Over My Hand: Using a Personalized Hand in VR to Improve Object Size Estimation, Body Ownership, and Presence

Sungchul Jung
Department of Computer Science,
University of Central Florida, USA
HIT Lab NZ, University of
Canterbury, New Zealand
sungchul.jung@canterbury.ac.nz

Gerd Bruder
Synthetic Reality Laboratory,
University of Central Florida, USA
gerd.bruder@ucf.edu

Pamela J. Wisniewski
Department of Computer Science,
University of Central Florida, USA
pamwis@ucf.edu

Christian Sandor
Nara Institute of Science and
Technology, Japan
sandor@is.naist.jp

Charles E. Hughes
Department of Computer Science,
University of Central Florida, USA
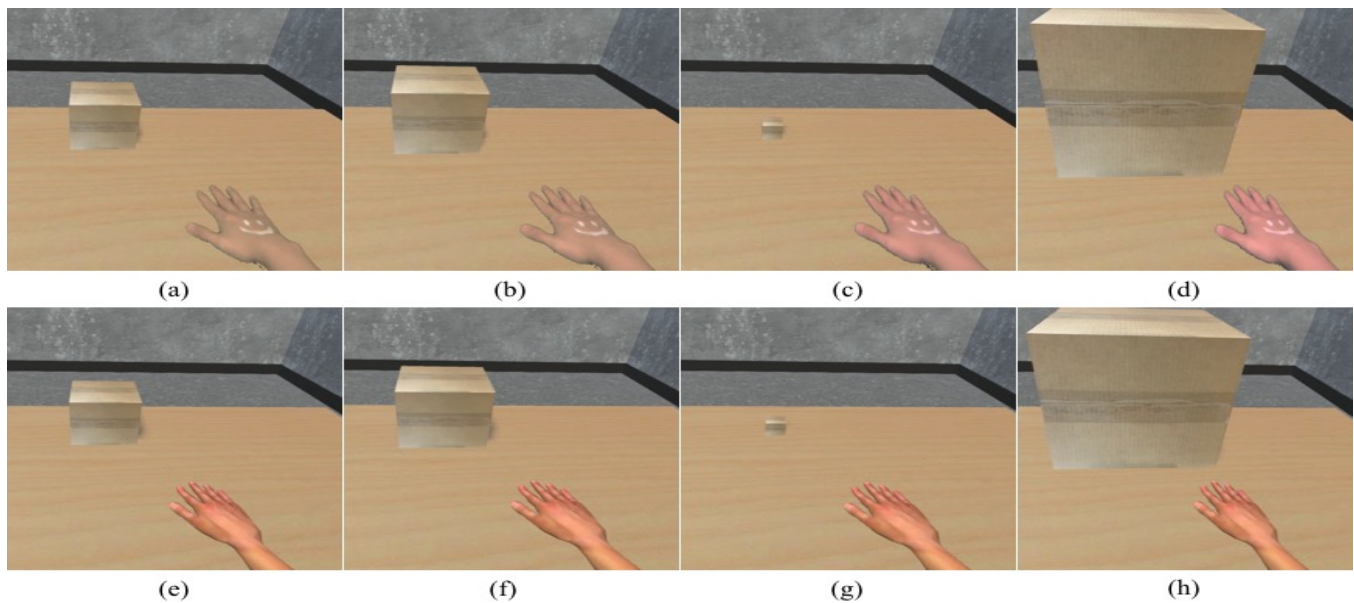ceh@cs.ucf.edu

Figure 1: Series of screenshots depicting a participant approximating the size of a virtual box on a table, while receiving supporting size cues from their hand resting on the table. The top row shows the personalized hand condition, whereas the bottom row shows the generic virtual hand condition. The left two columns show the perceptual matching task in which participants scaled a virtual box to match a previously seen physical box. The right two columns show the corresponding tasks where they attempted to scale a virtual box's size to a verbally communicated absolute value of 5 cm or 38 cm.

ABSTRACT

When estimating the distance or size of an object in the real world, we often use our own body as a metric; this strategy is called *body-based scaling*. However, object size estimation in a virtual environment presented via a head-mounted display differs from the physical world due to technical limitations such as narrow field of view and low fidelity of the virtual body when compared to one's real body.

In this paper, we focus on increasing the fidelity of a participant's body representation in virtual environments with a *personalized hand* using personalized characteristics and a visually faithful augmented virtuality approach. To investigate the impact of the personalized hand, we compared it against a generic virtual hand and measured effects on virtual body ownership, spatial presence, and object size estimation. Specifically, we asked participants to perform a perceptual matching task that was based on scaling a virtual

box on a table in front of them. Our results show that the personalized hand not only increased virtual body ownership and spatial presence, but also supported participants in correctly estimating the size of a virtual object in the proximity of their hand.

