# The Impact of Avatar Personalization and Immersion on Virtual Body Ownership, Presence, and Emotional Response

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Fig. 1. All twelve avatar types as used in the study. From left to right in $2 \times 2$ blocks: The synthetic generic female and male avatars created with Autodesk Character Generator [3], the scanned non-individualized female and male avatars, and the personalized female and male avatars created from 3D scans of participants. The upper row represents the avatars as shown in the motion capturing suit condition and the bottom row the avatars in the condition, in which participants were scanned in their own individual clothes. The face of the individualized female avatar is blurred for anonymization reasons.

**Abstract**—This article reports the impact of the degree of personalization and individualization of users' avatars as well as the impact of the degree of immersion on typical psychophysical factors in embodied Virtual Environments. We investigated if and how virtual body ownership (including agency), presence, and emotional response are influenced depending on the specific look of users' avatars, which varied between (1) a generic hand-modeled version, (2) a generic scanned version, and (3) an individualized scanned version. The latter two were created using a state-of-the-art photogrammetry method providing a fast 3D-scan and post-process workflow. Users encountered their avatars in a virtual mirror metaphor using two VR setups that provided a varying degree of immersion, (a) a large screen surround projection (L-shape part of a CAVE) and (b) a head-mounted display (HMD). We found several significant as well as a number of notable effects. First, personalized avatars significantly increase body ownership, presence, and dominance compared to their generic counterparts, even if the latter were generated by the same photogrammetry process and hence could be valued as equal in terms of the degree of realism and graphical quality. Second, the degree of immersion significantly increases the body ownership, agency, as well as the feeling of presence. These results substantiate the value of personalized avatars resembling users' real-world appearances as well as the value of the deployed scanning process to generate avatars for VR-setups where the effect strength might be substantial, e.g., in social Virtual Reality (VR) or in medical VR-based therapies relying on embodied interfaces. Additionally, our results also strengthen the value of fully immersive setups which, today, are accessible for a variety of applications due to the widely available consumer HMDs.

**Index Terms**—Avatars, presence, virtual body ownership, emotion, personalization, immersion

## 1 Introduction

Embodied Virtual Environments require digital alter egos of the users' physical selves. These virtual replicas are called avatars. Avatars are users' embodied interfaces to and their proxy in the artificially generated environments. On the one hand, avatars provide a means of direct interaction with the environments based on the simulation of physical properties and cause an effect between virtual objects and the virtual bodies constituting the avatars in the virtual worlds. On the other hand, avatars are our proxies. They are the direct extension of ourselves into the virtual domain while they also constitute a close resemblance we only experience from our real physical bodies. That is,


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they are the digital representations tightly bound to our embodied self, our self-perception, and our personality.

As a result, avatar appearance, behavior, presentation, and control scheme cause a variety of psychophysical effects with users in control of the avatars as well as on other users sharing the same virtual worlds with our avatars. The acceptance of and identification with our virtual counterparts is called *illusion of virtual body ownership* (IVBO) [18, 27, 42]. This identification can (temporarily) lead to a change of the user's behavior and self-image as described by the *Proteus* effect [52]. For example, the effect of avatar appearance on our behavior has been confirmed for a variety of properties including gender [43], posture [14], figure [34], skin color [35], age and size [4], or degree of realism and anthropomorphism [23, 27, 37].

A typical method used for studying the psychophysical effects of avatars and their appearance and properties on the respective owning and controlling users is based on the virtual mirror metaphor. In this metaphor users approach a simulated mirror reflecting their virtual alter ego. Virtual mirrors have been used and tested in fully immersive VR systems based on HMDs (e.g., [43, 45]) as well as in lesser immersive VR systems like CAVEs (see, e.g., [50]) or even in low immersive "fake mirror" displays [23]. Notably, although the different virtual mirrors imply specific properties potentially affecting desired psychophysical effects, the impact of the degree of immersion has not been of particular interest so far.

Additionally, current advances in capturing individualized human bodies either by using depth cameras [12] or photogrammetry methods [1, 16] motivated a closer look into the effects of realism and personalized avatars [25, 28, 29, 37]. Still, elaborate individualized ready-to-animate high quality virtual characters of users used to be a labor-intensive and time-consuming process, which only recently could be optimized to be applicable for prolonged and extensive embodiment studies [1, 16].

### 1.1 Contribution

This article reports novel findings on two factors triggering or promoting embodiment effects in Virtual Reality based on human-like avatars. We investigated (1) the impact of avatar personalization and (2) the impact of the degree of immersion on virtual body ownership, presence, and emotional response as effects of embodied interfaces. The work combines recent advances in the optimization of a photogrammetry-based 3D scan process with two virtual mirror setups of different degrees of immersion. 32 participants could be tested with personalized avatars resembling their physical selves due to an optimized 3D scan workflow.

We found several significant and notable effects. First, personalized avatars significantly increase body ownership, presence, and dominance compared to generic counterparts, even if the latter were generated by the same photogrammetry process and hence could be valued as equal in terms of the degree of realism and graphical quality. Second, the degree of immersion significantly increases the body ownership, agency, as well as the feeling of presence.

### 1.2 Structure

This article will continue with a review of the related work. This will be followed by a description of the experimental design and the methods applied, including a short description of the used technical apparatus and the system for the photogrammetry-based avatar generation. Section 5 describes the performed experimental procedure, which is followed by a documentation of the results in Section 6. The paper closes with a discussion of the results and future work.

## 2 Related Work

Virtual embodiment describes the application of an artificial body as a virtual alter ego and proxy for the user's real physical body in an artificially generated Virtual Environment (VE). Initial work has been motivated by the classical rubber hand illusion [9]. This illusion lets participants accept a physical rubber replica of one of their forearms and hands as to be their real physical and biological extremity and hence to effectively trigger a resulting body ownership (BO). Once a convincing coherence is achieved between the artificial limb and a participant's mental body schema, BO can strongly affect participants' reactions to perceived interaction effects with the proxy limb. Typically this is confirmed using threat conditions to the rubber proxy to provoke a stress reaction of the participant.

Ijsselsteijn et al. [18] and Slater et al. [42] confirmed BO to transfer to Virtual Reality and to artificially generated virtual worlds and stimuli. Similar to the real physical world BO, the respective virtual body ownership (VBO) is triggered and promoted from artificial virtual stimuli. Most important, the so-called Illusion of Virtual Body Ownership (IVBO) relies on (parts of) virtual bodies instead of physical replicas as visually perceivable anchors for VBO to be effective. These virtual replicas are our avatars, our embodied interfaces in and to the artificially generated environments.

