Virtual Reality
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ORIGINAL ARTICLE

Body size illusions influence perceived size of objects: a validation of previous research in virtual reality

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Abstract

Previous research indicates that the size of the own body affects the judgment of objects' size, depending on the amount of subjective ownership toward the body (Van der Hoort et al. in PLOS ONE 6(5):e20195, 2011). We are the first to transfer this own-body-size effect into a virtual environment. In a series of three experiments, participants ($N=68$) had to embody small, medium, and large avatars and judge the size of objects. Body ownership was manipulated using synchronous and asynchronous touch. We also included a new paradigm with an additional change of perspective to induce stronger ownership (Experiment 2). Additionally, we assessed whether the visibility of the body during the judgment phase influenced the results (Experiment 3). In all three experiments, we found an overestimation in a small and an underestimation in a large body compared to a medium body. However, size estimation did not depend on the degree of ownership despite clear differences in self-reported ownership. Our results show that a virtual reality scenario does not require a visuotactile manipulation of ownership in order to evoke the own-body-size effect. Our validation of the effect in a virtual setting may be helpful for the design of clinical applications.

Keywords Own-body-size effect · Ownership · Virtual reality · Size perception · Embodiment · Avatars

1 Introduction

The size of our body serves as a reference frame to the perception of our world (Harris et al. 2015; Proffitt and Linkenauger 2013). The influence of the body on mental processes is generally referred to as *embodied cognition* (Wilson 2002). In popular culture, the impact of shrinking humans to the size of insects has been considered numerous times (e.g., in the movie *Honey, I Shrunk the Kids* and its sequels; Cox and Johnston Cox and Johnston 1999). The question whether such a transformation of the physical size of the own body would affect the perception of the environment was investigated in a series of pioneering experiments by Van der Hoort and colleagues (Van der Hoort et al. 2011; Van der Hoort and Ehrsson 2014, 2016). Using an arrangement of cameras capturing artificial bodies and projecting the video feed onto participant's goggles, the participants had the feeling of being inside the body of dolls of various sizes (i.e., they had a feeling of body ownership; cf. De Vignemont 2011). The sensation of ownership resulted in an altered estimation of object sizes. In the present study, we provide a first-time replication of these experiments in a virtual reality (VR) setup. In a series of three experiments, we recreated the original procedures and transferred them into a virtual environment. We formulated hypotheses based on the original findings and aimed at reproducing the results. In the following, we will discuss the original experiments in more detail and point out how a VR adaptation extends the knowledge about embodiment and body ownership in virtual environments.

In the original experiments, having ownership of bodies with different sizes changed the perception of box-shaped objects: In comparison with ownership of a normal-sized body, ownership of a small body resulted in an overestimation of the size of objects and, conversely, ownership of a large body resulted in an underestimation (Van der Hoort et al. 2011). This tendency of the perceptual system to regress toward the middle is referred to as *contraction bias* (Poulton 1989). The contraction bias suggests a tendency

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to overestimate small and underestimate large magnitudes when there is a possibility to compare both to an intermediate reference magnitude. In the experimental setup, cameras captured the body of a doll lying on a mattress from a first-person perspective (1PP) and transmitted the video feed to a participant wearing a head-mounted display (HMD). Using this setup, the participant had the view of the doll as it was his or her own body, except for the size of the body, which varied between 30 and 400 cm. Van der Hoort et al. (2011) used synchronous and asynchronous stroking of the participant's body and the doll's body in order to manipulate the level of experienced ownership (Botvinick and Cohen 1998; Tsakiris and Haggard 2005). When applying this manipulation in combination with doll bodies of different sizes, the magnitude of the contraction bias was more pronounced in the synchronous condition (Van der Hoort et al. 2011). This was referred to as the *own-body-size effect*.

Van der Hoort et al. (2011) point out that the own-body-size effect is of great value in the context of tele-robotics and VR. They provide the following example of the benefit of simulated bodies: "a surgeon could experience a full-body illusion of "being" a microrobot performing surgery inside the patient's body." This type of setting could be implemented in VR. However, although Van der Hoort and colleagues explicitly point out that their findings are important for VR, they themselves did not use this technology. Therefore, it is a crucial question whether the own-body-size effect also applies to an immersive virtual environment (IVE). Does object perception in VR follow the same mechanisms as in real life? Previous studies suggested that perception in VR indeed differs from perception in real life. One example is the underestimation of room size and distances in VR (cf. Loomis and Knapp 2003; Renner et al. 2013). Additionally, the quality of current HMDs does not match the abilities of the human perceptual system (e.g., image resolution, frame rate, etc.). This limits the extent to which we can transfer results about human perception into VR. Moreover, there is also a reduced quality of depth cues, concerning for example shadows, textures, and occlusion of objects. Thus, it is not clear whether it is possible to replicate the own-body-size effect in a virtual setting and if the same rules for ownership and perception apply. To address these questions, we investigated the own-body-size effect in an IVE. We used the same paradigm as Van der Hoort and colleagues but with avatars instead of dolls and virtual objects instead of real objects. Our main goal was to assess the impact of an ownership manipulation on the own-body-size effect in an IVE.

There is still scarce knowledge about the use of VR technology and its influence on body ownership with the only exception being two studies. One study demonstrated an effect of the size of one's virtual hands on the perceived size of objects (Linkenauger et al. 2013). A contraction bias for objects was observed only when one's own hands were altered but not the hands of an avatar on the other side of the table. However, there was no assessment of ownership of the two perspective conditions. In the second VR study, Banakou et al. (2013) used mappings of body movements to embody participants into a virtual child or small adult body. They observed a general overestimation of the size of box-shaped objects for both bodies compared to a baseline condition where participants made judgments from the same perspective but without a visible body. There was no such difference during asynchronous mappings of the participant's movements. However, it was not the size but the implied age of the body that was supposed to be responsible for the size estimation bias. Furthermore, it is unclear in what way the advantage of having a body in the IVE could have contributed to these findings (cf. Ries et al. 2008; Mohler et al. 2010).

Although these studies demonstrate an effect of body size on judgments of object size, in both cases the setup was significantly modified when compared to the original studies by Van Hoort and colleagues. In the original paradigm, the size of the whole body affected size judgments in the far extra-personal space. Body size varied systematically from very small to very large bodies, and each condition was implemented with the same perspective. It is still unclear whether this original paradigm can be transferred successfully to an IVE. As mentioned above, the authors already discussed the importance for such a transfer in terms of tele-robotics. Besides that, a successful replication would confirm embodiment theory in an IVE by establishing a proposed mechanism in which the body acts as a reference frame for perception. This could also help to explain the so-called Proteus effects (Yee and Bailenson 2007), according to which a transformed self-representation in an IVE influences the user's behavior (e.g., his or her confidence in a negotiation task). As such, a successful replication would have implications for the design of virtual environments such as determining optimal body size transformations (cf. IJsselsteijn et al. 2006). It can also help to clarify whether future studies on embodiment can be transferred into IVEs. In embodiment research, IVEs have a number of benefits, including the possibility of flexibly altering one's own body and inducing ownership of exotic external bodies (e.g., animals). If basic external perception is influenced by virtual bodies, they can also have strong impacts on the perception of the own body. This has implications for the development of treatments for body image distortions such as *anorexia nervosa*. VR is already being used as a tool for investigating and treating eating disorders (Ferrer-García and Gutiérrez-Maldonado 2012). Future applications could involve body transformations to restore a healthy body image. Other potential areas of interest for body transformations are the treatment of phantom limb pain (Murray et al. 2007), body integrity identity disorder (First 2005), virtual training methods for motor tasks in the context of surgery or sports (Gurusamy et al. 2008), and self-identification in computer games (Klevjer 2012).