CCS CONCEPTS

• **Human-centered computing** → **User studies**; **Virtual reality**; *Mixed / augmented reality*;

KEYWORDS

Personalized Virtual Body; Virtual Body Ownership Illusion; Virtual Object Size Manipulation; Virtual Reality; Presence

1 INTRODUCTION

As immersive virtual reality (VR) technologies evolve, transformative virtual experiences are now becoming possible with effective means to observe and interact with computer-generated worlds. For example, when experiencing a virtual environment (VE) from a first-person perspective while wearing a head-mounted display (HMD), we can be a different person; we can move with our virtual body to another virtual place; or we can use our virtual hands to touch and manipulate the virtual objects around us. To understand such embodied virtual experiences, VR researchers have studied the concept of *presence* [29, 30], i.e., the sense of being in the virtual world, as well as *virtual body ownership illusion* [18], i.e., one's self-consciousness of one's own body regarding a given self-representation in the VE. Moreover, VR researchers have investigated how a virtual body changes our perception of sizes and distances in VEs.

Object size perception depends on various cues from our surrounding environment, such as depth cues, familiar object sizes, shadows, viewing angles, and more. Although object size estimation integrates multiple factors, this procedure is very sensitive and prone to estimation errors, as documented by the fact that size and distance estimation in VEs often differ from the real world [20, 26]. In the real world, an invariant in this process is our own body, which thus lends itself as a reliable metric; this process is called *body-based scaling* [23]. For example, we can use the known shape and size of our hand as a relative size cue when estimating the size of an unknown physical or virtual object. However, in VEs with different forms of one's body representation, such cues from our body can differ from what our perceptual system is trained on, which might be a cause of some of the observed differences.

Kilteni et al. [18] noted that semantic memory and knowledge help to shape generic human body information regarding posture, and structural properties of our body, if specific body information is given. In this scope, we hypothesize that not only the overall shape and size of our own body but also subtle *personalized body cues* and features on our hands such as scars or even temporary

changes such as paint applied to our hands are important cues that can facilitate improved size estimation in virtual worlds.

In this paper, we investigate a *personalized hand* as a supportive factor to increase not only the subjective feelings regarding virtual body ownership illusion and spatial presence but also the objective perception that allows users to estimate the relative size of virtual objects in the VE. Therefore, we compare two conditions: a highly-personalized hand created by combining temporary personalizations with an augmented virtuality hand approach [2, 6, 12, 14–16], and a generic virtual hand provided as a baseline condition denoting the most common use of a virtual body in VR.

This paper is structured as follows. Section 2 gives an overview of related work. Section 3 describes the experiment that we conducted to investigate our personalized hand approach. Section 4 presents the results with associated discussions in Section 5. Section 6 concludes the paper and suggests future research directions.

2 RELATED WORK

In this section, we describe related work on object size estimation, spatial presence, and virtual body ownership illusion in the scope of a personalized or generic body in VEs.

2.1 Object Size Estimation

A substantial body of literature exists on the topic of distance estimation in VR (e.g., see [20, 26] for review articles), which elucidated various factors that facilitate overestimation of close distances and underestimation of longer distances in VEs. Compared to this research on distance estimation, there is only limited research on size estimation in VEs. Overall, this limited research suggests that size is perceived reasonably accurately in VEs [9, 10, 17, 31] when rich familiar size cues are present in the environment. One type of familiar size cues that could reasonably support size estimation is the user's own body. To investigate the impact of a given virtual body and its size on the perception of visually perceived objects, Tajadura-Jimenez et al. and Banakou et al. conducted human-subject studies with a virtual mirror to reflect the participant's body size changes [4, 32] while Hoort et al. conducted a study with an invisible body condition [33]. These studies consistently showed that the size of the virtual body has a strong impact on the perception of virtual objects. Moreover, Linkenauger et al. focused on the user's hands and manipulated the size of a virtual hand while a participant was observing a virtual object [19]. Similarly, they also found that the size of the virtual hand of the participant was a critical factor in perceiving the sizes of other virtual objects. In this paper, we extend this research by investigating the benefits of a high-fidelity personalized hand in VEs.

2.2 Spatial Presence

Spatial presence refers to a sense of "being there" in a computer-generated virtual world [27, 29] or the perception of existing in another space [22]. In this scope, Slater introduced the concepts of *place illusion* and *plausibility illusion*, which together define presence [28]. According to Slater, the latter refers to the illusion that "the scenario being depicted is actually occurring" and that it requires a "credible scenario and plausible interactions between the participant and objects and virtual characters in the environment."

A reasonable body of literature has investigated the contributions of seeing one's body in VR on the sense of being spatially present in the virtual space. Even a generic virtual body, i.e., a basic body type that is used as a substitute for the user's actual physical body, can improve the user's sense of presence. Recently, due to the advent of advanced scanning technology for creating virtual self-representations for users in VR, researchers focused on the effect of personalization of the virtual body for spatial presence. For instance, Lucas et al. showed a positive effect of one's own body on the subjective feeling of presence using a scanned personal body in a 2D screen based third-person perspective game environment [21]. With similar scanning technology in a VR setup, Waltemate et al. provided a comparison between a wooden generic body and a 3D scanned personalized body that showed the personalized body's benefits on self-perception including virtual body ownership, although they did not find a significant difference on presence in their experiment [34]. Based on a similar scanning pipeline, Latoschik et al. conducted human-subject studies using a fully scanned personalized body including the individual's clothes in a VR environment [7]. The higher level of personalization with the individual's clothes showed benefits for presence and virtual body ownership in VR. While the visual quality of such a scanned body with consumer hardware is still very limited, which reduces its practical applicability, personalization of a user's virtual body is considered a strong factor that can facilitate a higher sense of spatial presence. In this paper, we extend this research direction by considering further temporary personalized characteristics such as washable paint or ink applied to the user's hands.

