5 Results

The statistical analysis was performed using R version 4.0.5 [33]. For sensitivity analysis, we used G*Power version 3.1.9.7 [15]. Before analyzing our dependent variables, we first compared the three groups in terms of their homogeneity in relevant demographics and control measurements using a one-way between-subject ANOVA. The results a summarized in Table 2. Although we found a significant difference in age, we considered the maximum age difference of $\Delta M = 2.6$ as not relevant. For the remaining variables, we did not find any significant differences. Since SSQ values decreased in all conditions over time, we refrained from calculating tests between pre and post-measurements. All data are available on request.

Table 2: The table shows the descriptive values as well as the statistical test results of the control variables between our groups. Asterisks indicate significant p-values.

	OST AR	VST AR	VR	
	M (*SD*)	*M* (*SD*)	*M* (*SD*)	*p*-value
Age	22.3 (1.9)	20.3 (2.4)	19.7 (1.1)	$< .001^*$
BMI	22.5 (2.6)	22.1 (3)	22.4 (2.9)	.881
RSES	24.0 (3.9)	22 (4.4)	22.9 (4.7)	.253
BSQ	85.2 (23.9)	80.0 (26.4)	79.6 (26.0)	.668
Pre SSQ	22.6 (17.7)	26.5 (24.5)	16.6 (14.0)	.173
Post SSQ	19.7 (18.4)	22.4 (22.0)	14.1 (16.5)	.272

5.1 Quantitative Measurements

By using non-normalized values, we calculated two planned contrasts for each variable of presence, embodiment, and body weight estimation within a one-way between-subject ANOVA model, comparing OST AR to either VST AR or VR. While all variables met the assumption of homoscedasticity within the ANOVA model, not all variables met the normality of residuals as a criterion for parametric tests. Nonetheless, one-way ANOVA is stated robust against violations of the assumption of normality given equal group sizes, and group sizes $n > 10$ [4]. Since our experiment met those requirements and a cross-check with the results of the non-parametric Kruskal-Wallis test revealed no difference in findings, we decided to report the results of parametric testing for all variables for reasons of clarity. All descriptive values are shown in Table 3.

For a further exploratory examination, we calculated a multiple linear regression to predict body weight estimations based on centered participants' BMI and condition (OST AR vs. VST AR vs. VR). The model met all criteria for parametric testing. All tests were performed against an α of .05.

5.1.1 Presence

Confirming hypothesis H1, participants using OST AR reported significantly lower general presence in the one-item question than participants using VST AR, $t(78) = 2.81, p = .006, d = 0.72$, or VR, $t(78) = 3.87, p < .001, d = 1.06$. For IPQ, participants in the OST AR condition reported lower scores for general presence, $t(78) = 2.22, p = 0.029, d = 0.58$ (IPQ GP), spatial presence, $t(78) = 2.97, p = 0.004, d = 0.73$ (IPQ SP), and realism, $t(78) = 2.53, p = 0.013, d = 0.69$ (IPQ REAL) than in the VST AR condition, but not for involvement, $t(78) = 0.22, p = 0.833, d = 0.06$ (IPQ INV). Similarly, they stated lower ratings for general presence, $t(78) = 3.70, p < 0.001, d = 1.10$, spatial presence, $t(78) = 4.89, p < 0.001, d = 1.48$, and realism, $t(78) = 2.94, p = 0.004, d = 0.80$ in the OST AR condition compared to the VR condition. Again, involvement did not differ significantly between the conditions, $t(78) = 1.70, p = 0.094, d = 0.45$. Results are shown in Fig. 5, left.

5.1.2 Embodiment

Contrary to hypothesis H2.1, the results of the one-item question for VBO did not differ significantly between OST AR and VST AR condition, $t(78) = 0.06, p = 0.951, d = 0.02$, and between OST AR and VR condition, $t(78) = 0.74, p = 0.464, d = 0.21$. Similarly, there was no significant difference in the VEQ ratings on VBO between OST AR and VST AR, $t(78) = 1.25, p = 0.216, d = 0.33$. However, OST AR and VR differed significantly in VEQ ratings on VBO, $t(78) = 2.17, p = 0.033, d = 0.63$. Results are shown in Fig. 5, middle.

Table 3: The table shows the normalized descriptive values in a range from 0 to 10 (except BWM) for each measurement per condition.

