Big Foot: Using the Size of a Virtual Foot to Scale Gap Width

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Spatial perception research in the real world and in virtual environments suggests that the body (e.g., hands) plays a role in the perception of the scale of the world. However, little research has closely examined how varying the size of virtual body parts may influence judgments of action capabilities and spatial layout. Here, we questioned whether changing the size of virtual feet would affect judgments of stepping over and estimates of the width of a gap. Participants viewed their disembodied virtual feet as small or large and judged both their ability to step over a gap and the size of gaps shown in the virtual world. Foot size affected both affordance judgments and size estimates such that those with enlarged virtual feet estimated they could step over larger gaps and that the extent of the gap was smaller. Shrunken feet led to the perception of a reduced ability to step over a gap and smaller estimates of width. The results suggest that people use their visually perceived foot size to scale virtual spaces. Regardless of foot size, participants felt that they owned the feet rendered in the virtual world. Seeing disembodied, but motion-tracked, virtual feet affected spatial judgments, suggesting that the presentation of a single tracked body part is sufficient to produce similar effects on perception, as has been observed with the presence of fully co-located virtual self-avatars or other body parts in the past.

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1. INTRODUCTION

Gibson [1979] argued almost 40 years ago that perception of the environment could not be accomplished without taking the relationship between it and the body into account. Since then, there has been a plethora of research aimed at understanding how the body influences our perception of spatial layout. Overall, the results seem to suggest that we may scale the layout of the environment in terms of the dimensions of our bodies, including using cues such as eye height [Leyrer et al. 2011; Warren and Whang 1987; Wraga 1999], hand size [Linkenauger et al. 2011], leg and arm length [Mark and Vogele 1988], and other bodily properties to determine dimensions in the world (for a review, see Proffitt and Linkenauger [2013]). Moreover, altering the body can lead to changes in the representation of the space surrounding the body. For example, if one holds an object that extends the space over which one can reach, then the space is perceived as larger [Witt et al. 2005]. Likewise, if one is holding an object that widens the body or increases it in height, then the perception of openings that can be walked through are altered [Stefanucci and Geuss 2009, 2010].

More recently, avatars have been used as a means of altering body size to further investigate the boundaries of these effects and to allow for body manipulations that are impossible in the real world (for a review, see Creem-Regehr et al. [2015]). For example, Linkenauger et al. [2013] enlarged or shrunk the size of a virtual hand and asked participants to judge the size of balls presented next to the hand. Results showed a clear influence of portrayed hand size on estimates of the size of the balls such that when the hand was large, the balls were perceived to be smaller and when the hand was shrunk, the balls were perceived as larger. In addition to asking participants to verbally report the size of objects near the hand, they asked participants to judge whether or not they could grasp different-sized objects while manipulating hand size to be large or small. Again, perceived hand size affected what participants believed that they could act on with larger hands, producing more responses that objects could be grasped than with smaller hands.

In addition to scaling the size of objects based on virtual hands, other research has shown that people may scale the size of objects to other visually specified body parts or body-based cues. Van der Hoort et al. [2011] found that when participants experienced their own virtual body, depicted through leg length and foot size of a mannequin, as being large, they judged objects in the virtual environment to be smaller and closer. However, when their virtual bodies were perceived as tiny, the opposite effect on perceived size and distance was observed. Important to note, however, was that feeling ownership of the body moderated the effect, such that when ownership was disrupted, the influence of body size on object perception was no longer present. Banakou et al. [2013] also showed an effect of virtual body size on perceived object size. In their study, when a virtual body that was perceived to be a child was shown to participants, they judged objects in the environment to be larger. Other work by Leyrer et al. [2011] also showed an effect of perceived eye height on the scaling of distance in virtual environments. When participants perceived themselves as taller in the virtual world as a result of a taller eye height, they judged distances to be closer. However, when participants viewed the world from a shorter eye height, distance perception was unaffected when compared to a no–eye height manipulation control condition. Interestingly, the effect of taller eye heights was present whether participants saw a virtual avatar in the virtual environment or not. Thus, using eye height to scale the distance to objects may not depend on the ability to see the body representation in addition to the changed viewpoint and seems to be more likely to occur when the eye height is raised compared to lowered.

Judgments about affordances—one's ability to perform an action—have also been used to assess the perception of space in virtual environments where avatars are present as an alternative to explicit judgments about size or distance. For example, Lin et al. [2012] showed participants a virtual avatar that had a leg length similar to their real leg length or a virtual leg length that was 15% greater than their real leg length. Participants were presented with varying heights of doorways or poles and were asked to judge whether they felt they could duck under or step over the objects. When compared to a condition in which no virtual avatar was presented, participants who had a larger avatar showed a change in the height at which they said that they could step over a pole in the expected direction (e.g., participants with a larger avatar judged that they could step over taller poles). However, the effect did not hold for doorways. Lin et al. [2013] also investigated the influence of a fully tracked, gender-matched avatar on the perception of stepping off of a ledge. When a virtual avatar was present, participants had a lower threshold for what they estimated that they could step off. In other words, they were more cautious in their responses.