2.3 Virtual Body Ownership

When investigating virtual body ownership in VR environments, Kilteni at el. suggested that several factors such as a virtual body's resemblance to human appearance, synchronous visuotactile cues, synchronous visuomotor cues, positional congruence, and anatomical plausibility are major components for virtual body ownership illusion [18, 25]. The sense of body ownership, which refers to self-consciousness of one's own body, has been regarded as one of the critical components to indicate the level of presence in VR ever since the first rubber hand experiment was conducted by Botvinick and Cohen using a fake rubber hand [5]. Building on this basic idea, Ye and Steed suggested an extended version of the body ownership study using improved VR technology including an HMD and hand trackers [35]. Using similar devices, Argelaguet et al. conducted a study that revealed strong correlations between the human visual and motor sensory systems when seeing one's hand in VR [1]. Hoyet et al. designed an experiment using an unnatural hand shape that had six fingers, and they showed that even the unnatural hand shape caused a sense of body ownership [13]. Since most experiments focused on human physical characteristics regarding virtual body ownership, Jung et al. developed an experimental platform to understand the relationship between personalized body cues and virtual body ownership illusion and spatial presence using a virtual mirror as an augmented virtual environment [14, 15]. Also, Jung et al. showed that a gradual transition of the user's body from real to virtual can improve body ownership and presence in comparison

Table 1: Anthropometry of a hand size comparison (*M* inches, *SD*)

	Our Data		Gordon et al. Data	
	Width	Height	Width	Height
Male	5.86, 0.54	7.17, 0.47	3.56, 0.17	7.63, 0.39
Female	4.33, 0.17	6.11, 0.01	3.13, 0.15	7.10, 0.38

to traditional HMD-based VR environments that use instantaneous transitions.

3 METHODS

In this section, we describe the experiment that we conducted to investigate the impact of a personalized hand on object size estimation, virtual body ownership illusion, and spatial presence.

3.1 Participants

Before recruiting participants, we conducted an a priori power analysis to compute the required sample size using G*Power [8]. For a medium effect size with a power of 0.8, we determined the need for a minimum of 24 participants. We recruited participants using on-campus fliers at the local university. We conducted our experiment with 17 male and 7 female participants (age $M = 26.6$, $SD = 9.3$). We had to exclude one participant's data from the analysis due to a strong feeling of dizziness during the experiment. All participants had normal or corrected-to-normal vision. Most participants had a higher education background and were studying in diverse majors, but mainly in computer science. We assumed that object size estimation performance would be sensitive to the participant's hand size in this experiment. Hence, we measured the width and height of each participants' right hand for male and female, respectively. Since a naturally open-fingered hand shape is neutral in daily life and the finger positions including thumb could perceptually affect body-based scaling, we measured the width from the tip of the thumb to the end of the smallest finger joint, in contrast to Gordon et al. [11] who took only the width across the finger knuckles. Thus our reported size is about 2 inches wider than theirs. We provide the anthropometry of hand sizes, comparing our collected data to Gordon et al. data in table 1. We confirmed the appropriateness of using our hand size since the comparison did not show a significant difference in height and the difference in width was justified by our means of measurement versus theirs.

Participants received a small monetary compensation for their participation.

3.2 Material

In this experiment, we used an experimental setup consisting of an HTC VIVE HMD, to which we attached and calibrated an Ovrvision Pro stereo camera rig (see Fig. 2b). Hence, the HMD was capable of either rendering a fully immersive virtual environment or one that integrated the video feed from the front-facing stereo cameras into the user's view of the virtual world. Participants were seated in front of a desk, which was covered in a green material for use as a Chroma Key (green screen) background (see Fig. 3b). Using this approach, all green pixels in the Ovrvision Pro camera

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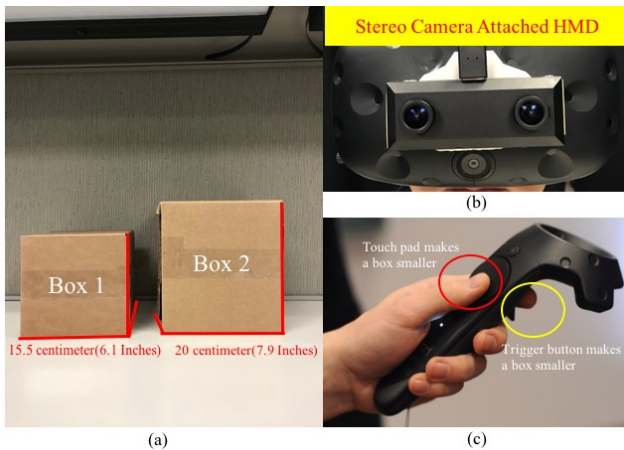