The IVBO promotes a variety of interesting psychophysical effects caused for the users controlling the avatars. Slater and Steed [44] confirmed that participants who had to interact with virtual objects through a virtual body had a higher sense of presence than those who interacted with a traditional user interface (pressing a button). Changing the visual and behavioral characteristic of a user's avatar will potentially also change the behavior [21], attitude [4, 35], and emotional involvement [14] of the user in control of the avatar. This *Proteus* effect [52] identifies a connection between our objective perception and a subjective interpretation and integration of the perceived information into our own cognitive models including expectations and preconception of role models. This effect has been explored for various dimensions, e.g., gender [43], posture [14], figure [34], skin color [35], age and size [4], exertion [53], or degree of realism and anthropomorphism [23, 27, 37].

Similar to BO, VBO is dependent on a convincing coherence between the real and the virtual body. For example, triggering the original rubber hand illusion relied on visuotactile stimulation of the real physical hand and the visual perception of the stimulus action performed on the artificial rubber proxy. This stimulation had to be synchronized in time and place to work effectively. Hence, the synchronized visuotactile stimulation acts like a promoter or even cause for inducing BO. Here, related work on IVBO and its promoters or triggers benefits from an extended design space: Virtual Reality technology allows to change virtual body appearance, behavior, and coverage with much less effort compared to physical setups where, e.g., the replication of a complete proxy body would only be possible with potentially complex and costly robotic tele-presence scenarios.

Related work on VBO differentiates two types of relevant factors to promote or trigger the illusion: (1) bottom-up factors (e.g., synchronous visual, motor, and tactile sensory inputs) are thought to be related to the multi-sensory integration and (2) top-down factors (e.g., similarity of form and appearance) [28, 48] are thought to be related to the conceptual interpretation of the observed virtual body parts.

Current results favor bottom-up factors such as first-person perspective, synchronous visuotactile stimulations, or synchronous visuomotor stimulations to be strong triggers for the IVBO effect [45]. Sanchez-Vives et al. could induce IVBO by using just visuomotor correlation without a visuotactile stimulus [40]. These findings were confirmed by Kokkinara & Slater [22], although a disruption of visuotactile or visuomotor synchrony could equally lead to a break in the illusion. Debarba et al. [15] did not find differences between 1PP (first person perspective) and 3PP (third person perspective) and suggested that visuomotor synchrony dominates over perspective.

The impact of top-down factors, i.e., of anthropomorphism or realism, for VBO is not as evident as the impact of the most important bottom-up factors. Lugrin et al. [28] found that VBO even slightly decreased for avatars with a higher human resemblance compared to a robot and a cartoon-like figure. As one reason for this finding they hypothesized this to be caused by a potential uncanny valley effect [32]. Latoschik et al. [23] used a different low immersive setup, but included individualized avatar faces scanned with a 3D depth camera. They did not find any difference in IVBO.

Both types of factors, bottom-up as well as top-down factors, rely on the avatar's visibility to the user. For a 3PP this can easily be achieved with a variety of graphics and VR setups. As for the 1PP, this is not as straightforward. Fully immersive systems based on HMDs do block out potentially diverting stimuli from the real physical surrounding, i.e., the real physical body. Similarly, see-through Augmented Reality (AR) glasses can be used since they would also allow to graphically occlude the real physical body. But both would initially only allow to see parts of one's own body. These parts are mainly restricted to the hands and forearms and the front side of the torso and the legs. However, projection-based large-screen VR systems of a potentially lesser degree of immersion [41], such as CAVEs [13], L-shapes, power walls, and alike, by design cannot prevent visibility of users' real physical bodies at all when looking directly at themselves.

To overcome the virtual body visibility drawbacks caused by the different VR and AR systems, IVBO research usually applies a virtual mirror metaphor [8]. A virtual mirror works for most VR and AR display types, it allows to inspect almost the complete full avatar body including the face, and a mirror is a well-known everyday tool in the real world. Hence it fosters suspension of disbelief and does not result in breaks in presence. The virtual mirror metaphor has been used in fully immersive VR systems based on HMDs (e.g., [28, 43, 45]) as well as in lesser immersive VR systems like CAVEs (see, e.g. [50]), and even in low immersive "fake mirror" displays [23]. Notably, although the displays used for these virtual mirrors significantly differ in the degree of immersion (as do some of the reported results from according studies), the potential impact of this factor on IVBO has not been investigated so far.

### 2.1 Discussion

Virtual embodiment can cause a variety of interesting effects as has been confirmed by prior work. Potential applications of avatars include virtual therapy, entertainment, or social Virtual Reality [6, 7, 24, 39, 46] and many more. It would be highly favorable to exactly know about the relevant triggers or promoters for IVBO and their respective relative effect strengths compared to each other. This would allow to, e.g., concentrate application design and development efforts on more important factors or to be able to manipulate and parameterize the to-be-caused target effects. The importance of visuomotor synchrony could repeatedly be confirmed. Findings for several other factors exist, but certainly would benefit from replication in different contexts. The context can have strong effects as could be shown in very recent work [26]. Relative effect strengths are only available for the apparently most important bottom-up factors.

Notably, we identified two factors which we would currently assess important, but whose impact on the IVBO and resulting embodiment effects is either missing or where the results are ambiguous or even contradictory at the moment. First, given the large variety of currently available VR and AR displays it is important to know the respective impact of the degree of immersion on the IVBO. Second, advances in capturing high quality 3D individualized human bodies by using photogrammetry methods [1, 16] enables a closer look into the impact of realism and personalized avatars as motivated by recent work [23–25, 28–30].

Unfortunately, until now, elaborated individualized high quality virtual characters of users, which are ready-to-animate, used to be a labor-intensive and time-consuming process, hence prior work either omitted personalized scans [28, 37], reduced the scan quality (using only depth cameras [23, 25]), or reduced the scan coverage (only scanning, e.g., heads [23]). The process to generate high quality 3D scans based on photogrammetry could just recently be optimized to be applicable for prolonged and extensive embodiment studies [1, 16]. For the work reported in this article we have utilized the avatar generation described in [1]

## 3 Rationale, Hypotheses, and Design

As pointed out in the preceding discussion (see Section 2.1), we identified ambiguous and missing results on the impact of (1) avatar personalization and of (2) the degree of immersion on VBO. The exploration of said potential impact(s) defines the overall research goal for the work reported here. Hence, avatar personalization and degree of immersion define the two independent variables.

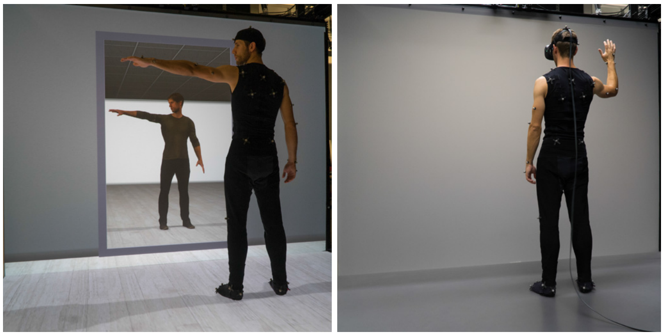

Fig. 2. The two VR setups used in the study. The participants were immersed in the same virtual room with a virtual mirror using an L-shape part of a CAVE (condition CM1, left) and a HMD (condition CM2, right). The participants wore a motion capturing suit to track their full-body motion by a passive marker-based motion capturing system. Note that in the L-shape condition the participants had to wear 3D glasses for stereoscopic visualization (not shown in the image).