		OST AR	VST AR	VR
		M (*SD*)	*M* (*SD*)	*M* (*SD*)
Presence	One-item GP	4.85 (2.01)	6.22 (1.80)	6.74 (1.53)
	IPQ GP	4.94 (1.93)	6.23 (2.47)	7.10 (1.99)
	IPQ SP	4.90 (1.80)	6.30 (2.03)	7.20 (1.24)
	IPQ INV	3.77 (2.01)	3.66 (1.68)	4.63 (1.91)
	IPQ REAL	3.61 (1.39)	4.57 (1.40)	4.72 (0.83)
Embodiment	One-item VBO	4.48 (1.89)	4.52 (2.49)	4.93 (2.23)
	VEQ VBO	4.10 (1.94)	4.81 (2.32)	5.34 (2.00)
	One-item AG	6.93 (1.47)	7.7 (1.75)	8.00 (1.39)
	VEQ AG	7.84 (1.10)	8.26 (1.32)	8.24 (0.91)
	BWM	1.57 (6.96)	-6.92 (11.46)	-3.08 (8.69)

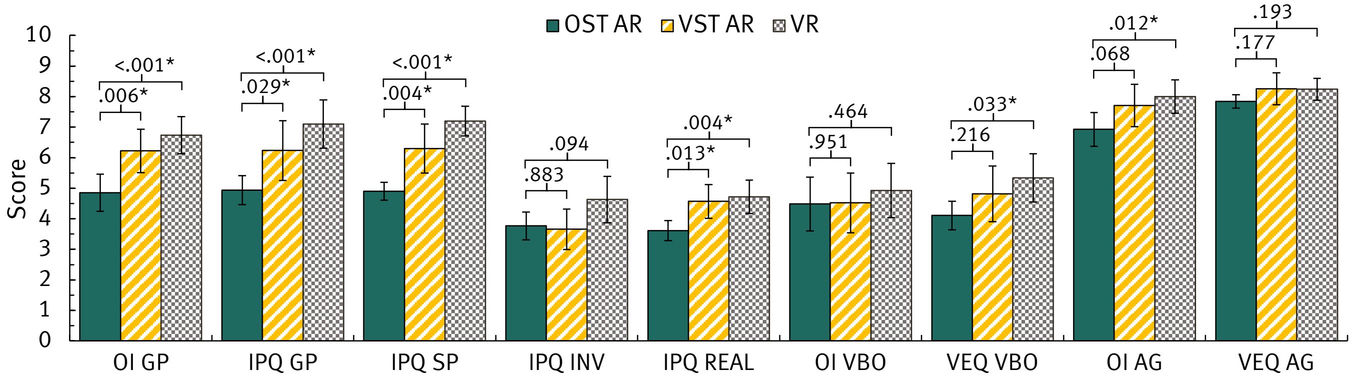

Figure 5: The bar chart shows the results of presence, VBO, and agency for all conditions normalized to a range from 0 to 10 together with the corresponding p-values. Error bars represent 95 % confidence intervals. Asterisks indicate significant p-values.

The one-item question results for agency did not differ significantly between OST AR and VST AR condition, $t(78) = 1.85, p = 0.068, d = 0.48$, but differed significantly between OST AR and VR condition, $t(78) = 2.56, p = 0.012, d = 0.75$. However, VEQ ratings on agency revealed neither significant difference between OST AR and VST AR, $t(78) = 1.36, p = 0.177, d = 0.34$, nor between OST AR and VR, $t(78) = 1.31, p = 0.193, d = 0.40$. Results are shown in Fig. 5, right.

A sensitivity analysis revealed that a t-Test in our ANOVA-model with a group sizes of $n = 27$ and an α-level of .05 would have revealed medium effects of $d = 0.78$ or greater with a power of .80 [9]. As the non-significant effect size d ranged between $d = 0.02$ and $d = 0.80$, we cannot completely discard a small effect of the condition on the perceived body ownership or agency.

5.1.3 Body Weight Estimation

Confirming hypothesis H3, body weight estimations differed significantly between the OST AR condition and the VST AR condition, $t(78) = 3.38, p = 0.001, d = 0.90$ or the VR condition, $t(78) = 1.86, p = 0.005, d = 0.59$. Results are depicted in Fig. 6.