Figure 2: Experiment setup: (a) Two different sizes of physical boxes for observation. (b) Stereo cameras attached to an HTC VIVE HMD for rendering a video see-through hand in the virtual environment. (c) An HTC VIVE controller to manipulate the virtual object size using two buttons.

images were identified as background pixels and only those pixels that corresponded to foreground objects were overlaid over the participant's rendered view of the virtual world in the HMD. As a result, the participants were able to naturally see their actual hands in the VE, although the visual appearance differed slightly due to its video representation. This form of virtual body feedback is sometimes called an *augmented virtuality (AV) body* and stands in contrast to the traditional form of a *virtual reality (VR) body*. In Milgram's reality-virtuality continuum [24], *augmented virtuality* denotes such environments in which the predominant virtual space is enhanced with real-world objects. In contrast, *augmented reality* denotes environments in which the predominant real space is enhanced with virtual objects.

The HMD and Ovrvision Pro were hooked up to an Intel computer with core i7 CPU and NVIDIA GeForce GTX 1080 GPU and 16GB of RAM. The computer was used for rendering using the Unity 3D engine, system control, and logging.

Furthermore, for the experiment, we prepared two physical boxes of different sizes, which had a uniform color and a uniform size in width, height, and depth (see Fig. 2a). The boxes had sizes that were either slightly smaller (15.5 cm) or larger (20 cm) relative to a participant's typical hand size using the anthropometry of hand sizes reported in table 1

Once the participants donned the HMD and were immersed in the VE, they could not see the physical boxes, but they saw a virtual box in front of them, which had a variable size (see Fig. 1). They could manipulate the size of the virtual box using an HTC VIVE controller with their left hand. To minimize the learning curve for the experiment, we designed the system with only two buttons – the touch-pad button made the box larger (see Fig. 2c, red circle) and the trigger button made it smaller (see Fig. 2c, yellow circle).

3.3 Study Design

In this experiment, we used a within-subject design with the three independent variables *Hand Representation* (Personalized AV Hand,

Generic VR Hand), *Perceptual Matching Task* (Relative Size Matching, Absolute Size Matching), and *Box Size* (relative: 15.5 or 20 cm, absolute: 5 or 38 cm). We used a Latin-square order on the first two conditions to avoid any ordering effect. The box sizes were, however, always presented as smaller then larger as our goal there was accuracy and we did not feel order had any influence in this condition. The experiment was approved by our organization's Internal Review Board Office.

3.3.1 Conditions. We designed the following two conditions for the independent variable *Hand Representation*:

- **Personalized AV Hand**: In this condition, the participants could see their own personal hands via the stereo cameras using the augmented virtuality approach described above. Furthermore, they could see any temporary personalized effects such as paint on their hands (see procedures below).
- **Generic VR Hand**: This condition did not use the stereo cameras and instead presented a virtual hand model to the participants at their own hand's physical pose. This baseline condition matches the common procedure in VR to use generic virtual hands without any personalization for users. For this condition, we adopted one-sized (width = 5.2 inches, height = 6.4 inches) gender-neutral virtual hand, and we confirmed its appropriateness based on the anthropometry of a hand size data in table 1

We deliberately chose these two experimental conditions even though they combine multiple factors, including the type of hand representation (AV and VR) and the ability to represent temporary personalized effects. We made the decision to combine these two factors to create the strongest personalized hand we could. Our rationale is that if we can show a significant benefit of this personalized AV hand over the most common representation, i.e., a generic VR hand, we would thus have shown the importance of these cues, while the detailed contributions of each of the involved factors could be investigated in future work.

For the *Perceptual Matching Task*, we chose two conditions. Participants were instructed to manipulate the size of the virtual box in front of them either to reproduce the relative size of a (previously seen) physical box or an absolute size that was communicated verbally (i.e., not previously seen):

- **Relative Size Matching**: In this condition, the participants were instructed to scale the virtual box to match the size of one of the two physical boxes (sizes: 15.5 or 20 cm) that they previously saw before they were immersed in the VE.
- **Absolute Size Matching**: Here, the participants had to scale the virtual box to match an absolute size (equal width, height, and depth) of the box (sizes: 5 or 38 cm). This absolute size was communicated verbally to them without a physical reference that could be used as a relative cue.

The rationale for using these sizes was that the user's familiar hand size could provide benefits in estimating the sizes of commonly encountered boxes. We conjectured that, if users had to deal with unusual sizes, they would depend on their intuition only rather than a process that augments memory with a body-based scaling process. For this reason, we chose sizes of frequently encountered packing boxes that could be lifted with one hand for the relative

size matching condition, while we chose less common box sizes for the absolute size matching condition assuming that leads to poorer scaling estimation regardless of the hand conditions.

3.3.2 Hypotheses. In this experiment, we considered the following research hypotheses:

H_1 Using a Personalized AV Hand results in more accurate object size estimation than a Generic VR Hand.

H_2 Using a Personalized AV Hand provides a higher sense of virtual body ownership illusion than a Generic VR Hand.