To assess the own-body-size effect in an IVE, we conducted three experiments, which we designed as close as possible to the original paradigm of Van der Hoort and colleagues. Thus, we created a virtual version of our laboratory room and placed avatars on a virtual mattress. The size of the avatar bodies varied in size from 30 to 350 cm. All participants experienced three different sized avatars during the experiments: a small, a medium, and a large avatar. The participants were lying on an identical mattress in the real room and experienced the virtual room via an HMD. The potential magnitude of ownership feelings toward the avatar was manipulated using synchronous and asynchronous visuotactile stimulation that was applied to the real and virtual body. In the asynchronous condition of the second and third experiment, also the view was changed to a third-person perspective (3PP) to further disrupt ownership feelings. In all three experiments, box-shaped objects were then presented in the far extra-personal space and participants had to judge their size. Whereas the avatar body was still visible in the first and second experiments during this judgment phase, in the third experiment we removed the body to assess whether the body acted as a visual reference cue.

In line with the findings of Van der Hoort and colleagues, we postulated the following hypotheses:

Hypothesis 1 The subjectively experienced amount of ownership is higher in the synchronous condition compared to the asynchronous condition.
Hypothesis 2 The size of objects during ownership of a small body is overestimated, and the size of objects during ownership of a large body is underestimated with respect to the medium-sized body (contraction bias).
Hypothesis 3 The contraction effect in the size estimation task is stronger in the synchronous condition compared to the asynchronous condition (own-body-size effect).

A successful manipulation of ownership is important for replicating the own-body-size effect (Hypothesis 1). Support for Hypothesis 2 would indicate that there is an effect of the size of the virtual body on the estimation of object size. However, in order to fully replicate the own-body-size effect, there should only be a contraction bias if there is a sufficient amount of ownership. Assuming that the manipulation of ownership is successful, the contraction bias is expected in the synchronous condition only (Hypothesis 3).

2 General method

2.1 Participants

Overall, 68 healthy adult participants were recruited (53 females and 15 males, age: $M = 22.3$ years, SD = 3.8 years). The numbers for each experiment were as follows: Experiment 1: 22 (18 females, 4 males, $M = 22.6$ years, SD = 4.6 years); Experiment 2: 26 (20 females, 6 males, $M = 22.5$ years, SD = 3.6 years); Experiment 3: 20 (15 females, 5 males, $M = 21.7$ years, SD = 3.1 years). All participants had normal or corrected-to-normal vision.

Participants received credit points as an exchange for their participation. All participants provided written informed consent to take part in this study and were treated in accordance with the protocol approved by the Ethical Committee of the Faculty of Human Sciences of the University of Bern and with the Code of Ethics of the World Medical Association (Declaration of Helsinki). All participants were debriefed after the experiment.

2.2 Design and material

2.2.1 Design

There were a total of six conditions that every participant had to undergo in a within-subjects design. This resulted from a 3-by-2 design with three different bodies (*small*, *medium*, and *large*; see Fig. 1) and two visuotactile stimulation conditions (*synchronous* and *asynchronous touch*). Conditions were presented in a random order. The dependent variables were ratings of presence and ownership and size judgments of the objects.

2.2.2 Virtual room and equipment

The experiment took place in a laboratory room with the dimensions 635 cm (length), 501 cm (width), and 277 cm (height). We created a virtual replica of the room with the exact same configuration and the exact same dimensions, including all tables, chairs, cabinets, and doors (Fig. 2). In a corner of the room lay a mattress, which was also replicated in the IVE. Participants wore an Oculus Development Kit 2 HMD (Oculus VR, LLC., Irvine, USA) that was connected to a laptop computer (Intel i7 processor, 16 GB RAM and NVidia GeForce GTX 970M graphics card). The computer was also replicated and shown in the IVE. Its size was always scaled in accordance with the respective virtual body. The reason for this was that participants had to use the trackpad of the computer for making size judgments. Therefore, their sense of touch had to match their visual input in order not to disrupt the illusion. We used neutral looking avatars that were matched for gender (WorldViz LLC., Santa Barbara, USA). Due to limitations of the room's available space, the size of the *large avatar* was set to 350 cm instead of 400 cm as in the study by Van der Hoort et al. (2011). However, as in the study of Van der Hoort et al., the size of the *small avatar* was 30 cm and the size of the *medium-sized*

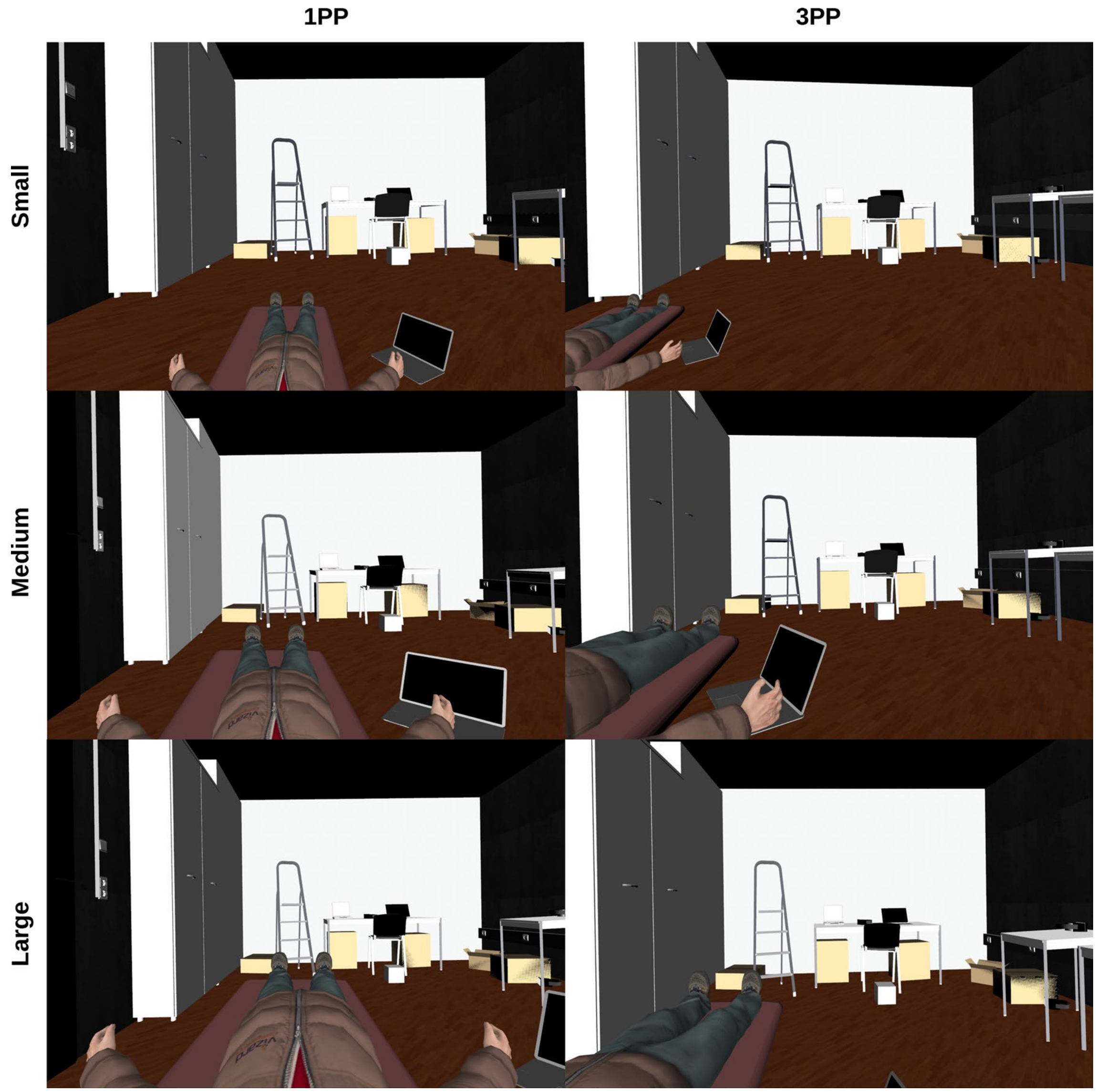

Fig. 1 Left side: the three body size conditions in the first-person perspective (used in all experiments). Right side: the three body size conditions in the third-person perspective (used in the asynchronous conditions in Experiments 2 and 3). Note that the bodies are shown from slightly above the participants' actual viewpoint in VR in order to compensate for the loss of stereoscopic information and to make size differences more visible. In the experiment proper, the bodies appear from an egocentric perspective