As potentially affected embodiment target effects we chose (E1) *virtual body ownership* (including agency), (E2) *presence*, and (E3) *emotional response* as our dependent variables. (E1) *virtual body ownership* is a frequently studied embodiment effect (see, e.g., [15, 28, 40, 45, 48]) and hence is targeted here as the central embodiment effect for any potential impacts found. Similarly, (E2) the feeling of virtual *presence* is one of the most prominent psychophysical effects of Virtual Reality. Prior work on presence has reported that immersion [41] as well as general embodiment [19, 44, 47] do affect presence. Hence it is an appropriate measure to study the impact of personalization thought as a continuation of non-personalized general embodiment and to either confirm the reported impact of immersion or any unexpected deviation from prior results. Finally, we chose (E3) *emotional response*. Again, findings have reported emotion to be affected by immersion [5, 49] as well as by embodiment [33]. Hence, we chose *emotional response* as a dependent variable in accordance to our rationale to choose *presence*.

From the reported impact of general embodiment and immersion to increase presence and emotional response we bias our initial hypotheses as follows:

H1: Increased personalization increases the strengths of the target effects.

H2: Increased immersion increases the strengths of the target effects.

For H1 we defined the independent variable *personalization* in terms of appearance similarity between a user's real physical body (including the face) and his/her avatar. We chose three conditions as levels for this variable:

CP1: Generic avatar created with Autodesk Character Generator [3] (see left $2 \times 2$ block in Figure 1).

CP2: Generic avatar generated from 3D photogrammetry scan following [1] (see center $2 \times 2$ block in Figure 1).

CP3: Individualized avatar generated from 3D photogrammetry scan following [1] (see right $2 \times 2$ block in Figure 1).

As given for CP3 by design, avatars of the same sex as the respective participant were also chosen for CP1 and CP2.

Both visualization conditions, the low immersive L-shape (CM1) and the high immersive HMD (CM2), are depicted in Figure 2. For H2 we defined the independent variable *immersion* following the definition by Slater [41] to mean *"the extent to which the actual system delivers a surrounding environment, one which shuts out sensations from the 'real world', which accommodates many sensory modalities, has rich representational capability, and so on"*.

The restriction of the L-shape part of the CAVE was purposely chosen to further limit the extend to which that system delivers a surrounding environment as a means to further reduce immersion of the L-shape condition in contrast to the HMD condition. As a result we chose two conditions (see Figure 2) as levels for this variable:

CM1: Less immersive medium, a two-screen L-shape part of a CAVE.

CM2: More immersive medium, a Head-Mounted-Display.

Notably, for both systems we used the same full body tracking system to provide a convincing visuomotor synchrony in addition to the same render engine to minimize potential confounds between systems. Also, we named this variable *medium* (and not only immersion) for the following reason: CM1 (L-shape) is inferior to CM2 (HMD) concerning the occlusion capability of the real body in the virtual mirror metaphor as described in the related work. In a CAVE-like environment, such as the employed L-shape, users will be able to see their own physical body when they look down on themselves. This is different for the HMD condition where participants will see just their artificial avatar looking down on themselves and looking into the virtual mirror.

Due to the required full body tracking, participants had to wear a tracking suit, which certainly would look different than their own cloth they were allowed to wear for the scan. This difference between the clothes worn during scanning and the motion capture suit worn during the trials could potentially impact our central hypotheses, which we investigated by including a third hypothesis:

H3: A difference in clothing between the mirrored avatar and the physical body negatively affects target effects.

Accordingly, we included *clothing* as an additional independent variable with the following two conditions as levels:

CC1: Participants scanned in their own clothes.

CC2: Participants scanned in motion capture suit.

CC1 and CC2 were tested between groups, whereas the six conditions resulting from the combination of CP1, CP2, and CP3 with CM1 and CM2 were tested randomized in-between subjects. An overview of the procedure is depicted in Figure 5, and a detailed description is given in the forthcoming sections. Figure 3 depicts an example of three conditions CP1-CC1, CP2-CC1, and CP3-CC1 as a combination of the three *personalization* CP1–CP3 levels with the CC1 condition as used in the experiment.

## 4 Apparatus

In our experiments the participants were immersed in a large, mostly empty room in order to minimize distraction (see Figures 2 left and 6). In this room there was a virtual mirror on one of the walls, which reflected the virtual world including the avatar of the participants. During the experiment the movements of the participants were tracked and mapped directly onto their avatar in real-time. In the following we describe the different devices and equipment used for the experiments.

### 4.1 Avatar Creation

In order to generate the individualized scanned avatars of the participants for condition CP3 we employed the avatar reconstruction pipeline of [1], which is outlined below and illustrated in Figure 4:

1. Scanner: In a first step the participants' faces and full bodies are captured using two custom-built multi-camera rigs, which consist of 8 and 40 synchronously triggered DSLR cameras, respectively.
2. Point Clouds: From the camera images we compute two dense textured point clouds through multiview-stereo reconstruction, using the commercial software Agisoft PhotoScan [2].