H_3 Using a Personalized AV Hand provides a higher sense of spatial presence than a Generic VR Hand.

H_4 Using uncommon box sizes that are not comparable to normal hand sizes and that have not been previously observed leads to incorrect estimations in both the Personalized AV Hand and Generic VR Hand conditions.

3.4 Measurements

3.4.1 Object Size Estimation. As discussed before, participants were asked to manipulate the size of a virtual box in front of them to match either a previously seen physical box size, or match a verbally communicated size. The virtual box was a cube with the same length on all three axes, to keep the box manipulation task simple. After scaling the virtual box to the size that the participants perceived to match the communicated size, we recorded the final size of the virtual box. We then computed the vector distance, *L2 norm Euclidean distance*, since it enables us to effectively determine the level of *overall similarity*. We ignored the directionality between the reported size and the real size, since we focused on the participant's intuitive comparison and its result in this experiment. A value that approaches zero means that participants were highly accurate in their object size estimation.

3.4.2 Perceived Measures. We assessed the dependent variables, virtual body ownership and spatial presence, using subjective measurements based on questionnaires. In this experiment, with slight modifications based on our study context, we adopted pre-validated questionnaires called *spatial presence (P)* and *self-presence (SP)* by [3], as well as *virtual body ownership illusion (VBOI)* by [1]. We handled the self-presence and the virtual body ownership as a single construct since they had similar contexts. Finally, we created a set of post questions for comparison purposes between the Personalized AV Hand and the Generic VR Hand. We show our subjective measurement items in Table 2.

3.5 Procedures

Before we conducted our study, each participant gave their informed consent and filled in demographic data while in a waiting area. After completion of the demographics questionnaire, the participant entered the experimental room.

As discussed in Section 3.2, we designed the personalized hand condition to encompass temporary personalization effects as well. Hence, we asked participants to decorate their right hand with washable paint at the beginning of the experiment. We did this to help each participant recognize their own hand even in the presence of some loss of fidelity resulting from the video feed.

Table 2: Questionnaire

| Item	Question
P $\alpha<0.8972$	To what extent did you feel like you were really inside the virtual room?
	To what extent did you feel surrounded by the virtual room?
	To what extent did you feel like you really visited the virtual room?
	To what extent did you feel that the virtual room seemed like the real-world?
	To what extent did you feel like you could reach out and touch the objects in the virtual room?
SP $\alpha<0.9375$	To what extent was the digital representation an extension of yourself?
	To what extent did you feel if the virtual object size manipulation happened to the digital representation it felt like it was happening to you?
	To what extent did you feel that the digitally represented body was your own body?
	To what extent did you feel that the digital representation was you? How much did the digitally represented hand position correspond with your commands?
VBOI $\alpha<0.9713$	I felt as if the digital representation of the hand was part of my body.
	During the experiment, there were moments in which I felt as if the digital hand was my own hand.

(a)　　　　　　　　(b)
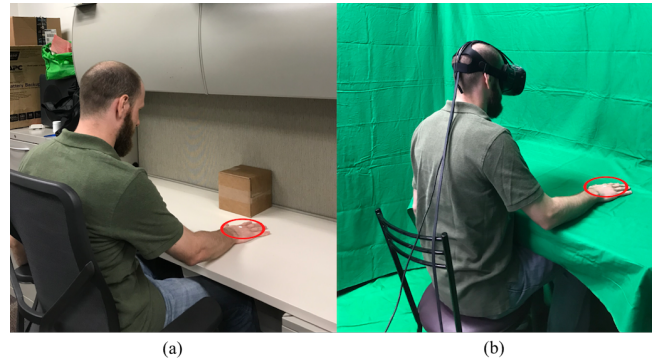
Figure 3: Experimental environment: (a) Participant observing a physical box, and (b) participant manipulating a virtual object in the VE. Participant were asked to decorate their right hand using washable paint (red colored circle), and place their right hand on the table in a static pose.

We left it up to each participant to decide on the type of decoration. As shown in Figure 1, one participant decorated their hand with a smiley face.

After participants decorated their hand, they were instructed to observe and memorize the sizes of two physical boxes, shown one at a time, while they placed their right hand on a table in a static pose (see Fig. 3a). The smaller box was displayed first and the larger box second. After the observation of these physical boxes, the participants were guided into the Chroma Key (green screen) environment, where they were instructed to assume the same pose as before (see Fig. 3b).

The participants were then informed of the perceptual matching task for which they could change the size of the virtual box that was presented in front of them. After a short instruction on the use of the controller, the participants donned the HMD with their eyes closed. After we launched the VR system, the participants opened their eyes and we confirmed that they could see their hand within their visual range without any head movement. Then, they were

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asked to manipulate the sizes of the given virtual boxes using the HTC VIVE controller with their left hand.

Depending on the condition, participants could then see one of the two hand representations (Personalized AV Hand or Generic VR Hand). Moreover, depending on the condition, they were then asked to manipulate the virtual box size to either match the size of one of the physical boxes (15.5 or 20 cm) they had just seen, or to manipulate the virtual box size to match the size of one of two boxes (5 or 38 cm) that were not observed prior to this experiment. The latter box sizes were communicated verbally to the participants in their preferred unit (e.g., centimeters or inches). Hence, in these conditions, they could not rely on relative size comparisons with previously seen boxes.