The prior work leaves open a few questions. First, the results on affordances are mixed. Sometimes, changing the size of the virtual body influences what actors believe they can do and other times it does not. Second, most of the prior work has compared either just the presence or absence of a virtual avatar on these judgments or has not manipulated the size of the body in both directions (i.e., making the body part in question both larger and smaller). One study that did show a compelling effect of both enlarging and shrinking the hand on grasping judgments [Linkenauger et al. 2013] focused only on objects presented in near space (e.g., reaching space around the body; see Cutting and Vishton [1995]). Thus, we believe that the prior work, while promising, leaves open the question of how symmetrically manipulating the size of virtual avatars affects the perception of affordances in extrapersonal space, or the space that is beyond reach but still relevant for locomotion.

Here, we test whether a change in the depiction of the size of feet affects the perception of what can be stepped over (e.g., a gap crossing). We both enlarged and shrunk the size of virtual feet in these experiments to assess potential boundaries of the effect. The foot is an interesting body part to consider manipulating given that it has not been altered before in a virtual environment. It is also directly relevant for making judgments about gap crossing as well as for estimating distances along the ground plane [Linkenauger et al. 2012]. Thus, the current work provides a possible replication of many of the previously reported effects of virtual bodies on space perception but also investigates a new manipulation of a virtual body in the context of a new affordance—the perception of gap crossings. In addition, participants reported on their perceptions of the gap in two ways: affordances and estimates of the width of the gap. It is important to note that affordances may provide a more task-relevant way of assessing the perception of spatial layout because they require participants to consider the space in terms of action [Wraga 1999]. Moreover, in general, affordance judgments made in the real world and visually matched virtual environments have been shown to be similar [Geuss et al. 2010]. Thus, in our experiment, participants experienced either an enlarged or shrunk set of feet that was tracked to the movements of their real feet. They estimated whether or not they could step over a variety of gaps and then subsequently estimated the extent of gaps with a visual matching task. Questions about ownership of the feet and perceived eye height were also assessed.

2. TESTING THE EFFECTS OF FOOT SIZE ON PERCEIVED GAP WIDTH

Participants judged whether or not they could cross gaps of different widths while viewing either an enlarged set of virtual feet or a shrunken set of virtual feet. The feet were rendered without ankles, legs, or other body parts in order to examine the effects of foot size without additional visual context about the size of the rest of the body (see Figure 1). Presenting the feet alone also allowed us to test whether disembodied body parts are sufficient to drive body-based effects on perception. After they made 24 decisions about whether or not they could cross various gaps (8 crossing distances estimated 3 times each), they also gave 12 perceptual estimates (4 gap widths estimated 3 times each). Forty-two University of Utah students and local volunteers (22 male, 20 female) were paid $10 for their participation or received course credit for their participation. One participant was excluded from the analysis

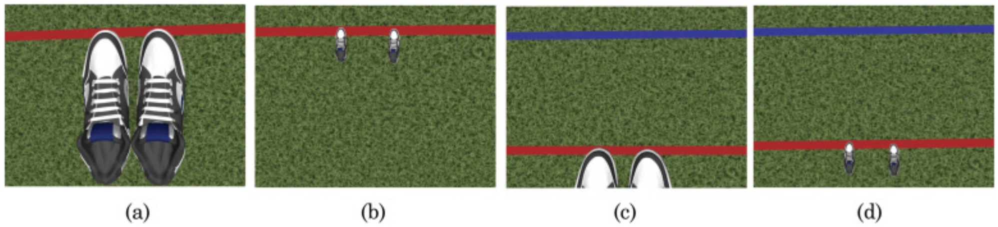

Fig. 1. The two images on the left depict the large (a) and small (b) virtual feet. The two images on the right show one gap width as depicted to participants in the large (c) and small (d) virtual feet condition.

because of an extreme measured foot size (>2 SD above the mean). With this outlier removed, the average measured foot size in the small foot condition was 27.97cm (SD = 2.16) and the average measured foot size in the large foot condition was 27.64cm (SD = 2.79). Participants had normal or corrected-to-normal vision and were able to walk and stand without assistance. All participants provided consent before the experiment began.