The further exploratory investigation of the impact of our conditions on the relation between the participant's BMI and the body weight estimation revealed a significant regression equation, $F(5,75) = 5.40, p < .001$, with an adjusted R^2 of .22. The prediction followed the equation $\mathrm{BWM} = 1.47 + 0.74 \cdot \mathrm{Participant\ BMI} - 8.03 \cdot \mathrm{Condition\ A} - 4.65 \cdot \mathrm{Condition\ B} + 0.86 \cdot (\mathrm{Participant\ BMI} \cdot \mathrm{Condition\ A}) + 0.45 \cdot (\mathrm{Participant\ BMI} \cdot \mathrm{Condition\ B})$ where Condition A was OST AR = 0, VST AR = 1, VR = 0 and Condition B was OST AR = 0, VST AR = 0, VR = 1. The regression did neither reveal a significant impact of the participants' BMI on body weight estimations in the OST AR condition $t(75) = 1.14, p = .255$, nor did it reveal a significant interaction between OST AR condition and VST AR condition, $t(75) = 1.01, p = .317$, or OST AR condition and VR condition, $t(75) = 0.52, p = .603$.

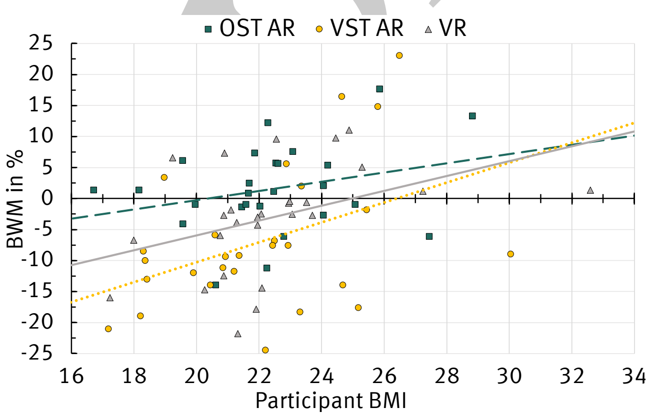

Figure 6: The chart shows body weight misestimations (BWM) in relation to the participants' BMI per condition.

5.2 Qualitative Feedback

The interviews have been evaluated using a Miro board [30] and following thematic analysis [7]. All answers were clustered on sticky notes within the context of their question. During our analysis, the initial deductive mapping of the answers was broken up, and the answers were inductively re-clustered into feedback on the perception of the holographic mirror itself and the perception of the avatar.

5.2.1 Perception of the Holographic Mirror

Setting up the equipment for the holographic mirror was judged as quick and easy by most participants ($n = 23$). 13 participants perceived the holographic mirror as part of the physical room (e.g., it seemed like the mirror was attached to the wall or they recognized the reflection of the virtual background). Seven participants criticized the virtual mirror, including its transparency, the image quality, and the computer-animated reflection. Two participants found it disturbing that they could still see the real world.

The limited FOV of the HoloLens 2 was noticed by a majority of participants ($n = 20$). 17 participants mentioned the narrow vertical FOV and six the narrow horizontal FOV. Four of them reported that not only the mirror but also the avatar was cut off at the legs. However, the narrow FOV was negligible for 14 participants, as everything relevant could still be observed. None of the participants stated that the limited FOV prevented them from performing tasks. The majority of the participants described the holographic mirror as not particularly bright in contrast to the environment ($n = 24$).

5.2.2 Perception of the Avatar

The avatar's general appearance was noticed positively by seven participants, as it appeared human and had a suitable body size or skin/hair color. Seven participants criticized the appearance because of wrong skin/hair color, clothing, or body proportions. The face was criticized in particular (no facial expression, fixed eyes, impersonal).

The general pose and movements of the avatar were positively evaluated, stating that the own movements were well mirrored ($n = 7$). Eight participants judged the movements to lack quality (robotic movements, bent hip, not accurately executed movements). Faulty or unnaturally bent elbows of the avatar seem to be the most problematic area, presumably due to different arm proportions between the generic avatar and the participants ($n = 9$). Other problematic areas of the avatar were the shoulders ($n = 6$); twisted arms ($n = 3$); the pose of the legs (left knee turned inwards or knock-knees) ($n = 7$); and the pose of the feet, which also were perceived as turned inwards ($n = 4$). In addition, three participants reported having perceived a trembling and a slight latency in relation to the real movement of the legs. Twelve participants perceived the movement of the hands as soft and precise, four perceived them as "choppy" or "robotic", and two perceived time-delayed movement, especially when the hands were not in the direct FOV. Overall, 17 participants noticed that their fingers did not move, and 22 described a wrong hand rotation (due to the mentioned missing degree of freedom). Five participants noted that finger movements would generally contribute to a realistic avatar appearance ("It is a mirror, all movements should be reflected there").