avatar was 180 cm. The participants were set to the same position in the room as the respective avatar. Real and virtual bodies were also both aligned perpendicular to the short wall of the room. Because the size of the avatar also affected the eye height, the virtual mattress was elevated or lowered to adjust for the difference. For the size estimation task, three white box-shaped objects were used. Their edge lengths were 10 cm, 20 cm, and 40 cm, in all conditions. They were presented in a random order in front of the participants at a fixed distance of approximately 450 cm from the position of the participants' eyes. A few other objects such as tables and chairs were also visible and served as familiar size cues (identical in the real and the virtual room). Other potential size cues, such as binocular disparity and eye convergence, were also implemented in the virtual room and remained constant across all conditions. However, due to technical limitations, it is currently not possible to alter the accommodation of the pupil in an HMD. Therefore, accommodation cues in the IVE did not conform to the real world but remained constant in all conditions. The HMD was set to allow only rotational but not translational movement to prevent participants from changing the perspective. The field of view (FOV) was set to 90°.

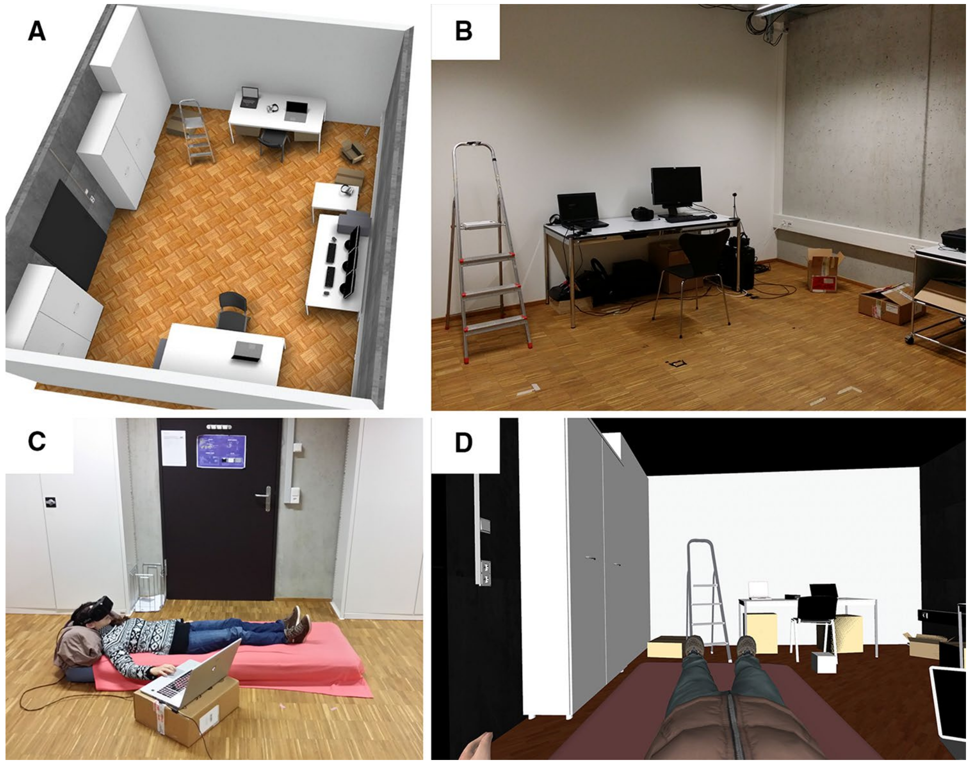

Fig. 2 **a** Virtual replica of the laboratory room. **b** Real laboratory room. **c** A participant is lying on the mattress making size judgments. **d** View of the participants during size judgments in Experiment 1 (shown is the large body condition). In Experiment 2, the view in the asynchronous condition was shifted to the right of the body, and in Experiment 3 the body was not visible during judgments. The white box on the right of the avatar had to be judged

2.2.3 Measurements

To assess the subjective ownership of the participants, we developed a small questionnaire that is composed of seven statements used by Van der Hoort et al. (2011) and Piryankova et al. (2014). An example item is "during the experiment, there were times when I felt as if the avatar's body was my body." Answers were given on a Likert scale ranging from *fully disagree* (1) to *fully agree* (7). Similar questionnaires were used in previous studies about ownership (e.g., Dobricki and de la Rosa 2013; Normand et al. 2011). Furthermore, the internal structure of these questionnaires has been assessed in psychometric studies (Longo and Haggard 2012; Longo et al. 2008). In our study, the internal consistency of the ownership questionnaire was good (Cronbach's $\alpha = 0.81$). The questionnaire can be found in the Appendix. All questions were presented in German.

Furthermore, we assessed levels of presence using the Pictorial Presence SAM questionnaire (Weibel et al. 2015), which consists of five pictograms each depicting different levels of presence. For each sequence, one of the pictograms that best fits the participants' subjective experience has to be chosen. The answer is then transformed into a number from one to five.

The third dependent measure was the subjective rating of the objects' size. Participants gave their judgments by choosing a numeric value from a list. The list contained values from 5 to 60 cm in steps of 5 cm.

2.3 Procedure

At the beginning of the experiment, the use of the HMD and the purpose of the virtual room were explained to the participants. They were then asked to lie down on the mattress and put on the HMD. There was a short phase in which the participants could familiarize themselves with the virtual room.

Next, the visuotactile stimulation was administered. This procedure differed between Experiment 1 and Experiments 2 and 3. It is described in the respective sections below.

After the stimulation phase, the three test objects were successively presented to the participants who had to judge their size by indicating the edge length via direct numerical assessment (chosen from a list of possible values; see Measurements section). Judgments were made using the trackpad of the nearby laptop computer. Participants did not need to remove the HMD in order to give their judgments. This part of the experiment differed between Experiments 1 and 2 (the virtual body was still visible) and Experiment 3 (the virtual body was invisible). At the end of a trial, they were asked to remove the HMD and complete the ownership and presence questionnaires on the computer. The whole procedure was repeated for each of the six conditions. An overview of the differences between the three experiments is found in Table 1.

3 Experiment 1

3.1 Method

The general structure of the experiment is described in the Procedure section. For the visuotactile stimulation, we used a rod to touch participants 20 times each on the lower left leg, the right thigh, and the stomach. This took about one and a half minute. There was also a virtual rod that touched the virtual body on the same spots. Each virtual touch was started by a button press. This allowed the examiner to apply touches either synchronously or asynchronously to the participant and the virtual body. For the asynchronous touch in Experiment 1, the examiner randomly delayed either the press of the button or the touch of the rod on the real body by approximately 1 s. The size of the rod remained constant with respect to the size of the virtual body.