2.1 Materials and Apparatus

The virtual environment (an outdoor Italian piazza designed by WorldViz with grass overlaid on the original tiled ground plane) was displayed using an NVIS nVisor SX60 HMD with a resolution of 1280 × 1024 pixels in each eye and a 42 (h) × 34 (v) degree field of view. Pincushion correction and calibration was accomplished based on Kuhl et al. [2009]. A WorldViz PPT tracking system was used for head and foot tracking. Foot tracking was used to animate the movement of the feet portrayed in the virtual environment to match that of the participants' movements in the real world.

2.2 Design and Procedure

Participants were randomly assigned to either the large or small foot size condition. The average foot size of men and women in the United States in 2012 was determined to be 25.95cm and from that, two foot sizes were calculated: one that was half the size of the average foot (small foot condition) and another that was twice the size of the average foot (large foot condition). All participants completed 24 yes/no affordance judgments as to whether or not they believed they could step across gaps of various sizes. There were eight different gap widths (0.45m, 0.60m, 0.75m, 0.90m, 1.05m, 1.20m, 1.35m, and 1.50m], which were shown three times each. Participants never saw the same gap width twice in a row, and the virtual piazza world was rotated between each trial so that participants were not facing the same direction for consecutive trials. Participants' responses were confirmed after each trial before recording them electronically and manually. In addition to the affordance estimates for crossing, all participants gave estimates for the width of four gap distances [0.50m, 0.90m, 1.30m, and 1.70m] three times each for a total of 12 distance estimates after performing the affordance judgments. Participants never saw the same distance twice in a row, and they faced a random direction (north, south, east, or west) of the virtual piazza environment for each estimation trial. Finally, after the distance estimations, all participants reported whether they felt that their eye height was equivalent to, taller than, or shorter than their perceived eye height in the real world. The procedure for this task is described in more detail later.

After giving consent in an anteroom separate from the virtual environment laboratory, the experimenters attached motion capture trackers to the participants' shoes and ankles using Velcro straps. Two markers were placed on each foot. One marker was placed on top of the foot (on its upper plane) and as close to the farthest edge of the toes as possible in order to account for the full length of the participants' feet. A second marker was attached along the upper Achilles tendon and at ankle height. This foot-tracking scheme facilitated a simple foot model in the virtual world that accurately rendered movement laterally and within a small range vertically. Flexion, extension, inversion, and eversion were not shown.

Once the participants felt that the straps were comfortable and secure around their feet and ankles, they were asked to stand up and move to a different part of the anteroom, where they stood on top of a piece of tape attached to the carpet. Participants were told that they would need to distinguish between the near and far edges of similar lines on the ground in the virtual environment. The near edge was described as the edge of the tape that was closer to the participants' feet while far was described as the edge of the tape that was present once the participants had stepped over the extent of the tape itself. Participants had a chance to ask questions; once they expressed a clear understanding of the difference between the near and far edges, they were blindfolded and led through a doorway into the main virtual laboratory.

Once in the main room (which was dark), participants kept their eyes closed until the HMD was properly adjusted. Throughout this adjustment period, the HMD was turned off. Once on, participants could see the WorldViz piazza virtual environment with grass overlaid on the ground. The grass was needed to prevent participants from using the original tiled flooring as an implicit cue for gap crossing or distance estimates.

Participants were then instructed to look down at their feet and asked if they could see both the heels and toes of their shoes. Participants were also asked if they could locate both a red and a blue virtual line on the ground. After they saw their feet and both lines, they were asked to align their toes with the far edge of the red line by moving in the real world. Once aligned, they were instructed to look from their toes at the far edge of the red line to the near edge of the blue line and to indicate "yes" or "no" as to whether or not they could step to the blue line so that at least their toes touched the blue line and one foot remained on the ground at all times. They were instructed to not actually try to step or to move their feet around in the real or virtual worlds.

After the last trial in the block of affordance judgments, participants removed the HMD and placed the blindfold back over their eyes. The participants were then led back to the anteroom, where they completed a video gaming experience questionnaire. After completing the questionnaire, participants were then instructed that they would be led back into the main room in a few minutes to make estimates of distances between two lines on the ground in the virtual environment. As part of a brief training phase in the real world to calibrate participants to different distances, participants aligned their toes with the far edge of a piece of tape on the ground and were told that the distance between their toes and the near edge of the first piece of tape was 1ft and that the distance between their toes and the near edge of a second piece of tape was 3ft.

After this brief training, participants were led blindfolded back into the virtual laboratory to don the HMD. Participants were first asked to look for their feet and make sure that they could see their toes and heels. They were also asked to align their toes to the far edge of the red line on the virtual ground. Once in place, participants were told to estimate the distance from their toes at the far edge of the red line to the near edge of the blue line in feet and inches. Most participants used feet and inches, but a few chose to give meters and centimeters instead even though the training was in feet. In order to remind participants of what their virtual feet looked like, the experimenter periodically asked participants to make sure that they could still see their toes and heels, and that their toes were still aligned with the far edge of the red line.