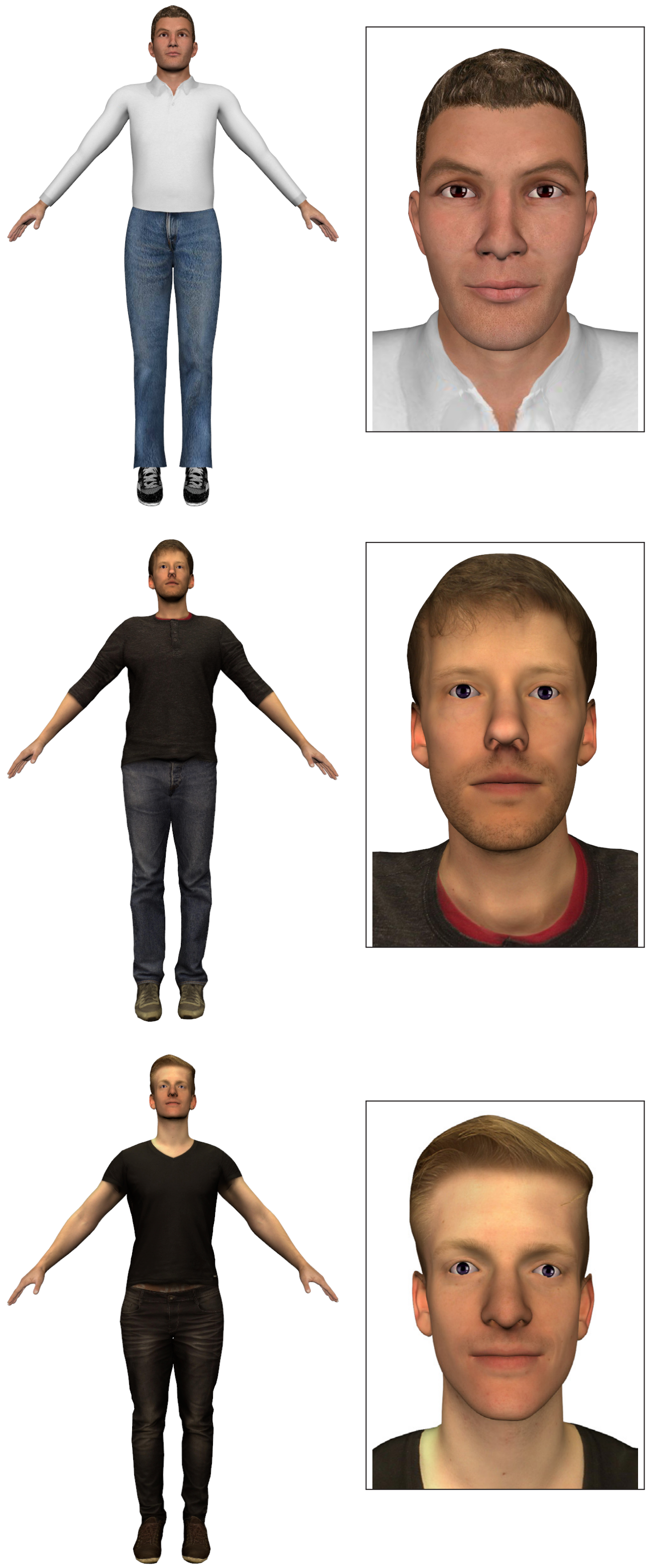

Fig. 3. Example screenshots including face close-ups of the three different avatar types as used in the clothed (CC1) male condition: generic avatar (top), generic scanned avatar (middle), individualized scanned avatar (bottom) of the participant.

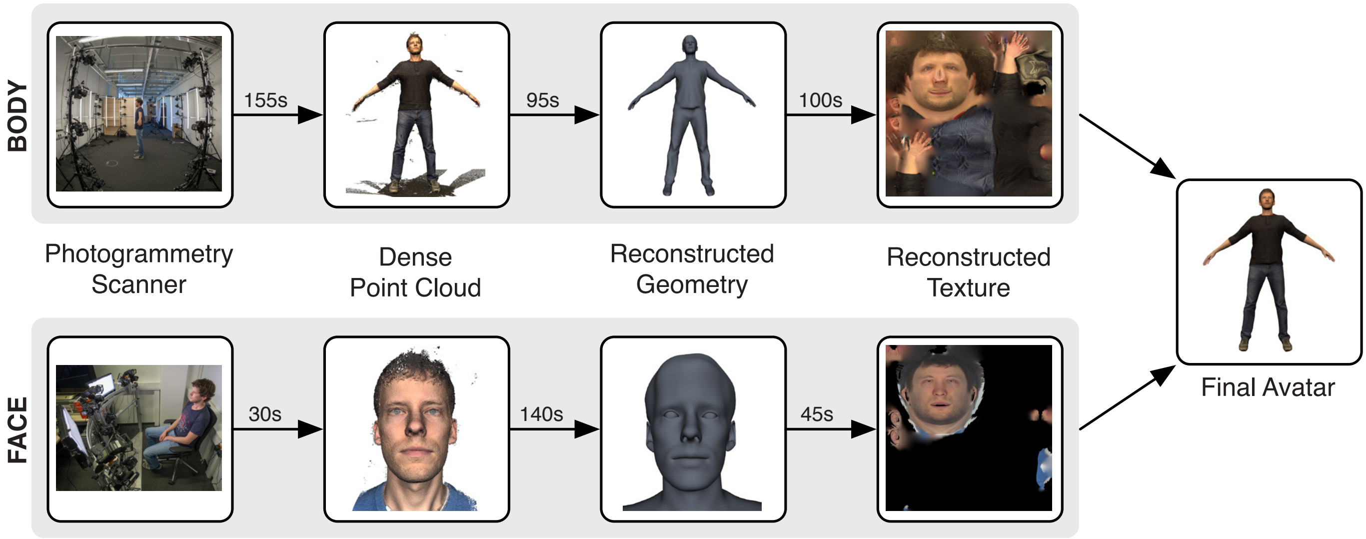


Fig. 4. Our avatar creation pipeline combines full-body scanning (top) and face scanning (bottom) to reconstruct high-quality avatars with detailed faces. Our two scanners consist of custom-built rigs of 40 cameras (full body) and 8 cameras (face). From their images we compute high-resolution point clouds through multi-view stereo reconstruction. A generic human template model is then fit to the body and face points to accurately reconstruct the model's geometry/shape. From this geometry and the camera images we compute high-resolution textures. In the end, body and face information are combined into a high-quality virtual avatar. The average time required for each step is given at the arrows symbols.

3. Geometry: In order to robustly deal with noise and missing data, a generic human template model (from Autodesk Character Generator [3], consisting of 60k triangles) is fit to the two point clouds using rigid registration, inverse kinematics, and deformable registration, while using a statistical human body model as regularization.
4. Texture: Once an accurate geometry/shape has been reconstructed, high quality 4k×4k textures can be computed from the mesh geometry, its UV texture layout, and the camera images [2].
5. Merge: Since the texture from the face scanner has more detail in the face region, it is merged into the texture from the full-body scanner using Poisson-based blending [36]. Similarly, the high-quality face geometry from the face scan replaces the less accurate face region from the full-body scan.

The initial template character is fully rigged, i.e., it provides a skeleton for full-body animation and facial blendshapes for face animation. These animation controllers are transferred onto the reconstructed individualized characters, which can therefore readily be animated in VR applications without any additional post-processing. For more details we refer the interested reader to [1].

Since the whole scanning and avatar generation process takes about ten minutes only, it can easily and conveniently be used to scan participants right before the VR experiment. Using this approach, we were able to create convincing avatars of consistently high quality for all participants of our study.

### 4.2 Full-Body Motion Capturing

A convincing virtual mirror requires to robustly and rapidly capture the participants' motions and to map them onto their avatars in real time. To this end we employ a passive, marker-based OptiTrack motion capturing system consisting of ten Prime 13W cameras running at 120 Hz. Participants therefore had to wear a tight black marker suit with overall 41 markers during the experiment (see Figure 2). Note that in the HMD condition the OptiTrack system was synchronized with the HMD's head tracking to avoid interference.