3.2 Results

3.2.1 Ownership and presence

To test whether the visuotactile stimulation had worked as intended, we analyzed questionnaire data from the ownership and presence questionnaires. An overview of descriptive statistics is found in Table 2. A two-way repeated measures analysis of variance (ANOVA) with *stimulation* and *body size* as factors indicated that ownership was higher in the *synchronous* condition compared to the *asynchronous* condition (main effect of stimulation), $F(1, 18) = 14.70$, $p = .001$, $\eta_p^2 = 0.45$. This was not true, however, for control questions, $F(1, 18) = 0.07$, $p = .796$, $\eta_p^2 = 0.00$, indicating that the effect of stimulation was limited to questions about ownership and that there was not a general tendency to agree with the statements. In both analyses, the interaction and the main effect of body size were not significant (all $p > .05$). Results for presence ratings were similar: There was only a main effect of stimulation, $F(1, 18) = 6.39$, $p = .021$, $\eta_p^2 = 0.26$. All other effects were not significant (all $p > .05$). These results indicate that the manipulation of ownership was successful (Hypothesis 1): Synchronous stimulation evoked higher levels of subjective ownership and presence. Additionally, ownership and presence did not depend on the size of the body.

Table 2 Descriptive statistics for ownership, control, and presence questions in Experiment 1

Scale	Synchronous condition	Asynchronous condition
Ownership	4.48	3.61
Control	3.11	3.06
Presence	3.50	3.17

Displayed are the marginal means for the synchronous and asynchronous stimulation conditions. $N = 57$ for all questions

In addition to the ownership and presence questionnaires, we also asked participants about their impression of the room's size and their judgments about their perceived age in all three avatar bodies. There was a linear effect of body size concerning the questions "I felt younger than I actually am" [$F(1, 18) = 22.07$, $p < .001$, $\eta_p^2 = 0.55$] and "I felt older than I actually am: [$F(1, 18) = 9.76$, $p = .006$, $\eta_p^2 = 0.35$], suggesting that participants felt younger in the small body and older in the large body. Similarly, there were linear effects of body size on the perceived size of the room: In the small body, the room appeared bigger than in the large body, $F(1, 18) = 40.82$, $p < .001$, $\eta_p^2 = 0.69$, and in the large body, the room appeared smaller than in the small body, $F(1, 18) = 23.92$, $p < .001$, $\eta_p^2 = 0.57$.

3.2.2 Size judgments

To test Hypotheses 2 and 3, we computed a two-way repeated measures ANOVA with *body size* and *stimulation* as factors and the difference between real size and estimated size of the test objects as dependent measure. According to Hypothesis 2, we expected a main effect of body size, whereas Hypothesis 3 required a significant interaction between body size and stimulation. We found a significant main effect of body size, $F(1.35, 24.29) = 11.41$, $p = .001$, $\eta_p^2 = 0.39$ (degrees of freedom were adjusted using Greenhouse–Geisser correction). There was a linear trend ($p = .002$) for body size, suggesting that there was an overestimation of size in the *small* body and an underestimation of size in the *large* body compared to judgments in the *medium* body (Fig. 3). Therefore, Hypothesis 2 is supported by our data: There was a contraction bias. However, there was no interaction between body size and stimulation, $F(2, 36) = 1.07$, $p = .355$, $\eta_p^2 = 0.06$, and the main effect of stimulation was also not significant, $F(1,$

Table 1 Overview of the experiments

Experiment	Ownership manipulation	Size judgments
Experiment 1	Synchronous versus asynchronous touch (both in 1PP)	Body visible
Experiment 2	Synchronous touch in 1PP versus asynchronous touch in 3PP	Body visible
Experiment 3	Synchronous touch in 1PP versus asynchronous touch in 3PP	Body not visible

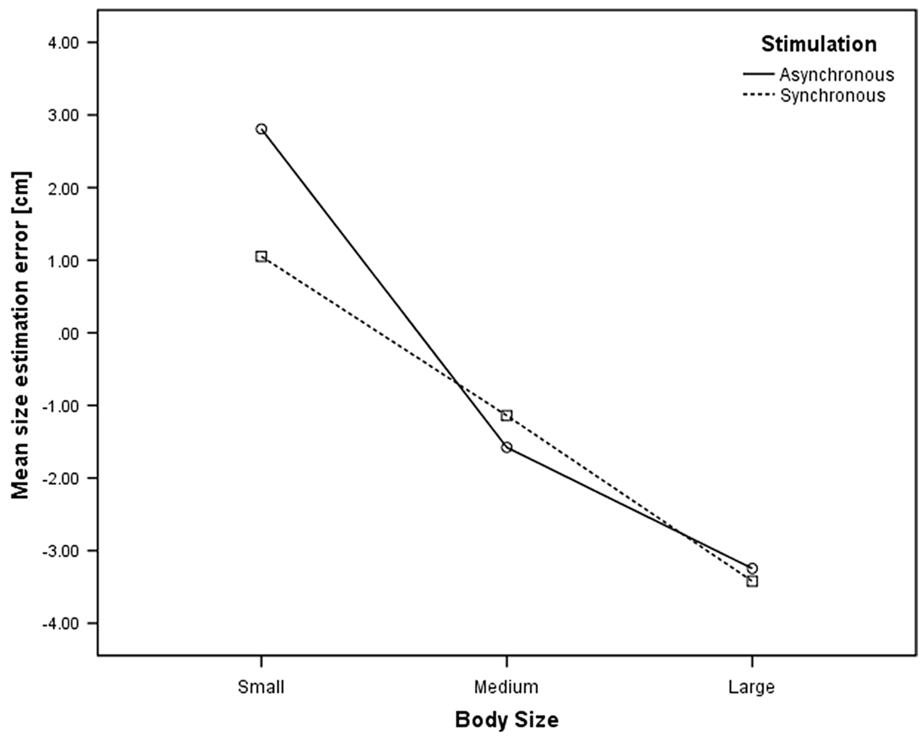

Fig. 3 Results of the two-way repeated measures ANOVA with the difference between real and estimated size of the test objects as dependent measure (Experiment 1)

18) = 1.05, p = .318, η_p^2 = 0.06 (Fig. 3). Thus, Hypothesis 3 (own-body-size effect) received no empirical support.

3.3 Discussion

We could successfully manipulate ownership according to the results in the questionnaires. We observed an effect of body size on the judgment of objects' size. Thus, we were able to reproduce the contraction bias. Nevertheless, we could not fully support the own-body-size effect as reported by Van Der Hoort and colleagues: There was no interaction between body size and stimulation. Two possible explanations need to be considered: (1) ownership *is not* crucial for the contraction bias and the mere presence of a virtual body at or near the location of the participant's real body accounts for the bias (explanation 1); or (2) ownership *is* crucial for the contraction bias (i.e., there is an own-body-size effect), but there was sufficiently high ownership in both the synchronous and asynchronous conditions in Experiment 1 so that the contraction bias was present in both conditions (explanation 2).