After the last distance estimation trial, participants remained in the main room. They were asked to close their eyes and allowed to take a break by removing the HMD if they needed to do so. Once they were ready, participants were asked to look down at their feet and report if they felt shorter than,

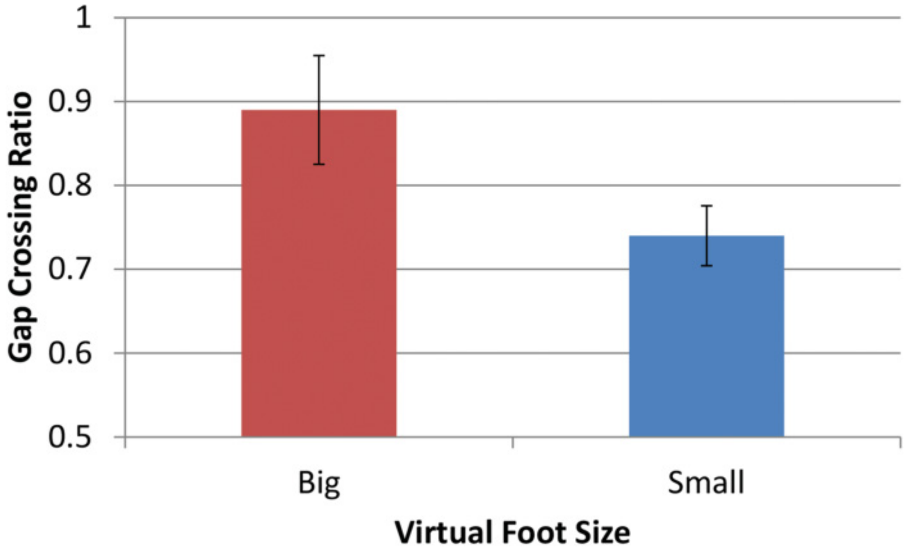

Fig. 2. Mean affordance judgments (represented as a ratio of estimated gap width that could be crossed over divided by real gap crossing ability) for each condition. Bars represent ±1 standard error.

taller than, or at their actual height. If they said shorter or taller than their actual height, participants were asked to express how much shorter or taller they felt using a percentage of their actual height. Participants were then taken back to the anteroom, where they completed a task-demand questionnaire and a body perception/ownership questionnaire. Participants' head and eye heights were also measured.

2.3 Results

2.3.1 *Affordances for Crossing.* In order to analyze the influence of altering the virtual size of one's foot on judgments of stepability, we first calculated the critical boundary. The critical boundary is the longest distance for which participants indicated that they could step over and against which all shorter distances were also judged as capable of being stepped over. This critical boundary was then scaled to participants' actual ability to step. This created a ratio for which values greater than one indicate that participants overestimated their ability to step (or alternatively underestimated the distance) and values less than one indicate that participants underestimated their ability to step (or alternatively overestimated the distance).

A univariate analysis of variance was conducted with ratio as the outcome and virtual foot size (large or small foot) as the sole independent variable[1]. Analyses revealed a main effect of virtual foot size, $F(1, 38) = 4.47$, $MSE = 0.24$, $p = 0.041$, $\eta_P{}^2 = 0.10$. Participants who saw a large virtual foot judged that they could step across relatively wider gaps ($m = 0.89$, $sd = 0.29$, *95% CI* $= 0.765, 1.015$) than participants who saw a small virtual foot ($m = 0.74$, $sd = 0.16$, *95% CI* $= 0.667, 0.805$). Figure 2 graphically depicts these findings. The results suggest that the size of one's foot can be used to scale judgments of stepability. Given the possibility that variations in actual foot size also contributed to these effects, we ran a second univariate analysis of variance with measured foot size as a covariate.

[1]One participant was removed as an extreme outlier for the affordance ratio (>2 SD above the mean), so that a total of 40 participants were analyzed.