The motion capture software was running on a dedicated PC with Microsoft Windows 7 operating system and was equipped with a $4 \times$ 2.4 GHz Intel Xeon E5-2609 CPU and 16 GB of RAM. The motion data of 19 tracked joints were sent via a 1 Gigabit network to the PC running the render engine.

### 4.3 Visualization Systems

The employed L-shape (CM1) features front and floor projection, of which each screen has the dimensions of 3 m $\times$ 2.3 m. Stereoscopic visualization is driven by two projectors for each screen using INFITEC filters and glasses. The projectors had a spatial resolution of $2100 \times 1200$ pixels and a refresh rate of 60 Hz. In order to minimize latency due to network data transfer, the four projectors were driven by a single PC (Intel Xeon E5-2609 CPU with $4 \times 2.4$ GHz, 32 GB RAM, running Microsoft Windows 7). This machine was equipped with two Nvidia Quadro K5000 GPUs, each of which was connected to the two projectors of one screen.

For the HMD condition (CM2) we employed the HTC Vive. It features a spatial resolution of $1080 \times 1200$ pixels per eye, provides a wide horizontal field of view of 110°, has a refresh rate of 90 Hz, and a very robust and low-latency tracking of head position and orientation. The HMD was connected to a PC with Intel Xeon E5-1620 CPU with $4 \times 3.5$ GHz, 36 GB RAM, and a Nvidia GTX 1080 GPU, running Microsoft Windows 10.

In order to minimize confounding factors, both systems were driven by the same custom-built render engine, which was implemented in C++, employs modern OpenGL 4, and was specifically designed for low-latency visualization using a single-PC multi-GPU design [50]. In the L-shape condition, the rendering of floor and front wall was done in parallel on the two GPUs, while the left and right eye's views were rendered in a serial manner. For the HMD condition, the HTC Vive was controlled using the OpenVR framework.

Our engine supports character animation and visualization at high frame rates and low latency, while still providing a reasonable graphical quality. Both animation and visualization are implemented in terms of OpenGL shaders, and build on standard techniques like linear blend skinning, Phong lighting, and soft shadow mapping. On the hardware described above, our high-quality characters (60k triangles, 4k×4k texture) could be animated and rendered at 95 fps in the L-shape condition and at 90 fps on the HMD.

We measured end-to-end motion-to-photon latency of the virtual mirror setup by following the approach of [50]: A motion-tracked person moves an arm periodically up and down, and a high-speed camera (Sony RX100 V) records both the real person and the rendered animated avatar. Counting the frames in the resulting video that the avatar is offset from the real person reveals the latency. For the L-shape

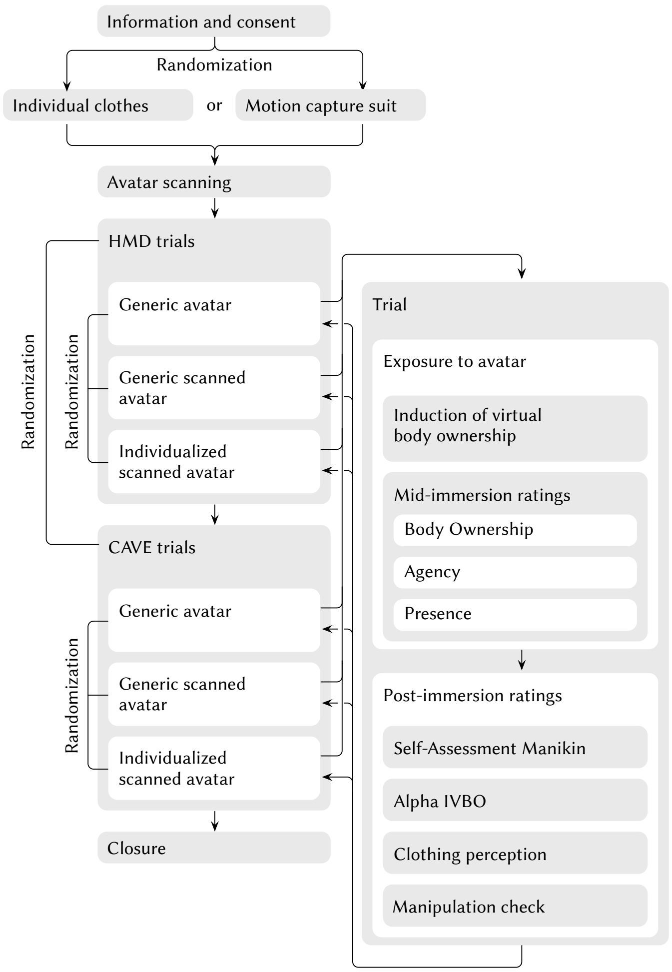


Fig. 5. Illustration of the experimental procedure. For each participant, an avatar was generated either in individual clothes or with a motion capture suit. For each avatar appearance condition participants completed an experimental trial in the L-shape and HMD setup in randomized order. In a trial virtual body ownership was induced, then subjective mid and post immersion ratings were assessed.

setup we measured an average end-to-end latency of 62 ms using this technique.

However, we were not able to measure latency with this technique for the HMD, since the camera cannot record the real person and the HMD lenses simultaneously at a sufficient resolution. Instead, we recorded the real person and the desktop monitor showing the preview window of the HTC Vive. This measurement revealed an average latency of 67 ms. As HMDs are optimized for low latency, we expect a lower latency for the HMD itself. Note that these latency values are for the full-body tracking only. The head tracking of the HTC Vive is independent of the OptiTrack motion capturing.

With the reported end-to-end latencies of 62 ms and 67 ms, respectively, both visualization setups performed below the critical thresholds for perceived sense of agency and sense of ownership as reported for a virtual mirror experiment by Waltemate et al. [51].

## 5 Procedure and Stimulus

An overview of the overall experimental procedure is illustrated in Figure 5.

### 5.1 Participants

32 participants were recruited for this study. All performed preparation (including scanning) and the trials. Three of which had later to be excluded due to problems with data recording. The final analyzed sample therefore consisted of 29 participants, 15 female and 14 male, with age ranging from 19 to 33 years ($M = 24$). None reported severe motor, auditive, or visual disabilities/disorders. All participants with visual impairment wore corrective glasses/lenses during the experiment.

All participants gave written informed consent and got paid for their participation. The study was conducted in accordance with the Declaration of Helsinki, and had ethical approval from the ethics committee of Bielefeld University.

Fig. 6. The virtual environment used for the experiment shown for the two stages of the trials: Before each trial the virtual mirror was turned off (left) and turned on as soon as the trial begun (right).

### 5.2 Preparation

Participants first read general information about the devices and techniques used in the experiment and afterwards filled in and signed the consent form.