We provided a short break to the participants after they completed one of the size matching conditions. After finishing the experiment with one of the hand conditions, each participant filled in a subjective questionnaire. After they completed all conditions of the experiment, we asked them to fill in a post-questionnaire.

4 RESULTS

In this section, we show results for the objective responses of estimated virtual object size accuracy and subjective questionnaire responses for spatial presence and virtual body ownership illusion. For the analysis, we used a total of 23 participant data sets. As discussed before, we had to remove one of the original 24 participants from the analysis due to a strong sense of dizziness.

4.1 Object Size Estimation

Figure 4 shows the pooled results in the form of a histogram for the perceptual matching task in which participants had to manipulate the size of the virtual box to match the size of a previously seen physical box (relative) or match the size to an absolute verbally communicated size (absolute). We used solid lines for the Personalized AV Hand conditions and dotted lines for the Generic VR Hand conditions. The figure further shows the results for the vector distances in the form of means and standard deviations for the experimental conditions.

We confirmed the assumptions of the repeated measures ANOVA with a Shapiro-Wilk test and Mauchly's sphericity test at the 5% significance level. We found a significant main effect of box representation on the size estimation accuracy, $F(3, 179) = 25.01$, $p = 0.001$, $\eta_p^2 = 0.295$ while the hand representation showed $F(1, 179) = 2.05$, $p = 0.154$, $\eta_p^2 = 0.0113$, with an overall higher accuracy for the Personalized AV Hand ($M = 0.058$, $SD = 0.067$) compared to the Generic VR Hand ($M = 0.07$, $SD = 0.068$). Since we conjectured that the significant value difference in absolute size data produced noise in hand representation, we conducted a Post-hoc test. The test revealed that the Personalized AV Hand resulted in significantly higher accuracy than the Generic VR Hand for the relative matching task ($p = 0.001$, Cohen's $d = -0.842$) but not for the absolute matching task ($p = 0.854$).

Due to the different box sizes in the relative and absolute matching conditions, we could not compare these results directly. Instead, we compared the box sizes within these conditions using paired t-tests. The results showed that, for the relative matching task, the size estimation accuracy between the two box sizes did not

Table 3: Statistical results for the subjective measures.

	Spatial Presence	Self-Presence	VBOI	SP+VBOI
Cronbach's α	0.8972	0.9375	0.9713	0.9624
Anderson-Darling Test	$p < 0.05$	$p < 0.05$	$p < 0.05$	$p < 0.05$
p-Value	$p < 0.01$	$p < 0.01$	$p < 0.01$	$p < 0.01$
Personalized Hand (M,SD)	**(5.1, 1.2)**	**(5.3, 1.3)**	**(5.3, 1.6)**	**(5.3, 1.4)**
Virtual Hand (M,SD)	(4.5, 1.5)	(3.5, 1.8)	(3.3, 1.8)	(3.4, 1.4)

show a significant difference ($p = 0.241$, Cohen's $d = -0.253$), with a higher relative accuracy for the physical box with a size of 15.5 cm ($M = 0.034$, $SD = 0.028$) compared to the box with a size of 20 cm ($M = 0.042$, $SD = 0.035$). However, we found that for the absolute matching task, the size estimation accuracy differed significantly between the two box sizes ($p = 0.001$, Cohen's $d = -0.974$), and revealed a higher accuracy for the task to match a box of 5 cm ($M = 0.054$, $SD = 0.045$) than a box of 38 cm ($M = 0.127$, $SD = 0.096$).

4.2 Perceived Measures

Since we adopted a set of questions to measure subjective responses, we assessed the construct validity of multiple items in the same categories using Cronbach's alpha before we analyzed the collected subjective data from each questionnaire. All four items were satisfied with $\alpha > 0.8$, and so we were able to analyze the data from the subjective questionnaires.

Figure 5 shows the subjective questionnaire results. We provide the interquartile range with outliers and median symbols in all box plots along with median confidence intervals at the 95% level with a white colored dotted box inside each bar.

To analyze the effects, we performed Mann-Whitney U tests for all items at the 5% significance level, since our data did not show a normal distribution with the Anderson-Darling test. Table 3 shows the results of these tests.

4.2.1 Virtual Body Ownership Illusion (VBOI). As shown in Figure 5 and Table 3, we found a significantly ($p < 0.001$) higher virtual body ownership illusion for the Personalized AV Hand condition compared to the Generic VR Hand condition. Since the items, VBOI and Self-Presence represented similar features we tested them with Cronbach's alpha to see if we can confirm them as one construct and it showed a strong relation with $\alpha > 0.96$. Thus, we assume we can treat these as one dependent variable in this study.

4.2.2 Spatial Presence and Self-Presence. Similar to the results for the virtual body ownership illusion, we found a significantly higher rating of Spatial Presence ($p < 0.001$) and Self-Presence ($p < 0.001$) for the Personalized AV Hand condition compared to the Generic VR Hand condition.