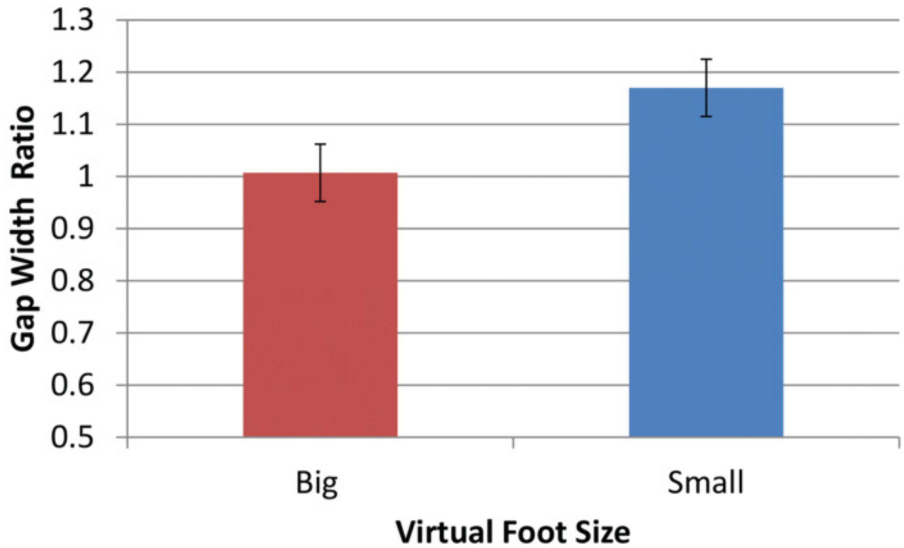

Fig. 3. Mean estimates of gap width represented as a ratio of perceived/actual width for each condition. Bars represent ±1 standard error.

Measured foot size showed a significant effect on affordance ratios, $F(1, 37) = 5.48$, $p = 0.025$, $\eta_P{}^2 = 0.12$, and the effect of virtual foot size reduced in effect size, $F(1, 37) = 3.96$, $p = 0.054$, $\eta_P{}^2 = 0.10$. The trending effect suggests that even after controlling for actual foot size, participants' judgments of their stepability were influenced by their virtual foot size.

2.3.2 *Gap Width Estimates.* Estimates of gap width were scaled by the actual distance being judged. A distance (0.50m, 0.90m, 1.30m, and 1.70m) by 2 foot-size (large, small) repeated measures ANOVA was conducted with ratios of estimate over actual as the outcome, distance as within-subjects factors, and foot size as a between-subjects factor[2]. There was a main effect of distance, $F(2.03, 73.03) = 20.89$, $MSE = 0.03$, $p < .001$, $\eta_P{}^2 = 0.37$. Bonferonni post-hoc tests revealed that the 0.50m distance was estimated to be relatively shorter ($m = 0.95$, $sd = 0.31$, *95% CI* = 0.847, 1.045) than the other three distances ($ps < 0.001$), the 0.90m ($m = 1.08$, $sd = 0.25$, *95% CI* = 0.999, 1.158) distance relatively shorter than the 1.70m distance ($m = 1.18$, $sd = 0.27$; $p = 0.001$, *95% CI* = 1.0091, 1.272), but no difference between the 1.70m distance and the 1.30m distance ($m = 1.15$, $sd = 0.28$; $p = 1$, *95% CI* = 1.066, 1.239). There were no significant interactions.

Again, there was a main effect of foot size: $F(1, 36) = 4.50$, $MSE = 0.23$, $p = 0.041$, $\eta_P{}^2 = 0.11$. Participants who saw a large virtual foot ($m = 1.007$, $se = 0.055$) estimated the distances to be relatively shorter than participants who saw a small virtual foot ($m = 1.17$, $se = 0.055$; see Figure 3). It should be noted that the mean gap width estimate for the large foot condition is nearly accurate while the small condition overestimated. We attribute this to the fact that the range of gap distances tested was near to the observer; however, future work using accurately matched-size feet (and no feet) would help to make more definitive claims about absolute accuracy in this context.

[2]Two additional participants were removed as extreme outliers for the gap width judgments, and one participant was excluded for missing data so that a total of 37 participants were analyzed. Results reported are Greenhouse-Geisser corrected given a failure to meet assumption of sphericity.

Given the possibility that variations in actual foot size also contributed to these effects, we ran a second repeated-measures analysis of variance with measured foot size as a covariate. Measured foot size showed no significant effect on size estimates, $F\,(1, 35) = 0.23$, $p = 0.64$, $\eta_P{}^2 = 0.006$, and the effect of virtual foot size remained, $F(1, 35) = 4.48$, $p = 0.041$, $\eta_P{}^2 = 0.11$.

2.3.3 *Relationship between Distance and Gap Affordances.* Both gap width estimates and affordances for crossing exhibited an influence from foot size in the same direction and to a similar degree. The magnitude of change in gap width estimates when examining small as compared to large feet was 13.9%, while the change in affordance judgments was 20.3%. However, these tests are group averages. We were also interested to see if, on an individual level, participants' gap width estimates were related to their affordance judgments.