Explanation 1 would contradict results by Van Der Hoort et al. (2011), Van Der Hoort and Ehrsson (2014; 2016), Linkenauger et al. (2013), and Banakou et al. (2013). Furthermore, explanation 2 receives support from previous research findings: It has been shown that the mere perspective of looking at a body from a 1PP in an IVE leads to strong experiences of ownership. For example, Normand et al. (2011) reported that in the asynchronous condition, administered in the 1PP, a considerable amount of participants (between 23 and 32%) reported high scores in the ownership questionnaire. The role of perspective was also emphasized in various other studies (e.g., Kokkinara et al. 2016; Maselli and Slater 2013; Petkova et al. 2011b; Slater et al. 2010). It was noted that 1PP "dominates visuotactile synchrony in its contribution towards body ownership illusions" (Kilteni et al. 2012). Hence, asynchronous visuotactile stimulation might not have been able to sufficiently disrupt ownership in Experiment 1. Even though we have found a difference of experienced ownership between the synchronous and asynchronous conditions, there were still considerably high levels of ownership present in the asynchronous condition as indicated by the descriptive statistics of Experiment 1 (Table 2). It is therefore plausible that the contraction bias occurred in both the synchronous and asynchronous condition. We therefore administered a second experiment, where we used a different visuotactile stimulation aimed at disrupting ownership in the asynchronous condition more strongly than in Experiment 1.

4 Experiment 2

4.1 Method

We used the same design and procedure as in Experiment 1 except for the ownership manipulation. In addition to the visuotactile stimulation, we now changed the perspective of the participants. Therefore, the intention of Experiment

2 was to create an even stronger difference between conditions in terms of ownership. In the synchronous condition, participants were touched synchronously and had a 1PP view of the virtual body, the same as in Experiment 1. In the asynchronous condition, however, participants had a 3PP view of the body (see the right side of Fig. 1). The virtual body was moved to the left by about one time the width of the respective avatar's body. Additionally, the participants could only see the touches being applied to the virtual body, but they could not feel them on their real body. The reasoning for the absence of tactile stimulation was that real touches being applied to seemingly empty virtual space could create confusion in the participants. Additionally, the touches could be associated with the avatar body by the participants, even if they were asynchronous.

4.2 Results

4.2.1 Ownership and presence

Again, we tested whether the modified stimulation procedure (additional perspective change) had worked as intended. Descriptive statistics are shown in Table 3. There were significant main effects of stimulation in two-way repeated measures ANOVAs for ownership, $F(1, 23) = 117.26$, $p < .001$, $\eta_p^2 = 0.84$, and presence, $F(1, 23) = 30.06$, $p < .001$, $\eta_p^2 = 0.57$. In both analyses, no significant interactions and main effects of body size could be observed. Additionally, we found no significant effects for control questions (all $p > .05$). These results again indicate a successful induction of ownership in the synchronous condition (Hypothesis 1). Furthermore, the effect sizes of the main effects of stimulation for ownership and presence were both higher than in Experiment 1, suggesting an even stronger effect of stimulation. The marginal mean of the ownership ratings in the asynchronous conditions (2.36) was now considerably below the middle of the scale (4; see Table 3).

Again, we asked participants about their impression of the room's size and their own perceived age. We found a linear effect of body size for the questions "I felt younger than I actually am" [$F(1, 23) = 29.66$, $p < .001$, $\eta_p^2 = 0.56$] and "I felt older than I actually am" [$F(1, 23) = 10.23$, $p = .004$, $\eta_p^2 = 0.31$], suggesting that participants felt younger in the small body and older in the large body. Similarly, in the small body, the room appeared bigger than in the large body, $F(1, 23) = 41.13$, $p < .001$, $\eta_p^2 = 0.64$, and in the large body, the room appeared smaller than in the small body, $F(1, 23) = 45.35$, $p < .001$, $\eta_p^2 = 0.66$.

Table 3 Descriptive statistics for ownership, control, and presence questions in Experiment 2

Scale	Synchronous condition	Asynchronous condition
Ownership	4.44	2.36
Control	2.36	2.14
Presence	3.53	2.89

Displayed are the marginal means for the synchronous and asynchronous stimulation conditions. $N = 72$ for all questions

4.2.2 Size judgments

As in Experiment 1, we tested Hypotheses 2 and 3 using a two-way repeated measures ANOVA. In line with Hypothesis 2, we found a main effect of body size on size judgments, $F(1.56, 35.96) = 21.03$, $p < .001$, $\eta_p^2 = 0.48$ (degrees of freedom were adjusted using Greenhouse–Geisser correction; Fig. 4). As in Experiment 1, there was a linear trend ($p < .001$), suggesting that there was an overestimation in the *small* body and an underestimation in the *large* body compared to the *medium* body (contraction bias, Hypothesis 2). However, the interaction did not turn out significant, $F(2, 46) = 0.92$, $p = .405$, $\eta_p^2 = 0.04$. Additionally, we found no main effect of stimulation, $F(1, 23) = 0.53$, $p = .474$, $\eta_p^2 = 0.02$. See Fig. 4 for details. Therefore, as in Experiment 1, we could not support Hypothesis 3 (own-body-size effect).

4.3 Discussion

Again, we could show a contraction bias in size judgments. However, the bias was not stronger in the synchronous condition compared to the asynchronous condition. Therefore, the additional manipulation of perspective did not lead to a stronger own-body-size effect. Altering the perspective of the virtual body has already been used in previous studies (e.g., Petkova et al. 2011a). These studies demonstrated considerable levels of ownership in conditions with a 1PP (Petkova et al. 2011a, b; Maselli and Slater 2014). We observed lower ownership ratings in the asynchronous 3PP condition in Experiment 2 than in the asynchronous 1PP condition of Experiment 1, and there was also a clear difference between 1PP and 3PP in Experiment 2. Thus, the change in perspective in Experiment 2 successfully improved the impact of the ownership manipulation. Nevertheless, there was no effect of ownership on size judgments.

It is still possible that the contraction bias we found in our study reflects an effect of visual comparison rather than ownership. This explanation was already addressed and ruled out for the original paradigm in the follow-up studies by Van der Hoort and Ehrsson (2014, 2016). To rule out this possibility in our experiments, we administered a third experiment.

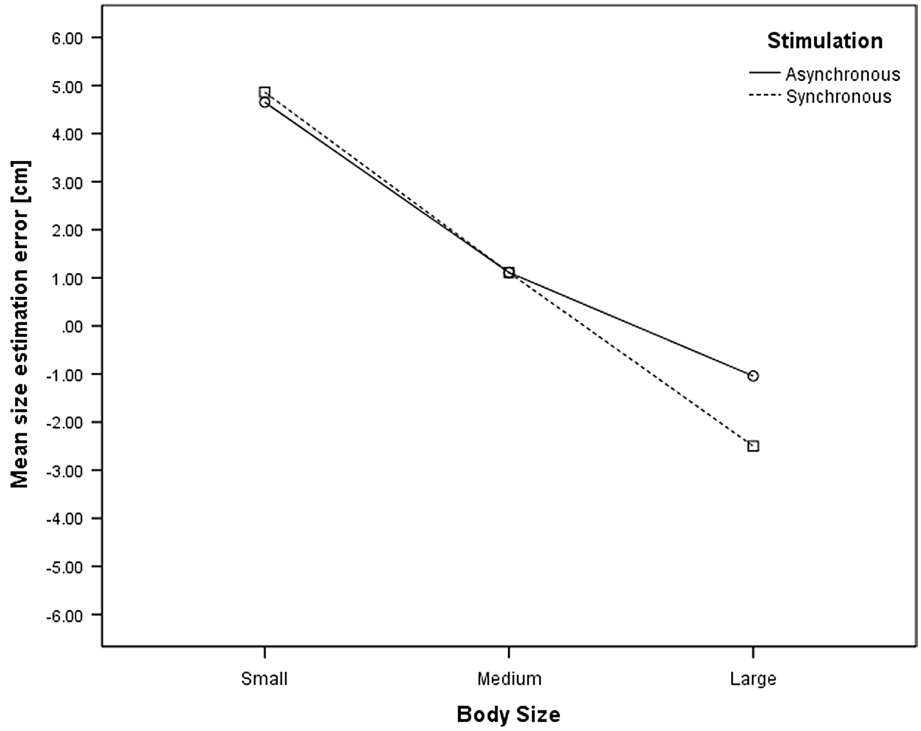

Fig. 4 Results of the two-way repeated measures ANOVA with the difference between real and estimated size of the test objects as dependent measure (Experiment 2)

5 Experiment 3

5.1 Method

In Experiment 3, we tested whether the removal of the body as a visual reference cue during size judgments would negatively affect the contraction bias. The same design and procedure as in Experiment 2 were used except that, after the stimulation phase, the virtual avatar body was removed and the judgments of the test objects had to be made without the possibility of using the body as a visual reference. Therefore, results of Experiment 3 can be attributed more closely to the previous manipulation of ownership by ruling out a visual comparison effect during the judgment phase.