4.2.3 Post Comparison Questionnaire. Figure 6 shows the results of the post comparison questionnaire, which comprised of a direct forced choice between the two hand representations, seen in the pie charts. Most of the participants stated that the Personalized AV Hand made them feel as if they were in the virtual office (Spatial Presence), as if the observed hand was their own hand (Self-Presence and VBOI), and as if they could estimate object sizes more accurately. Regarding system preferences, 21 participants (91.3%)
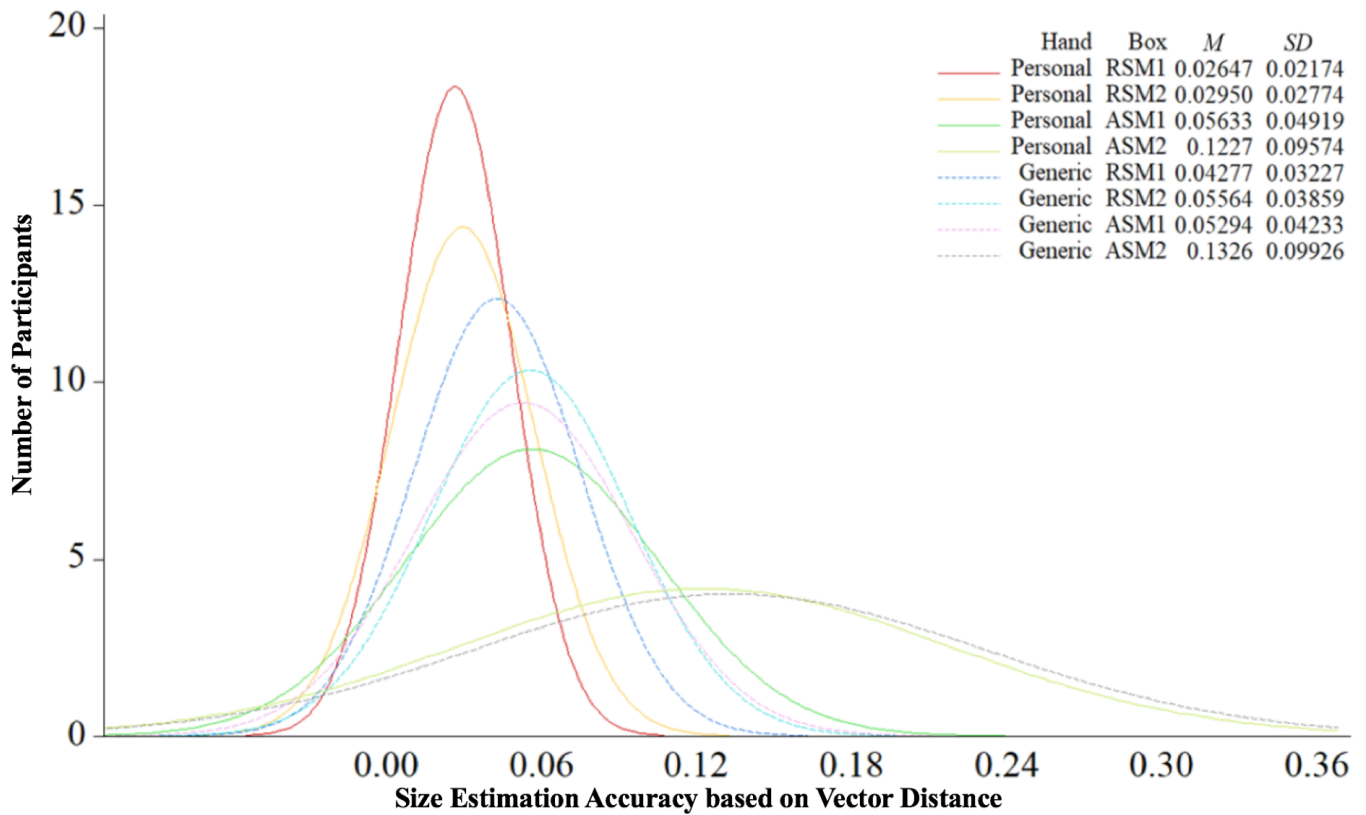
Hand	Box	M	SD
Personal	RSM1	0.02647	0.02174
Personal	RSM2	0.02950	0.02774
Personal	ASM1	0.05633	0.04919
Personal	ASM2	0.1227	0.09574
Generic	RSM1	0.04277	0.03227
Generic	RSM2	0.05564	0.03859
Generic	ASM1	0.05294	0.04233
Generic	ASM2	0.1326	0.09926

Figure 4: Pooled results for the perceptual matching task in which participants manipulated the size of the virtual object. RSM denotes "Relative Size Matching" and ASM denotes "Absolute Size Matching". Each line represents a histogram of the computed vector distance between the actual and estimated size. For example, the red line indicates the highest accuracy in size estimation among the experimental conditions.
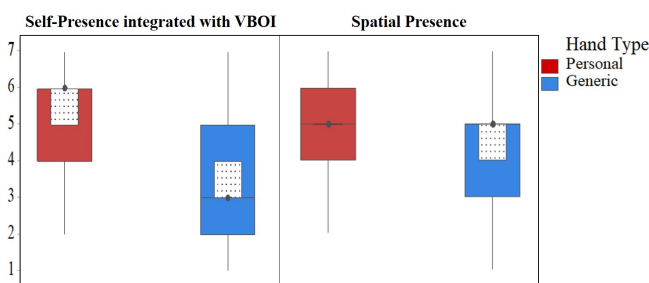