To test this, we conducted a correlation between gap width estimates, after collapsing across distances, and affordance judgments. Pearson's correlation revealed no significant relationship between size estimates and affordance judgments: $r = -0.183$, $p = 0.271$.

2.3.4 *Perceived Eye Height.* It is possible that with different-sized virtual feet, participants may have perceived that they were closer to or farther from the ground. Given that actual manipulations of eye height can affect estimates of distance and size [Dixon et al. 2000; Wraga 1999], we felt it important to try to gain preliminary insight as to whether foot-size manipulations altered other aspects of body perception that may have contributed to participants' size or distance estimates. To investigate whether perceived eye height was altered by the foot manipulations, we conducted a univariate ANOVA with estimates of percentage change in perceived eye height as the dependent variable and virtual foot size (large, small) as a between-subjects factor. Results revealed no significant difference between estimates of eye height for those in the small-foot condition ($m = -0.073$, $se = 0.049$, *95% CI* $= -0.172$, 0.027) and those in the large-foot condition ($m = -0.18$, $se = 0.05$, *95% CI* $= -0.282$, -0.078), $F(1, 37) = 2.34$, $MSE = 0.05$, $p = 0.13$, $\eta_P{}^2 = 0.06$.

2.3.5 *Subjective Reports of Ownership.* It is possible that one group felt more strongly that they owned the virtual feet, which could have affected whether or not they used the feet to scale the virtual environment. To assess whether participants felt that they owned the virtual feet in each condition, we administered the self-assessment questionnaire developed and validated by Dobricki and de la Rosa [2013]. Their questionnaire identified three central components involved in ownership of virtual avatars: bodily self-identification, agency, and spatial presence. We administered 4 questions from their original set for each of the 3 components. When possible, the questions were modified to fit our study, such as asking whether participants felt that the virtual feet belonged to them rather than the "virtual body" as used in the original version. The questionnaire was administered on a computer screen such that participants moved a marker along a line to indicate their responses along a continuum from "not at all" to "very much." The value (in pixels) of the marker position was scaled from 0 to 1. We averaged across the 4 questions for each component and conducted a multivariate ANOVA for which we analyzed whether condition (large or small feet) predicted an effect on any of the components. The results revealed no effect of condition on any of the components. Participants in the large-feet condition identified the body as their own ($m = 0.41$, $se = 0.05$) in a manner similar to the small-feet condition ($m = 0.29$, $se = 0.05$, $p = 0.08$). There was also no difference in their ratings of agency over the feet across conditions (large: $m = 0.78$, $se = 0.05$; small: $m = 0.69$, $se = 0.05$, $p = 0.24$). Finally, both groups felt similar levels of spatial presence (large: $m = 0.75$, $se = 0.05$; small: $m = 0.65$, $se = 0.05$, $p = 0.16$). Given these results, we do not believe that differences in subjective feelings of ownership with the feet accounted for the effects of foot size on estimates of gap width or action capability.

3. GENERAL DISCUSSION

In both the large- and small-feet virtual conditions, we saw an influence of the manipulation of foot size on both measures of perception: the crossing-affordance judgment and the gap-width estimates. When viewing the environment with large feet, participants indicated that distances were relatively shorter and that they could step over wider gaps. In contrast, when viewing the environment with small feet, participants indicated that the gap distances were relatively larger and judged that they could step over only relatively shorter gaps. In addition, the change due to foot size was similar across both conditions. The fact that there was an effect even though only feet were rendered suggests that some of the benefits of co-located self-avatars may be achievable without the complexity of full body tracking and rendering.

This study is the first to show an effect of virtual foot size on both estimates of action capabilities and the perceived distance across a gap (two measures of the extent of extrapersonal space). We used both measures because we hypothesized that the feet may have served as a means with which to scale the world [Proffitt and Linkenauger 2013]. Both judgments of afforded actions and perceptual estimates of dimensions of the world were altered, suggesting that changes to the size of the virtual feet play some role in scaling of the environment. We were primarily interested in judgments of action capability, but we surmised that an effect on those judgments could have been due to a misperception of the distance across the gap. In other words, if the gap was perceived as smaller when the feet were enlarged, then this could lead to, or serve as, a basis for a decision that the gap was easier to cross. Alternatively, size estimates could have been constrained by whether or not participants believed that they could act. That is, if participants felt that they could easily step over the gap, then they may have inferred that it must be narrow. Interestingly, we found an effect of virtual foot size on both measures, but these effects were not correlated within participants. Thus, it seems as though participants' estimates of what they could do did not entirely depend on how large they perceived the gap to be or vice versa. Also notable is that actual foot size influenced stepping affordance judgments but did not predict gap size estimates. It is possible that the change in virtual foot size influenced affordance and size judgments in different ways. Whereas the affordance judgments may have been scaled based on perceived stepping ability of the virtual or real foot, the gap width judgments may have been scaled to the visual size of the foot. Although speculative, this explanation would lead to the current results showing virtual foot size effects on both measures, but through different mechanisms that vary across individuals. Future work could test whether allowing participants to actually step and then receive feedback about their action might affect the magnitude of the effect of foot size on affordance judgments and gap width estimates.