5.2 Results

5.2.1 Ownership and presence

Descriptive statistics are shown in Table 4. Again, there was a significant main effect of stimulation for ownership, $F(1, 19) = 39.98$, $p < .001$, $\eta_p^2 = 0.68$. Ownership was higher in the synchronous condition. There was also a main effect of body size for ownership, $F(1.95, 37.11) = 4.63$, $p = .017$, $\eta_p^2 = 0.20$ (degrees of freedom were adjusted using Greenhouse–Geisser correction). Ownership was significantly higher in the *normal* body compared to the *large* body ($p = .014$, Tukey's adjusted post hoc tests). There was no significant main effect of stimulation for presence, $F(1, 19) = 1.39$, $p = .253$, $\eta_p^2 = 0.07$. In contrast to Experiments 1 and 2, there was an additional significant main effect of stimulation for control questions, $F(1, 19) = 9.08$, $p = .007$, $\eta_p^2 = 0.32$, meaning that statements not related to ownership received more support in the synchronous condition. All other effects were not significant (all $p > .05$). These results conflict with the expectations of Hypothesis 1. The fact that there was also a difference between stimulation conditions in the control questions could be due to a response bias. Additionally, there was no effect on presence ratings.

Table 4 Descriptive statistics for ownership, control, and presence questions in Experiment 3

Scale or question	Synchronous condition	Asynchronous condition
Ownership	4.11	2.98
Control	2.27	1.98
Presence	3.52	3.45

Displayed are the marginal means for the synchronous and asynchronous stimulation conditions. $N = 60$ for all questions

As in the previous experiments, we asked participants about their impression of the room's size and their own perceived age. We observed the same effects as in Experiments 1 and 2 except that participants did not feel significantly older in the large body. There was a linear effect of body size for the question "I felt younger than I actually am"

[$F(1, 19) = 7.31$, $p = .014$, $\eta_p^2 = 0.28$] but not for the question "I felt older than I actually am" [$F(1, 19) = 3.75$, $p = .068$, $\eta_p^2 = 0.17$], suggesting that participants felt younger in the small body but not significantly older in the large body. Additionally, in the small body, the room appeared bigger than in the large body, $F(1, 19) = 47.47$, $p < .001$, $\eta_p^2 = 0.71$, and in the large body, the room appeared smaller than in the small body, $F(1, 19) = 61.10$, $p < .001$, $\eta_p^2 = 0.76$, similar to Experiments 1 and 2.

5.2.2 Size judgments

As in Experiments 1 and 2, we used a two-way repeated measures ANOVA. Again, there was a significant main effect of body size, $F(2, 38) = 6.09$, $p = .005$, $\eta_p^2 = 0.24$ (Fig. 5). The linear trend ($p = .002$) showed that there was a contraction bias (overestimation of size in the *small* body and underestimation of size in the *large* body compared to the *medium* body). Therefore, Hypothesis 2 could be supported using nonvisible bodies in the judgment phase. However, as before, Hypothesis 3 (own-body-size effect) received no support: There was no interaction between body size and stimulation, $F(2, 38) = 1.06$, $p = .358$, $\eta_p^2 = 0.05$, and there was no main effect of stimulation, $F(1, 19) = 2.10$, $p = .164$, $\eta_p^2 = 0.10$ (Fig. 5).

5.3 Discussion

To conclude a full validation study of the own-body-size effect, we administered a condition where there was no visible body during the judgment phase. Again, we could show that there was a contraction bias. Since the body could not act as a visual reference during the judgment of the objects, it is probable that cognitive aspects associated with the body led to the contraction bias. These aspects include ownership but also priming of the previously presented body. A direct visual comparison can be ruled out as an explanation for the results since no body was visible during the judgment phase. However, it is still possible that participants made a mental visual comparison between the objects and their memory of the body. There was no instruction to imagine a visual body. Nevertheless, we are unable to rule out this explanation completely and further research could clarify the role of mental comparisons (e.g., by changing the instructions of the task or asking participants about their strategies).

As in Experiments 1 and 2, we could not show that the contraction bias depended on the stimulation condition. Again, there was a significant difference in the amount of experienced ownership as indicated by the questionnaire data. However, surprisingly, although we used the same visuotactile stimulation procedure as in Experiment 2, the difference of ownership between conditions was descriptively not as pronounced as in Experiments 1 and 2. A possible explanation is that we only assessed ownership at the end of each trial, thereby including both the ownership induction

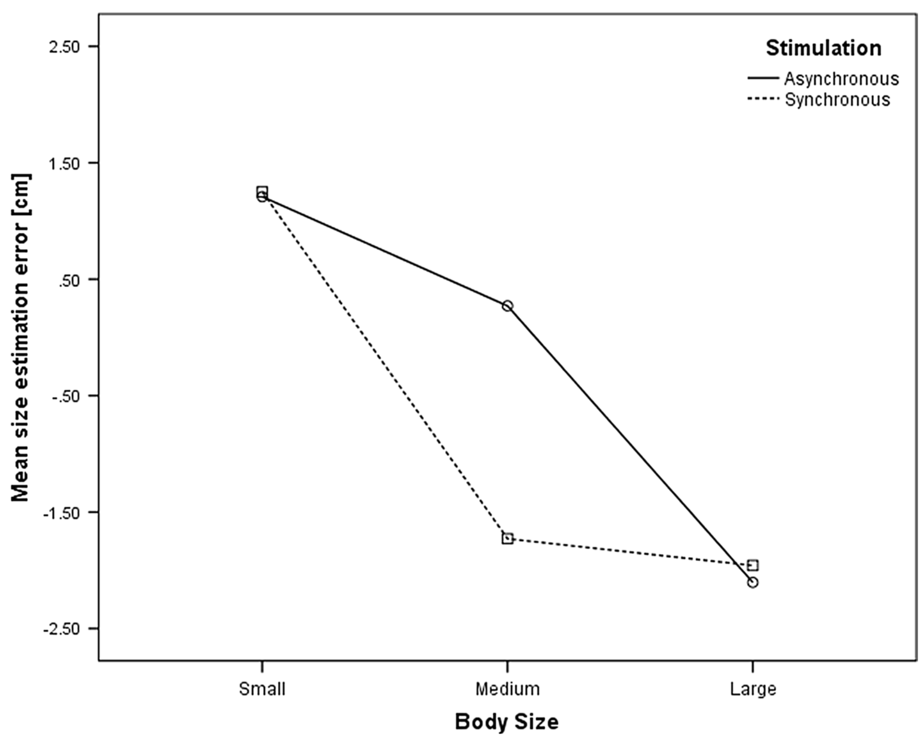

Fig. 5 Results of the two-way repeated measures ANOVA with the difference between real and estimated size of the test objects as dependent measure (Experiment 3)

and the size judgment phase in the subjective ownership rating. Participants, in hindsight, might have experienced the judgment phase as having lower ownership because there was no body visible during the latter part of the experiment. This could have lowered the overall ownership ratings. Nevertheless, we expected a difference between stimulation conditions. Another point to consider is that there was a higher agreement with control questions in the synchronous condition. Analyses of the control questions showed that both received more agreement in the synchronous condition: Participants had a stronger impression of having two bodies at the same time and a higher agreement with the statement that the avatar began to visually resemble their own body. A possible explanation is that the removal of the avatar after the ownership induction interfered with participants' interpretation of the control questions. Potentially, seeing the virtual world alternatingly with and without a virtual body could have led to an impression of having two bodies at the same time when the virtual body was present and synchronous. Similarly, the body could have appeared visually similar to the own body because of the striking difference between having a body and having no body in the virtual world. Nevertheless, ownership questions received more support in the synchronous condition, indicating that there was still an ownership difference.