Depending on the clothing condition, participants then either got scanned in their own clothes (CC1) or put on the motion capture (MoCap) suit (without markers attached) and were scanned wearing the suit (CC2). We randomized this condition so that we scanned half of the participants in their own individual clothes and the other half in the MoCap suit. After the scan the participant's height was measured to scale the avatars of all conditions (CP1–CP3) to the correct height.

While the participants' avatars were computed, they filled in demographic and simulator sickness questionnaires, and put on the MoCap suit if they did not wear it already. Subsequently, the retro-reflective markers were attached, mostly to the MoCap suit, but some markers were also glued directly onto the skin to enable a more precise skeleton tracking (see Figure 2).

### 5.3 Experiment

After the initial preparation phase participants read the instructions of the main part of the experiment. Among other information, which is laid out in the following paragraphs, they were given the definition of presence in these instructions. Additionally, they were explicitly instructed to relax their hands as well as their face to minimize the effects of absent hand and face tracking.

The main part of the experiment took place in the same area of the L-shape for both *media* conditions: L-shape as well as HMD as illustrated in Figure 2. Each trial consisted of six conditions per participant: three personalization conditions (CP1–CP3) and two immersion conditions (CM1, CM2). Participants either started with the L-shape and continued with the HMD or vice-versa in a randomized manner. Accordingly they performed the three personalization conditions in randomized order for each *media* condition. Figure 5 illustrates this procedure. In the clothing condition CC2, where participants were scanned in the MoCap suit, all avatars also wore the MoCap suit (top row in Figure 1) to factor out possible biases due to different clothes of the non-individualized avatars.

The virtual mirror was turned off before the trial to control the exposure time of the stimulus. The mirror was turned on and the avatar was shown to the participants as soon as the trial started. Both stages are illustrated in Figure 6. Subsequently, audio-instructions were played via loudspeaker. These instructions informed participants about which movements to perform and where to look at during the trial. The movement-related audio-instructions were:

1. *"Lift your right arm and wave to your mirror image in a relaxed way."*
2. *"Now wave with your other hand."*
3. *"Now walk in place and lift your knees as high as your hips."*
4. *"Now stretch out both arms to the front and perform circular movements."*
5. *"Now stretch out your right arm to the side and perform circular movements."*
6. *"Now stretch out your left arm to the side and perform circular movements."*

Each of the given movement instruction was followed by an instruction to look back and forth at the movement in the mirror and at the own body (*"Look at the movement in the mirror – on your own body – in the mirror – on your own body."*). This approach served two purposes: (a) all participants performed the same movements, and (b) participants were asked to constantly register the coherences between their body seen from 1PP body and their mirrored avatar to maximize potentially induced VBO, specifically the visuomotor synchrony between their movements. Depending on the immersion-related media conditions CM1 (L-shape) or CM2 (HMD) participants either saw their physical (CM1) or virtual (CM2) body from 1PP. Hence, while this was aiming at maximizing VBO by taking advantage of a strong bottom-up VBO trigger, it theoretically could also have negatively impacted VBO in the CC1 condition where participants had been scanned in their own clothes. Hence, the rationale for the additional in-between groups factor *clothing*.

After the described instructions and while participants were still immersed in the virtual environment, they were asked the mid-immersion questions related to body ownership, agency, and presence. See upcoming Section 5.4 on Measures. Finally, the virtual mirror was turned off, and participants were asked to take off the 3D glasses or the HMD and to leave the area of the L-shape.

Following each trial (evaluating a particular avatar in a particular visualization setup) participants filled in the respective questionnaires for our dependent variables on a desktop computer. The next section gives the complete list of the measurements taken during and after the trials.

After all trials were done, participants took off the MoCap suit and got compensated for their participation.

### 5.4 Measures

While participants were still immersed in the virtual environment we took mid-immersion one-item measurements aiming at body ownership, agency, and presence. To this end, participants were asked to answer the following questions spontaneously on a scale from 0 (not at all) to 10 (totally):

1. Subjective body ownership, adapted from [20]: *"To what extent do you have the feeling as if the virtual body is your body?"*
2. Subjective agency, adapted from [20]: *"To what extent do you have the feeling that the virtual body moves just like you want it to, as if it is obeying your will?"*
3. Subjective presence, as proposed in [10]: *"To what extent do you feel present in the virtual environment right now?"*

All participants were told in the instructions that *"Presence is defined as the subjective impression of really being there in the virtual environment."* These subjective one-item measurements taken during immersion are accepted to have high sensitivity and reliability [10, 17, 41].

Self-Assessment Manikin (SAM) scales [11] were used for non-verbal pictorial assessment of self-reported affective experience directly after exposure to the virtual environment. This measure assumes the conceptualization of emotion as three independent dimensional-bipolar factors valence, arousal, and dominance. Validity and reliability of the SAM scales are confirmed [11] and have been supported by numerous studies [31]. In the underlying model, valence indicates the degree of pleasure or displeasure that the participant experiences during exposure. Arousal represents the experienced degree of physiological activation, whereas dominance signifies the perceived state of own social dominance or submission.

After exposure to the virtual environment and the virtual avatar the subjective sensation of virtual body ownership was assessed with the Alpha-IVBO scale [38], consisting of the three sub-scales acceptance, control, and change as dimensions linked to the virtual body ownership. The acceptance component refers to accepting the virtual body as the own body (e.g. "I felt as if the body I saw in the virtual mirror might be my body.", "The virtual body I saw was humanlike.", "I felt as if the body parts I looked upon were my body parts."). The control component relates to the concept of agency (e.g. "The movements I saw in the virtual mirror seemed to be my own movements", "I felt as if I was controlling the movement I saw in the virtual mirror"). The change component reflects changes in self-perception (e.g. "At a time during the experiment I felt as if my real body changed in its shape, and/or texture.", "I felt an after-effect as if my body had become lighter/heavier.", "During or after the task, I felt the need to check whether my body still looks like I remember it."), see [38] for the original questionnaire. The question order was randomized. Participants were asked to indicate spontaneously and intuitively how much they agree to each statement in a 7-point Likert style response format (0 – strongly disagree, 3 – neither agree or disagree, 6 – strongly agree), i.e., higher values would indicate a stronger illusion regarding each sub-scale. Cronbach's $\alpha$s calculated for each within-factor measure (including both between-factor conditions) ranged between 6.79 and 9.34.

To determine perceptual changes in relation to the clothing manipulation, participants were asked

- *"To what extend did you have the feeling to wear different clothing from the clothes you were actually wearing?"*

on a scale of 0 (not at all) to 10 (totally), adapted from [43].

In order to assess if the personalization manipulation had been successful, participants were asked

- *"To what extent did you have the feeling that the virtual body was similar to your own?"*

on a scale of 0 (not at all) to 10 (totally).