Also, we anecdotally felt as if the size of the virtual feet affected our perceived eye height in the environment, but participants did not significantly differ in their estimates of perceived eye height across feet conditions. Thus, changes in the perception of gap width and estimates of action capability appear to not have been due to a change in perceived eye height. Because participants could have inaccurate representations of units (such as feet or meters) and imprecise understandings of percentages and not know their actual height, it could be that the measure used to assess perceived eye height may not have been sensitive enough to detect a change if indeed there was one. Further, not seeing virtual legs attached to the feet could have affected the perception of eye height or foot size. Future work could test whether the addition of the rest of the body alters these judgments. Although not a statistically significant effect, participants in the large-foot condition, on average, reported lower perceived eye heights, which is consistent with the phenomenal experience of feeling closer to the ground when viewing larger feet. Future work is needed to better understand what information might underlie participants' decisions about action as well as their perceptual judgments of the scale of the real and virtual worlds, including the lack of a view of any other body part.

Participants' perceptions of the feet were indexed with a questionnaire assessing only feelings of ownership, presence, and control [Dobricki and de La Rosa 2013]. We did not directly ask participants to estimate the size of their virtual feet. Thus, the magnitude of the effect could have varied across participants given that they may have perceived the change in size to their feet differently. Distortions of the perceived size of other body parts, such as the hands and arms, have been shown to affect affordances and estimates of space in prior work [Linkenauger et al. 2014; Linkenauger et al. 2013; Piryankova et al. 2014]. Also, we decided to show participants virtual feet that were either 50% or 200% the size of the average foot size in the United States. Such a manipulation did not take into account the size of the participants' real feet, thus the change may have been larger or smaller for different participants, leading to differences in the magnitude of the effect observed across individuals. Finally, we tracked participants' movements of their feet in order to increase feelings of ownership. However, participants were not given time to move their feet in this study beyond positioning their feet on the tape. Future work could provide visuo-tactile feedback (stroking the participants' real feet while they watch their virtual feet being stroked) such as what has been used in other studies that examined body ownership of virtual avatars [Banakou et al. 2013; Kokkinara and Slater 2014]. Doing so might increase participants' acceptance of the virtual feet and their size as their own to a different degree.

An open question is whether or not altering the perceived size of the feet may affect other aspects of space perception. We observed an effect of foot size on decisions about a stepping action and the perception of ground distances, which are both highly relevant to the feet. Would altering the size of the feet affect the space over which participants believed they could reach? In other words, we are not certain whether the observed effects are tied only to the relevant affordance and perception of scale or whether they may generally affect all aspects of the space around them. Evidence from work on perceptual-motor recalibration in the context of locomotion suggests that recalibration for one type of locomotion (e.g., walking) does not always generalize to other types of locomotion (e.g., wheeling a chair; see Kunz et al. [2013]). It is possible that if we gave participants experience walking around the virtual world with their newly scaled bodies, then they would recalibrate to their new size and over- or underestimates of the perception of the scale of the environment could dissipate. Alternatively, feelings of ownership could increase and participants would then be more likely to use information about their bodies to scale the world. This is an intriguing question for future work as well.

4. CONCLUSION

We showed that the perceived size of virtual feet can affect decisions about action and perceptual estimates of scale in a virtual environment. People who experienced large virtual feet thought that they could step over wider gaps and judged that the widths of the gaps were smaller when compared to people who saw small virtual feet. These effects were not due to a change in perceived eye height nor were they due to differences in feelings of ownership of each foot size. Our results suggest that rendering animated virtual feet that are not connected to legs or a torso is sufficient to observe changes in the scaling of the space around the feet.

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REFERENCES

D. Banakou, R. Groten, and M. Slater. 2013. Illusory ownership of a virtual child body causes overestimation of object sizes and implicit attitude changes. *Proceedings of the National Academy of Sciences* 110, 12846–12851.

S. H. Creem-Regehr, J. K. Stefanucci, and W. B. Thompson. 2015. Perceiving absolute scale in virtual environments: How theory and application have mutually informed the role of body-based perception. In *The Psychology of Learning and Motivation*, B. Ross (Ed.). Academic Press: Elsevier Inc., Waltham, MA, 195–224.