6 Discussion

Our work's goal was to design and develop a holographic OST AR mirror system, allowing users to interact with the real world during full-body illusion experiences and to evaluate the system with regard to presence and embodiment as well as body weight perception. Additionally, we compared our evaluation's results to the results of similar and comparable VST AR and VR systems from previous work [57]. As expected, participants using our OST AR felt a significantly lower presence compared to VST AR and VR. However, for VBO and agency, we did not find clear differences between the systems. For body weight estimations, we could observe significant differences between OST AR and VST AR, but only descriptive differences between OST AR and VR. We further received extensive qualitative feedback supplementing the quantitative measurements and containing valuable information for further improvements.

6.1 Presence

We hypothesized that participants using OST AR would report a lower feeling of presence than participants using VST AR or VR (H1). The expectations could be confirmed for the relevant dimensions general presence, spatial presence, and realism. Hence, our hypothesis H1 could be confirmed. Our results are in line with previous work [8, 12, 52] and confirm our prior assumptions. The presumed reason for the differences could be the systems' different degrees of immersion, clearly affecting general and spatial presence. Interviews tend to confirm this assumption. For example, most participants immediately noticed the HoloLens 2's narrow field of view. Interestingly, the partial transparency of the virtual objects was reported as negative by only one participant.

Another factor influencing presence might be the perceived coherence and plausibility of the experience [24] as reflected by the realism score. For example, a rendered avatar as a mirror image within the real environment might be not be perceived as plausible as a rendered avatar as a mirror image within a rendered virtual environment. The discrepancy between reality and virtuality was also evident in the interviews, as the avatar's appearance was perceived as incongruous to the environment, particularly when seeing the real body next to the virtual body. Compared to the real environment, the virtual mirror was described as highly salient because of its transparency, image quality, and computer-animated reflection. Although we observed a significantly lower presence compared to more immersive systems, the question arises whether this difference is of relevance or negligible in behavior change scenarios. However, these questions need to be answered by dedicated studies.

6.2 Embodiment

For embodiment, we hypothesized that participants using OST AR would report a lower feeling of VBO (H2.1) and agency (H2.2) towards their avatar than participants using VST AR or VR. We could not confirm our hypothesis for VBO (H2.1), since we only found significant differences between VR OST and VR in the VEQ scores. These are generally unexpected but interesting results. The continuous visual observation opportunity of the real body in the egocentric perspective, as already discussed by other researchers [17, 57], was expected to lower VBO to a greater extent as observed and to lead to more significant differences. Similar to presence, place illusion and the plausibility of the virtual mirror image [24] could have also played a more important role. At the same time, research on full-body illusions in AR is still sparse, contributing to the difficulty in hypothesis formulation and allowing for unexpected findings. The qualitative statements support the quantitative results, as no particular display technology-related reason could be identified that clearly hinders VBO. In the context of our work, this result can be interpreted rather positively since the advantages of AR mentioned above might be utilized without a major loss of VBO. However, further research needs to consolidate our findings, especially when fully personalized or less realistic avatars are used.

Contrary to our hypothesis for agency (H2.2), we only found significant differences between OST AR and VR in the one-item question with tendencies for differences between OST AR and VST AR. Initially, we expected that the participants' direct view on the real body in our OST AR system would impact even more negatively on agency [17]. Compared to VST AR, where the real environment can only be experienced delayed via video stream, or VR, where the entire scene is rendered delayed, the full motion-to-photon latency in OST AR can also be experienced visually and not only proprioceptively. Supporting this assumption, the results of the qualitative data show that delays and inaccuracies in the avatar's movements were particularly noticeable at the arms and legs. Therefore, it is really surprising that the overall differences in agency have not been stronger, suggesting that agency in AR mirror systems might be more robust than expected. It also indicates that the measured latency of our system, averaging slightly above the threshold where agency might become affected [53], had a rather small impact. Similar has already been observed by Latoschik et al. [23] for their screen-based AR mirror system. Considering our evaluation's descriptive results and our post-hoc power analysis, we surely can not finally rule out an influence of the used display technology on both embodiment dimensions. Further research needs to confirm our findings.

6.3 Body Weight Estimation

We hypothesized that participants using OST AR would estimate the avatar's body weight differently than participants using VST AR or VR (H3). We could confirm this hypothesis since participants using OST AR estimated the avatar's body weight in comparison to VST AR and VR significantly higher. This is a particularly interesting finding, as it provides the first empirical indications that the display technology, depending on the display properties itself, impact on body weight perception as previously assumed [57]. It urges caution when concluding on absolute misestimations of body weight during self-assessment tasks supported by immersive systems, especially when testing user groups with a potentially disturbed body image. For example, underestimating the body weight of a highly personalized avatar as an obese user could be misinterpreted as a misperception caused by a disturbed body image, although the system itself promotes this underestimation. Before interpreting body weight estimations of a single person, a validation of the system's accuracy as a quality criterion based on a large sample seems inevitable. By predetermining system-specific deviation parameters, the absolute misestimations of individuals could be better interpreted.