## 6 RESULTS

Each scale was analyzed by separately applying a 3-factorial mixed-design analysis of variance (split-plot ANOVA) with the within-factors *immersion/medium* and *personalization* and the between-factor *clothing*. When necessary, Huynh-Feldt corrections of degrees of freedom were applied. Post-hoc comparisons were realized using pairwise $t$-tests. A priori significance level was set at $p < .05$, two-tailed. Partial $\eta^2$ ($\eta_p^2$) is reported as a measure of effect size.

### 6.1 Medium

The univariate analysis showed significant main effects of the within-factor medium (HMD, L-shape) for the mid-immersion scales body ownership ($F_{1,27} = 17.66$, $p < .010$, $\eta_p^2 = .40$), agency ($F_{1,27} = 7.71$, $p = .010$, $\eta_p^2 = .22$), and presence ($F_{1,27} = 32.04$, $p < .001$, $\eta_p^2 = .54$). Here, we further observed significant main effects for the post-immersion Alpha-IVBO sub-scales acceptance ($F_{1,27} = 14.57$, $p = .001$, $\eta_p^2 = .35$) and change ($F_{1,27} = 18.78$, $p < .001$, $\eta_p^2 = .41$).

### 6.2 Personalization

Significant main effects of the within-factor personalization were found for the mid-immersion scales body ownership ($F_{2,54} = 27.43$, $p < .001$, $\eta_p^2 = .50$) and presence ($F_{2,54} = 32.04$, $p = .001$, $\eta_p^2 = .21$), as well as for the post-immersion scales SAM dominance ($F_{2,54} = 9.98$, $p < .001$,

Table 1. Univariate main effects.

| Scale | Personalization$^{\dagger}$ | Medium$^{\dagger}$ | Clothing$^{\dagger}$ |
|---|---|---|---|
| Mid-immersion Body Ownership | *** (.50) | *** (.40) | |
| Mid-immersion Agency | | .010 (.22) | |
| Mid-immersion Presence | .002 (.21) | *** (.54) | |
| SAM Valence | | | .037 (.15) |
| SAM Dominance | *** (.27) | | |
| IVBO Acceptance | *** (.48) | .001 (.35) | |
| IVBO Change | | *** (.41) | |
| Clothing Perception | .023 (.14) | | *** (.41) |
| Manipulation Check: Similarity | *** (.67) | .034 (.16) | |

*Note.* $^{\dagger}$ $p$ ($\eta_p^2$); *** $p < .001$;

Table 2. Marginal means for the within-factor medium.

| Scale | HMD$^{\dagger}$ | L-shape$^{\dagger}$ | $p$ |
|---|---|---|---|
| Mid-immersion Body Ownership $^{a}$ | 5.00 ($\pm$ .31) | 4.66 ($\pm$ .41) | *** |
| Mid-immersion Agency $^{a}$ | 8.13 ($\pm$ .27) | 7.75 ($\pm$ .27) | .010 |
| Mid-immersion Presence $^{a}$ | 6.77 ($\pm$ .30) | 4.56 ($\pm$ .45) | *** |
| IVBO Acceptance $^{c}$ | 3.61 ($\pm$ .21) | 2.92 ($\pm$ .23) | .001 |
| IVBO Change $^{c}$ | 1.76 ($\pm$ .23) | 1.23 ($\pm$ .23) | *** |
| Manipulation Check: Similarity $^{a}$ | 4.80 ($\pm$ .30) | 4.26 ($\pm$ .32) | .034 |

*Note.* $^{\dagger}$ *Mean [$\pm$ standard error of the mean (SEM)];* *** $p < .001$;
*Likert scale range from low to high:* $^{a}$ *0 – 10,* $^{c}$ *0 – 6;*

$\eta_p^2 = .27$) and the Alpha-IVBO sub-scale acceptance ($F_{2,54} = 25.16$, $p < .001$, $\eta_p^2 = .48$).

## 6.3 Clothing

For the between-factor clothing, a significant main effect for the scale SAM valence was found ($F_{1,27} = 4.80$, $p = .037$, $\eta_p^2 = .15$). The perception scale for clothing showed a significant main effect for the between-factor clothing ($F_{1,27} = 18.83$, $p < .001$, $\eta_p^2 = .41$) and for the within-factor personalization ($F_{1.64,44.25} = 4.45$, $p = .023$, Huynh-Feldt-$\varepsilon = .82$, $\eta_p^2 = .14$).

The manipulation check scale for similarity showed a significant main effect for the within-factors personalization ($F_{2,54} = 55.45$, $p < .001$, $\eta_p^2 = .67$) and medium ($F_{1,27} = 5.00$, $p = .034$, $\eta_p^2 = .16$).

An overview of significant main effects and effect sizes is given in Table 1. Marginal means for significant main effects are listed in Table 2 for the within-factor medium, in Table 3 for the within-factor personalization, and in Table 4 for the between-factor clothing.

# 7 Discussion

### H1: Personalization Impact

H1 assumed that increased personalization increases the strengths of the target effects. This could be confirmed particularly for the IVBO sub-scale *Acceptance* and was also strengthened by the mid-immersion BO results. Personalization also had a notable impact on increasing presence which, on the one hand confirms the known impact of general embodiment on presence, e.g., from [19,44,47], but it also adds a novel finding concerning the specific appearance of the respective avatars. Finally, personalization also had a significant impact on increasing *SAM Dominance*. Hence, in general we found increased personalization to trigger a notable and significant increase of the strengths of the target effects for all three dependent variables (E1) body ownership, (E2) presence, and (E3) emotional response. The comparison of the marginal means also supports personalization to be the relevant factor here, since the main differences were recorded between the personalized avatar and the other two conditions and not between the other two non-personalized conditions alone.

Personalization did not affect all sub-scales in the respective measures, but it did have an impact on the measures thought to potentially be correlated to the participants' self-perception and identity, i.e., *SAM Dominance* and *IVBO Acceptance*. Our mid-immersion one-item presence measure did not include any sub-scales but was affected as a whole. Consistently, personalization did not have an impact neither on mid-immersion *Agency* nor on *IVBO Control*. Both can be thought to be much more affected by bottom-up visuomotor synchrony. This result is in line with the general assumption that the identification of similarity is a separate top-down factor for triggering the IVBO. The manipulation check for *Similarity* also confirmed that the personalized avatars were significantly identified to have a stronger resemblance to the respective participants. This validates the overall assumption that the scanned avatars do increase the resemblance to the participants' physical selves and it also confirms the quality of our apparatus and the applied scanning method.

### H2: Immersion Impact

H2 assumed that increased immersion increases the strengths of the target effects. This hypothesis could partly be confirmed. We could identify an amplification impact particularly for the IVBO sub-scales *Acceptance* and *Change* and for all mid-immersion measures for VBO, agency, and presence. The medium also revealed an impact on the similarity check, which is in line with and closely related to the IVBO *Acceptance*. The comparison of the marginal means between the HMD and the projection-based L-shape confirms the impact as to increase between the CM1 condition (the L-shape) thought to be of lesser immersion and the CM2 condition of higher immersion (the HMD) which is in line with the existing results on the impact of immersion on presence as expected from [41].