J. E. Cutting and P. M. Vishton. 1995. Perceiving layout and knowing distances: The integration, relative potency, and contextual use of different information about depth. In *Perception of Space and Motion*, W. Epstein and S. Rogers (Eds.). Academic Press, New York, 69–117.

M. W. Dixon, M. Wraga, D. R. Proffitt, and G. Williams. 2000. Eye height scaling of absolute size in immersive and nonimmersive displays. *Journal of Experimental Psychology: Human Perception and Performance* 26, 582–593.

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

M. N. Geuss, J. K. Stefanucci, S. H. Creem-Regehr, and W. B. Thompson. 2010. Can I Pass? Using affordances to measure perceived size in virtual environments. In *Proceedings of the 7th Symposium on Applied Perception in Graphics and Visualization ACM*. 61–64.

J. J. Gibson. 1979. *The Ecological Approach to Visual Perception*. Houghton Mifflin, Boston.

E. Kokkinara and M. Slater. 2014. Measuring the effects through time of the influence of visuomotor and visuotactile synchronous stimulation on a virtual body ownership illusion. *Perception* 43, 43–58.

B. R. Kunz, S. H. Creem-Regehr, and W. B. Thompson. 2013. Does perceptual-motor calibration generalize across two different forms of locomotion? Investigations of walking and wheelchairs. *PLoS ONE* 8, e54446.

M. Leyrer, S. A. Linkenauger, H. H. Bülthoff, U. Kloos, and B. Mohler. 2011. The influence of eye height and avatars on egocentric distance estimates in immersive virtual environments. In *Proceedings of ACM Symposium on Applied Perception in Graphics and Visualization.* 67–74.

Q. Lin, J. J. Rieser, and B. Bodenheimer. 2012. Stepping over and ducking under: The influence of an avatar on locomotion in an HMD-based immersive virtual environment. In *Proceedings of ACM Symposium on Applied Perception*. 7–10.

Q. Lin, J. J. Rieser, and B. Bodenheimer. 2013. Stepping off a ledge in an HMD-based immersive virtual environment. In *Proceedings of the ACM Symposium on Applied Perception*. 107–110.

S. Linkenauger, H. Y. Wong, M. Geuss, J. Stefanucci, K. C. McCulloch, H. H. Bülthoff, B. J. Mohler, and D. R. Proffitt. 2014. The perceptual homunculus: The perception of the relative proportions of the human body. *Journal of Experimental Psychology: General* 144, 103–113.

S. A. Linkenauger, M. Leyrer, H. H. Bülthoff, and B. J. Mohler. 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, e68594.

S. A. Linkenauger, B. J. Mohler, D. R. Proffitt, and H. H. Bülthoff. 2012. The role of visual foot size in perceiving object size from texture gradient. *Journal of Vision* 12, 902.

S. A. Linkenauger, J. K. Witt, and D. R. Proffitt. 2011. Taking a hands-on approach: Apparent grasping ability scales the perception of object size. *Journal of Experimental Psychology: Human Perception and Performance* 37, 1432–1441.

L. S. Mark and D. Vogele. 1988. A biodynamic basis for perceiving action categories: A study of sitting and stair climbing. *Journal of Motor Behavior* 19, 367–384.

I. V. Piryankova, H. Y. Wong, S. A. Linkenauger, C. Stinson, M. R. Longo, H. H. Bülthoff, and B. J. Mohler. 2014. Owning an overweight or underweight body: Distinguishing the physical, experienced and virtual body. *PLoS ONE* 9, e103428.

D. R. Proffitt and S. A. Linkenauger. 2013. Perception viewed as a phenotypic expression. In *Action Science: Foundations of an Emerging Discipline*, W. Prinz, M. Beisert, and A. Herwig (Eds.). MIT Press, Cambridge, MA, 171–198.

J. K. Stefanucci and M. N. Geuss. 2009. Big people, little world: The body influences size perception. *Perception* 38, 1782–1795.

J. K. Stefanucci and M. N. Geuss. 2010. Duck! Scaling the height of a horizontal barrier to body height. *Attention, Perception, and Psychophysics* 72, 1338–1349.

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

W. H. Warren and S. Whang. 1987. Visual guidance of walking through apertures: Body-scaled information for affordances. *Journal of Experimental Psychology: Human Perception and Performance* 13, 371–383.

J. K. Witt, D. R. Proffitt, and W. Epstein. 2005. Tool use affects perceived distance but only when you intend to use it. *Journal of Experimental Psychology: Human Perception and Performance* 31, 880–888.

M. Wraga. 1999. The role of eye height in perceiving affordances and object dimensions. *Perception and Psychophysics* 61, 490–507.

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