Further exploration raises additional questions regarding the impact of the display technology on body weight estimations and the interplay with other factors. Although we employed a full-body illusion in a similar quality as Wolf et al. [57], we could not confirm the previous observations where a significant influence of participants'

BMI on body weight estimates was shown. While this effect has priorly been observed as a result of employing avatar embodiment [58] or avatar personalization [48], it is really interesting to observe that the predictive influence of BMI on body weight estimations decreases in our case with the different used display technology. This could point to another underlying mediator influenced by a general altered avatar perception due to system technology. However, further research is required to evaluate this observation systematically.

6.4 Implications

With regard to user experience and future use of AR full-body illusions in mental health, we showed that participants using our holographic AR mirror perceived similar high feelings of embodiment as participants using a high-immersive VR mirror system [57] similar to those used for mental health supporting applications [27, 50]. For presence, we measured lower feelings as usually observed for VR mirror systems [52, 57]. However, the relevance of the observed level of presence in our OST AR system is very difficult to assess without having conducted a controlled comparative study on efficacy since literature in this direction seems sparse [17].

More important seems to be the observed differences in body weight estimations between our OST AR systems and the systems used for comparison. The observed deviations, especially between the two AR systems, were enormous. For example, an avatar with an original weight of 68 kg would on average be estimated to weigh 63.29 kg in VST AR and 69.07 kg in OST AR. This example shows that an absolute interpretation of the weight estimate might be meaningless without a prior determination of the systemic bias. However, before this bias can be accurately determined, further research is needed on the underlying factors that influence the overall perception of the avatar and, in particular, body weight in immersive environments. This conclusion does not mean that a drastically weight-modified avatar could not be used in both systems as an adequate stimulus for behavioral change with the help of the Proteus effect. Consequently, the strength of the induced effect might differ for the same stimulus depending on the display technology and its bias.

Besides the noticed and discussed difference in presence and body weight estimations, our system offers users the opportunity to remain in the real environment while still having the possibility to confront themselves with a realistically appearing modified self-replica. Hence, direct comparisons between the virtual and the real body seem feasible without a heavy loss in the feeling of embodiment. Furthermore, an interaction between users and non-immersed people during exposition seems possible. A final potential advantage to be mentioned is the ease of use of our AR mirror system. With the technologies used, the users only have to put on the HoloLens 2 without having to attach additional markers or picking up controllers, being directly able to observe their mirror image.

6.5 Limitation and Future Work

In addition to the limitations already discussed and to the directions for further work already mentioned, we would like to add a few more points. First, in our evaluation, we did not collect comparative data but relied on data from previous work. When interpreting the results of our statistical analyses, it should be noted that although we tried to create the most comparable circumstances, there were still differences between our OST AR system and the VR and VST AR systems (e.g., markerless tracking vs. tracker-based tracking, different environments). For this reason, a holistic comparison under controlled conditions within the same time period is essential to confirm our findings.

Second, our work showed partially significant differences in body weight perception between the previously collected VST AR and VR conditions and our developed OST AR condition. The used OST display differed by its nature in many aspects from the previously used displays (e.g. FOV, resolution, luminosity). These properties have also led to significant differences in presence. Future research is needed to systematically investigate which displays' exact properties cause the observed differences in perception and how relevant they are for different use cases. When comparing presence between AR and VR, the use of questionnaires tailored to cross-media comparisons, such as the ITC-SOPI [25], should be considered.

Third, we investigated the feasibility of AR full-body illusions and evaluated their user experience in terms of potentially relevant treatment effect mediators. However, although our work was motivated toward mental health, finding the optimal setup for therapeutic use was not our intention. Therefore, future work needs to embed our results in an appropriate therapeutic setting. With rapidly advancing technology, the use of personalized and modifiable avatars might also be considered [2, 13, 48].

7 Contribution and Conclusion

Our presented novel holographic AR mirror expands the range of full-body illusion systems for behavior modification in the broad context of the Proteus effect towards OST display technology, which has so far been sparsely used. Our work further provided initial comparative insights between OST AR, VST AR, and VR embodiment mirror systems, revealing differences in presence and body weight perception that need to be further explored for a final classification in the given context. Interestingly, the AR mirror conveyed a similar feeling of embodiment as the more immersive solutions.

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