Figure 5: Plots showing the subjective questionnaire results for self-presence and spatial presence.
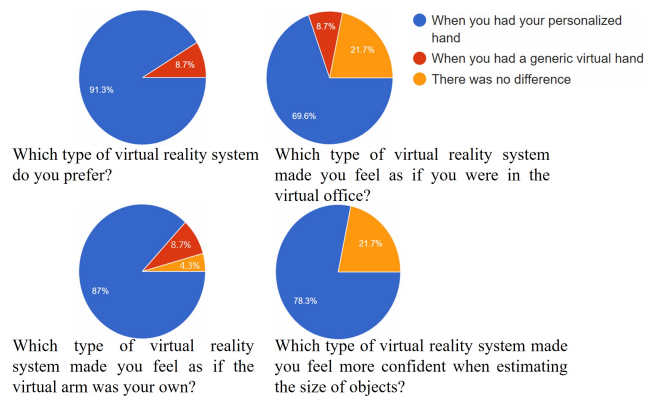

Figure 6: Results of the post comparison questionnaire. We represented the results with a pair (number of votes, percentage). When asked directly, almost all participants indicated a strong preference for the personalized hand.

preferred the Personalized AV Hand while only 2 participants (8.7%) preferred the Generic VR Hand.

5 DISCUSSION AND LIMITATIONS

In this experiment, we found support for all four of our research hypotheses, which showed the benefits of the personalized hand over the generic virtual hand.

In support of our Hypothesis H_1, we found that the object size estimation accuracy was significantly higher for the personalized

hand condition compared to the generic virtual hand. Specifically, we found a significantly higher accuracy for the relative size matching tasks in which participants had to scale a virtual box to the size of a previously seen physical box, whereas we did not observe a significant difference in the results when they had to scale the virtual box to a verbally communicated size that was neither comparable to common hand sizes nor to prior visual experiences, and this supports our Hypothesis H_4.

The subjective questionnaire responses showed a significant effect that the personalized hand elicited a higher sense of spatial presence and virtual body ownership illusion compared to the generic hand condition. These results support our Hypotheses H_2 and H_3. Moreover, when asked for their preference, most participants indicated that they preferred the personalized hand over the generic hand in the experiment.

Implications. Based on results from this experiment, we would recommend that VR developers adopt the personalized hand in areas that require size-sensitive tasks, such as simulation of surgical procedures or usability tests that include activities influenced by product sizes. Even in scenarios that do not involve size-sensitive tasks, personalized body parts increase presence and VBOI, illusions that can increase the effectiveness of a scenario, especially one that involves training that needs to transfer to the real world. To render the personalized hand, a green screen is not always necessary; one may use a commercial depth camera combined with a stereo camera. The choice of green screen versus depth camera depends on other aspects of the environment, e.g., do we want the hand to be seen in the context of nearby real objects or virtual content? The former is best done with a depth camera and the latter is easier with a green screen.

Limitations. In this study, we found some technical limitations. First, the stereo camera's color accuracy dropped and noise increased after about one minute, such that two participants observed an increased reddish tinge in their hand as can be seen in Figure 1(a-d). We believe that the color change did not have an impact on our experiment since only two participants reported it, and they also stated that it did not influence them. Second, two participants reported a "floating hand" effect while they performed the task. Since we rendered the hand on the stereo camera's view plane, dropped frames or the participant's head movement (though we asked participants not to move) could have caused the floating effect. While this might have had a negative effect on how the personalized hand was perceived, our results show an overall strong preference of participants for the personalized hand, such that the impact of this effect probably was not very strong. Further, three participants reported difficulty controlling the virtual box size, even though we designed the manipulation to be very simple by using only two buttons. Overall, we believe that none of these limitations had a noticeable effect on the results.

6 CONCLUSION AND FUTURE WORK

In this paper, we investigated the effects of a personalized hand on spatial presence, virtual body ownership, and object size estimation in a virtual environment. We implemented a high-fidelity personalized hand based on an augmented virtuality approach and we

enhanced it with temporary personalizations by applying washable paint to their physical hand. We compared this personalized hand condition with a generic virtual hand as a baseline condition, which denotes a common type of virtual body in VR. We found a significantly higher accuracy in object size estimation for the personalized hand in a perceptual matching task in which participants had to scale a virtual object and match its size to a previously seen physical object. We further found a significantly higher spatial presence and virtual body ownership illusion, as well as a general preference of our participants for the personalized hand compared to the generic virtual hand.

In future work, we plan to perform an experiment to understand whether our temporary personalizations, such as a smiley face drawn on the user's physical hand before being immersed in VR, could be used as a general-purpose method to support virtual body ownership with arbitrary virtual hand representations.

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