6 General discussion

In our study, we were able to demonstrate the own-body-size effect in an IVE setting. We remained as close as possible to the original setup (Van der Hoort et al. 2011). In Experiment 1, we used a well-established method of manipulating ownership by applying either synchronous or asynchronous touches to virtual bodies. In Experiment 2, we applied either synchronous or no touches and manipulated the perspective of the virtual body. We used an approach that was inspired by the results of previous VR studies, showing that manipulating the perspective in VR can be more effective than visuotactile stimulation (e.g., Maselli and Slater 2013; Petkova et al. 2011a, b; Slater et al. 2010). In Experiment 3, we ruled out that visual comparison of the virtual body and the test objects affected the own-body-size effect.

In all three experiments, we found a significant contraction bias. However, the visuotactile ownership manipulation had no effect. The supposedly stronger manipulation of ownership in Experiment 2 did not impact this finding. In addition, the contraction bias was observed in Experiment 3 when using invisible bodies in the judgment phase. In sum, we could successfully demonstrate the contraction bias in an IVE. Our results support previous findings that suggest an effect of the size of one's own body on the perception of objects (Banakou et al. 2013; Linkenauger et al. 2013; Van der Hoort et al. 2011). In all of our experiments, a larger body led to an underestimation of object size and a smaller body led to an overestimation. However, using an IVE, we could not show an influence of the amount of ownership on the strength of the contraction bias. It is possible that other mechanisms hinder the comparability of the findings from the virtual and the real world, respectively. For example, as mentioned above, distances are systematically underestimated in an IVE (Renner et al. 2013). There were two studies that already used an IVE to investigate effects of virtual bodies on object size judgments and they could demonstrate that the size of the body affects judgments (Banakou et al. 2013; Linkenauger et al. 2013). However, these studies did either not accurately manipulate or measure ownership sensations toward the virtual bodies or they did not demonstrate a contraction bias but rather a general overestimation of objects for ownership of small bodies. Results from these studies did therefore not elucidate how the strength of body ownership is associated with the contraction bias in an IVE. The IVE in our experiments elicited a contraction bias and therefore affected perception in the same way it was affected in the real world. However, the feeling of ownership toward virtual bodies was, although present, not as decisive for the perception of the virtual world as expected. This is in contrast to the original proposition of the effect by Van der Hoort and colleagues.

Another explanation for the lacking influence of ownership is that, in VR, only a little amount of ownership is needed to induce the contraction bias. We tried to rule out this explanation in Experiment 2. We observed larger differences between the stimulation conditions in self-reported ownership than in Experiment 1 and ownership was low in the asynchronous condition. Therefore, we could confirm that altering the perspective of the body is a promising approach for manipulating ownership in an IVE. However, this manipulation did not affect the size judgments. Even a lower amount of ownership was able to produce the contraction bias. Possibly, an IVE itself is already convincing the user that he or she is connected to the avatar. Users could automatically inherit properties from their virtual manifestations due to the visually compelling character of the environment, regardless of the amount of ownership reported in questionnaires. This explanation could pose problems for inducing disownership in future VR embodiment studies since conditions with low ownership could entail the same behavioral consequences as high ownership conditions. Yet another conceivable explanation for our results is priming. In all three experiments, priming of the concepts smallness and largeness in the ownership phase of the respective conditions could have influenced the size judgments. However, this is unlikely the case because we would expect that priming of smallness would lead to smaller judgments of objects and vice versa.

Overall, our results show that caution needs to be taken when transferring embodiment studies into VR setups. Visual perception does not necessarily involve exactly the same processes in an IVE as in a real environment. It is conceivable that an ownership sensation of a virtual body has different properties when compared to an ownership sensation of a physically present body-like object. Furthermore, the own-body-size effect could be more fragile than previously thought and depend on the characteristics of the ownership manipulation.

One limitation of our study is that we only used self-reports of ownership and no physiological measures (e.g., skin conductance response to a threat). Even though self-reports have been used throughout ownership research, physiological measures could still provide a more sensitive assessment of ownership and reveal aspects that cannot be captured with self-reports. However, there are only few studies that specifically address differences between both forms of measurement and they either reported similar effects for both forms of measurement (e.g., Palomo et al. 2017) or even a stronger effect for subjective measurements (Rohde et al. 2011).

To summarize our findings, we showed that the size of the body serves as a reference frame for the perception of object size. A visual comparison between the body and the object is not responsible for the effect. Furthermore, we could increase the impact of an ownership manipulation on perceived ownership by additionally manipulating the perspective. In future studies, this procedure could be further improved by altering the perspective to a larger degree, so that the virtual body is outside of the near-personal space of the participant in order to induce an ownership disrupting condition. Additionally, in future studies, other means of manipulating ownership in an IVE such as real-time movements of avatars could be considered.

6.1 Conclusions

We demonstrated that high levels of ownership need not be a crucial factor for evoking a contraction bias in a VR setting. This means that caution is advised when assessing behavioral consequences of body ownership in VR, especially regarding perception. Ownership feelings need not reflect the entire relationship a user forms to his or her virtual self-representation. Our results have implications for potential VR therapies for body disorders such as anorexia nervosa or muscle dysmorphia. For example, Keizer et al. (2016) could show that it is possible to decrease overestimation of body size in anorexia nervosa patients by manipulating the virtual body. Furthermore, in the context of social phobias, the illusion of having a large body could be used in the sense of the Proteus effect (Yee and Bailenson 2007) to enhance self-confidence. Regarding body ownership, it has been shown that experiencing ownership of avatars is able to modulate pain thresholds (Martini et al. 2014) and to reduce racial bias (Maister et al. 2013). The results from our study demonstrate the importance of the perspective in eliciting such ownership feelings. We can also draw conclusions about VR content development: Demonstrably, very large or very small virtual body representations are suitable for evoking strong ownership feelings. Humans seem to have an astonishingly high tolerance for accepting exotic or impossible bodies as their own frame of reference. This enlarges possibilities for game designers to engage users in widely different avatars and opens up the possibility to use microrobots in surgery, as Van der Hoort et al. (2011) point out. Our results indicate that it is feasible to experience ownership of a small artificial body. However, the contraction bias needs to be taken into consideration when performing complex spatio-visual tasks such as surgery.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

Informed consent Participants were treated according to the Code of Ethics of the World Medical Association (Declaration of Helsinki), and informed consent was obtained.

Appendix: Ownership questionnaire

Questions

During the experiment, there were times when …

… I felt as if the avatar's body was my body (ownership).

… I had the feeling that I was looking at myself (ownership).

… it seemed as though the touch I felt was caused by the object touching the avatar (ownership).

… I had the feeling that I was lying in the same location as the avatar (location).

… I felt I could move the avatar, if I wanted to (agency).

… I felt as if I had two bodies (control question).