The significant result for the *IVBO Change* sub-scale does support an impact that lately was indicated for a similar very low immersive virtual mirror we have developed. Since the *Change* factor seems to be an important factor for the Proteus effect, applications which rely on the latter could benefit from higher immersion. In contrast to the related work that did not find a difference of VBO between 1PP and 3PP [15], degree of immersion does have an impact although one could assume a 3PP to, in general, have a lower immersion compared to a 1st person perspective. This is an interesting contradiction seeking for an explanation. Also, our media conditions did not reveal any impact of immersion on emotional response as potentially could have been expected [5, 49]. An explanation for this might be twofold. On the one hand, our choice of task purposely did reduce any distracting additional stimuli as much as possible and was focusing on uniform body movements and their perception. Specifically, we tried to avoid power posing and alike. Hence, the identified impact of the personalization factor might have overshadowed any impact of immersion.

### H3: Clothing Impact

H3 assumed that a difference in clothing between the mirrored avatar and the physical body negatively affects target effects. Besides the significant effect on the respective control measure (see below), there only was a minor effect of this factor on *Valence*, which could be attributed to a certain extent to participants to feel uncomfortable when asked to wear different clothes. It should be noted that a motion capture suit most certainly is inferior in both personally preferred comfort and appearance/look. The marginal means support the preference for the individual clothes. There was a significant impact of the clothing on the clothing perception as the according control measure, which confirms this factor to be clearly noticeable and hence potentially effective. But besides the minor effect on *Valence*, which in turn was not affected by any other of our independent variables, we could reject H3 and hence rule-out any suspected impact induced by the varying occlusion capability of the real body in the virtual mirror metaphor between CM1 (the L-shape) and CM2 (the HMD).

## 7.1 Limitations

We chose to induce the illusion in a most controlled way in order to prevent any third variable bias. The overall task to inspect one's own real/virtual body from 1PP and the respective reflection in the virtual mirror purposely aimed to avoid additional confounds from a more complex game application context, which we lately identified

Table 3. Marginal means for the within-factor personalization.

| Scale | (1) Generic hand-modeled avatar† | (2) Generic scanned avatar† | (3) Individualized scanned avatar† | $p$ (1 to 2)§ | $p$ (1 to 3)§ | $p$ (2 to 3)§ |
|---|---|---|---|---|---|---|
| Mid-immersion Body Ownership [a] | 4.42 (± .42) | 4.75 (± .38) | 6.82 (± .35) | | *** | *** |
| Mid-immersion Presence [a] | 5.28 (± .35) | 5.58 (± .36) | 6.14 (± .34) | | .002 | .015 |
| SAM Dominance [b] | 6.62 (± .28) | 6.79 (± .26) | 7.35 (± .24) | | *** | .004 |
| IVBO Acceptance [c] | 2.66 (± .23) | 3.11 (± .23) | 4.02 (± .22) | .033 | *** | *** |
| Clothing Perception [a] | 3.802 (± .49) | 4.01 (± .43) | 2.80 (± .41) | | | .016 |
| Manipulation Check: Similarity [a] | 2.92 (± .45) | 3.11 (± .46) | 7.56 (± .30) | | *** | *** |

*Note.* † *Mean (± SEM);* § *pairwise comparison of indicated levels; *** $p < .001$; Likert scale range from low to high:* [a] *0 – 10,* [b] *1 – 9,* [c] *0 – 6;*

Table 4. Marginal means for the between-factor clothing.

| Scale | Motion capture suit† | Individual clothes† | $p$ |
|---|---|---|---|
| SAM Valence [b] | 6.63 (± .32) | 7.56 (± .29) | .037 |
| Clothing Perception [a] | 1.96 (± .54) | 5.10 (± .49) | *** |

*Note.* † *Mean (± SEM); *** $p < .001$;*
*Likert scale range from low to high:* [a] *0 – 10,* [b] *1 – 9;*

to potentially interfere with bottom-up factors for VBO [26]. We suggest to carefully investigate potential generalization in cases of more complex stimuli such as immersive video games.

Also, facial expression is an important channel for social signals and as such is very prone to the detection of derivations and hence the potential provocation of eeriness. Nevertheless, in contrast to [23], we had to avoid facial expressions due to the unreliable face detection in our setup of the HMD condition. Alternative sensing methods might overcome this problem in future work. Finally, with average end-to-end latencies of 62 ms and 67 ms we also had to restrict movements to medium speeds and accelerations in order to not break bottom-up visuomotor synchrony.

## 8 Conclusion

This article reported novel findings on (1) the impact of avatar personalization and (2) the impact of the degree of immersion on virtual body ownership, presence, and emotional response as potential effects of embodied interfaces. We have developed a 3D-scanning system based on photogrammetry and an optimized processing workflow which allows to capture personalized avatars in short time (about 10 minutes each). This apparatus was used for the first time in a self-perception user study combining effects of personalization and immersion. In particular, this study greatly benefited from the optimized scanning and reconstruction process. So far, the generation of high quality personalized avatars was a labor-intensive process which required a lot of manual intervention and hence rendered similar undertakings time-consuming and costly. Hence, the impact of avatar personalization on body ownership, presence, and emotional response was – to our best knowledge – not known so far.

We found several significant and notable effects. First, personalized avatars significantly increase virtual body ownership, virtual presence, and dominance compared to generic counterparts, even if the latter were generated by the same photogrammetry process and hence could be valued as equal in terms of the degree of realism and graphical quality. Second, the degree of immersion significantly increases virtual body ownership and agency, and we could confirm its impact on the feeling of presence. As such, our findings add two important factors that impact the IVBO and virtual presence to the existing body of knowledge and they additionally contribute insight into the influence of our investigated factors on certain emotional responses.

### 8.1 Future Work

Given the number of confirmed factors which trigger IVBO there still are many open questions as to their mutual strengths and importance. Ideally, we imagine a correlation matrix that assigns every pair of impact factors some ordinal relation, hence a need for replicable studies filling this matrix, which in turn would greatly help developers to decide on which aspects to concentrate resources if the goal is a manipulation of embodiment effects. This matrix is a global goal we would like to follow with our future work. Accordingly, this goal would include a closer examination of the relation between personalization, immersion (including perspective), emotion, and context, as motivated by the open questions resulting from the work reported here.

Related work gave some indication that an uncanny valley effect might also exist for avatars. We did not encounter such an effect here, but we also can neither confirm nor deny the existence of such an uncanny valley. We have not measured eeriness in our study and cannot substantiate any claims about our avatars and where and on which side of the (potential) valley they would reside in terms of eeriness. We are planning to tackle this question in future work and are planning to include face tracking into the study design as motivated by [23].

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