… the avatar began to resemble my own body in terms of shape, skin tone, or some other visual feature (control question).

Answer scale

Fully disagree O 1 O 2 O 3 O 4 O 5 O 6 O 7 Fully agree

References

Banakou D, Groten R, Slater M (2013) Illusory ownership of a virtual child body causes overestimation of object sizes and implicit attitude changes. Proc Natl Acad Sci 110(31):12846–12851

Botvinick M, Cohen J (1998) Rubber hands 'feel' touch that eyes see. Nature 391(6669):756

Cox PF (Producer), Johnston J (Director) (1999) Honey, I shrunk the kids [motion picture]. Walt Disney Pictures, Burbank

De Vignemont F (2011) Embodiment, ownership and disownership. Conscious Cogn 20(1):82–93

Dobricki M, de la Rosa S (2013) The structure of conscious bodily self-perception during full-body illusions. PLoS ONE 8(12):e83840

Ferrer-García M, Gutiérrez-Maldonado J (2012) The use of virtual reality in the study, assessment, and treatment of body image in eating disorders and nonclinical samples: a review of the literature. Body Image 9(1):1–11

First MB (2005) Desire for amputation of a limb: paraphilia, psychosis, or a new type of identity disorder. Psychol Med 35(6):919–928

Gurusamy K, Aggarwal R, Palanivelu L, Davidson BR (2008) Systematic review of randomized controlled trials on the effectiveness of virtual reality training for laparoscopic surgery. Br J Surg 95(9):1088–1097

Harris LR, Carnevale MJ, D'Amour S, Fraser LE, Harrar V, Hoover AE et al (2015) How our body influences our perception of the world. Front Psychol 6:819

IJsselsteijn WA, de Kort YAW, Haans A (2006) Is this my hand I see before me? The rubber hand illusion in reality, virtual reality, and mixed reality. Presence Teleop Virt 15(4):455–464

Keizer A, van Elburg A, Helms R, Dijkerman HC (2016) A virtual reality full body illusion improves body image disturbance in anorexia nervosa. PLoS ONE 11(10):e0163921

Kilteni K, Normand JM, Sanchez-Vives MV, Slater M (2012) Extending body space in immersive virtual reality: a very long arm illusion. PLoS ONE 7(7):e40867

Klevjer R (2012) Enter the avatar: the phenomenology of prosthetic telepresence in computer games. In: Sageng J, Fossheim H, MandtLarsen T (eds) The philosophy of computer games. Philosophy of engineering and technology, vol 7. Springer, Dordrecht

Kokkinara E, Kilteni K, Blom KJ, Slater M (2016) First person perspective of seated participants over a walking virtual body leads to illusory agency over the walking. Sci Rep 6:28879

Linkenauger SA, Leyrer M, Bülthoff HH, Mohler BJ (2013) Welcome to wonderland: the influence of the size and shape of a virtual hand on the perceived size and shape of virtual objects. PLoS ONE 8(7):e68594

Longo MR, Haggard P (2012) What is it like to have a body? Curr Dir Psychol Sci 21(2):140–145

Longo MR, Schüür F, Kammers MP, Tsakiris M, Haggard P (2008) What is embodiment? A psychometric approach. Cognition 107(3):978–998

Loomis JM, Knapp JM (2003) Visual perception of egocentric distance in real and virtual environments. Virtual Adapt Environ 11:21–46

Maister L, Sebanz N, Knoblich G, Tsakiris M (2013) Experiencing ownership over a dark-skinned body reduces implicit racial bias. Cognition 128(2):170–178

Martini M, Perez-Marcos D, Sanchez-Vives MV (2014) Modulation of pain threshold by virtual body ownership. Eur J Pain 18(7):1040–1048

Maselli A, Slater M (2013) The building blocks of the full body ownership illusion. Front Hum Neurosci 7:83

Maselli A, Slater M (2014) Sliding perspectives: dissociating ownership from self-location during full body illusions in virtual reality. Front Hum Neurosci 8:693

Mohler BJ, Creem-Regehr SH, Thompson WB, Bülthoff HH (2010) The effect of viewing a self-avatar on distance judgments in an HMD-based virtual environment. Presence Teleop Virt 19(3):230–242

Murray CD, Pettifer S, Howard T, Patchick EL, Caillette F, Kulkarni J, Bamford C (2007) The treatment of phantom limb pain using immersive virtual reality: three case studies. Disabil Rehabil 29(18):1465–1469

Normand JM, Giannopoulos E, Spanlang B, Slater M (2011) Multisensory stimulation can induce an illusion of larger belly size in immersive virtual reality. PLoS ONE 6(1):e16128

Palomo P, Borrego A, Cebolla A, Llorens R, Demarzo M, Baños RM (2017) Subjective, behavioral, and physiological responses to the rubber hand illusion do not vary with age in the adult phase. Conscious Cogn 58:90–96

Petkova VI, Björnsdotter M, Gentile G, Jonsson T, Li TQ, Ehrsson HH (2011a) From part-to whole-body ownership in the multisensory brain. Curr Biol 21(13):1118–1122

Petkova VI, Khoshnevis M, Ehrsson HH (2011b) The perspective matters! Multisensory integration in ego-centric reference frames determines full-body ownership. Front Psychol 2:35

Piryankova IV, Wong HY, Linkenauger SA, Stinson C, Longo MR, Bülthoff HH, Mohler BJ (2014) Owning an overweight or underweight body: distinguishing the physical, experienced and virtual body. PLoS ONE 9(8):e103428

Poulton EC (1989) Bias in quantifying judgments. Erlbaum, Hillsdale

Proffitt DR, Linkenauger SA (2013) Perception viewed as a phenotypic expression. In: Prinz W, Beisert M, Herwig A (eds) Action science: foundations of an emerging discipline. MIT Press, Cambridge, pp 171–198

Renner RS, Velichkovsky BM, Helmert JR (2013) The perception of egocentric distances in virtual environments—a review. ACM Comput Surv 46(2):23

Ries B, Interrante V, Kaeding M, Anderson L (2008) The effect of self-embodiment on distance perception in immersive virtual environments. In: Proceedings of the 2008 ACM symposium on virtual reality software and technology. ACM, pp 167–170

Rohde M, Di Luca M, Ernst MO (2011) The rubber hand illusion: feeling of ownership and proprioceptive drift do not go hand in hand. PLoS ONE 6(6):e21659

Slater M, Spanlang B, Sanchez-Vives MV, Blanke O (2010) First person experience of body transfer in virtual reality. PLoS ONE 5(5):e10564

Tsakiris M, Haggard P (2005) The rubber hand illusion revisited: visuotactile integration and self-attribution. J Exp Psychol Hum Percept Perform 31(1):80

Van der Hoort B, Ehrsson HH (2014) Body ownership affects visual perception of object size by rescaling the visual representation of external space. Atten Percept Psychophys 76(5):1414–1428

Van Der Hoort B, Ehrsson HH (2016) Illusions of having small or large invisible bodies influence visual perception of object size. Sci Rep 6:34530

Van der Hoort B, Guterstam A, Ehrsson HH (2011) Being Barbie: the size of one's own body determines the perceived size of the world. PLoS ONE 6(5):e20195

Weibel D, Schmutz J, Pahud O, Wissmath B (2015) Measuring spatial presence: introducing and validating the pictorial presence SAM. Presence Teleop Virt 24(1):44–61

Wilson M (2002) Six views of embodied cognition. Psychon Bull Rev 9(4):625–636

Yee N, Bailenson J (2007) The Proteus effect: the effect of transformed self-representation on behavior. Hum Commun Res 33(3):271–290