Big Feet for Little People: Scaling Gap Affordance Judgments of Children and Adults with Virtual Feet

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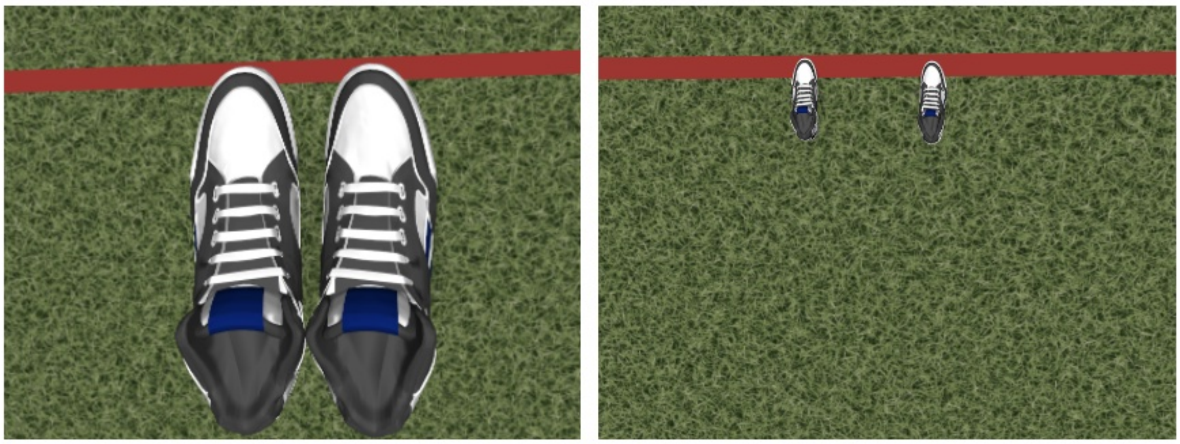

Figure 1: Renderings of the virtual feet used to manipulate participants' foot size. The large virtual feet were 1.5 times larger than participants' actual foot size (left) and the small virtual feet were 0.75 times the size of their actual foot (right).

Abstract

Virtual reality (VR) has become widely accessible through the development of more commercially available head-mounted displays (HMDs). This accessibility has particularly increased the use of VR in children. However, much of the previous research on understanding perception and action in virtual reality has only been conducted on adults, leaving many open questions about how children perceive and interact with virtual environments. In this paper, we examine whether there are age-related differences in judging the ability to step over a gap using immersive VR. Affordances are a useful measure for understanding objective perceptions of the actions that can be performed in an immersive virtual environment. Such measures are particularly well suited for children given they can easily respond yes or no as to whether they perceive that they can step over a gap. Further, manipulations of the size of virtual body parts could allow us to ascertain how much children rely on the perceived size of their bodies to make decisions about actions. In Experiment 1, adults and children saw motion-tracked virtual feet that were either larger or smaller than their actual foot size. They had to respond as to whether they could step over gaps that varied in width. They also gave perceptual estimates of the width of the gap in feet or meters. The results showed that adults who experience the smaller virtual feet underestimated their stepping ability more than adults with the larger feet. However, children had the opposite effect, such that seeing smaller virtual feet led to an overestimation of their stepping ability. To test whether this age-related difference in body scaling was due to misperception of foot size, adults and children matched virtual shoes to their actual feet size in Experiment 2. This matching task showed no perceptual differences between the age groups. Across our two experiments, we showed that children scale gap affordance judgments differently than adults and this difference cannot be explained by difference in perceptions of the size of virtual feet. The results suggest that children can effectively make perception and action judgments in virtual reality, but do not always do so in the same manner as adults. Such a finding has implications for the design of virtual reality games, educational tools, and training systems that are becoming increasingly common for children.

Index Terms: Affordances, children, virtual environments.

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1 Introduction

Gibson argued in his theory of *affordances* that perceiving our environment requires consideration of the relationship between it and our body, thereby stating that perception and action are inherently linked [22]. Thus, the perception of affordances is an understanding of whether a person's physical attributes are suitable for interacting with environmental features. Early work in affordance theory showed that adults' estimates of whether the environment affords stepping, sitting, or passing through are systematically scaled to their own body dimensions [37, 56]. For example, adults will perceive that they can walk through a doorway without turning if it is wider than their shoulder width, including a slight safety margin [56].

Affordance judgments are becoming more popular in evaluations of perception in immersive virtual environments (IVEs). Historically, egocentric distance judgments have been used to study the perceptual accuracy of IVEs compared to the real-world, such as blind-walking or verbal estimates (see [8, 9, 49] for reviews). However, due to constraints of the physical lab space and large underestimations of distance observed in IVEs [30, 29], these judgments may not be the most accurate and can be biased due to inaccuracies in cognitive representations [9]. Affordance judgments, however, only require decisions about actions (e.g., whether people can step over something or pass through it) and do not require performing an actual action across a large space (as in some estimates for distance perception). This makes these judgments an ideal measure for virtual environments that may be displayed in smaller physical laboratory spaces. Affordance judgments also allow for an objective perceptual estimate of the environment that is not grounded in an understanding of a stored representation (i.e., feet or meters) as is the case for other judgments of space like verbal reports of distance. Thus, affordance judgments may be less susceptible to cognitive bias while also having a clear correct or incorrect response based on actual body capabilities. They provide an objective measure of the perception of virtual environments that can be conducted in many sized laboratories [51].

Although previous research has explored affordance judgments in virtual reality (VR) with adults, children have been historically excluded. With VR technology becoming more accessible to children in both home and laboratory settings, it cannot be assumed that children perceive virtual environments, or specifically affordances, in the same manner as adults. Given the importance of body dimensions in affordance judgments and the rapid change that children undergo in body size during development around the age of puberty, it is possible that children nearing or at puberty could perceive affordances differently in VR than adults. Such a finding has implications for the use of VR in training, education, and other applications that are now becoming more widespread for children.

This paper addresses the question of whether children scale affordances to body properties similarly as adults. To answer this question, we recruited children (8-12 years-old) and adults to give affordance judgments of stepping over a gap using immersive VR. In order to evaluate the role of the body when perceiving stepping over affordances, we manipulated the size of virtual feet so that they were either smaller or larger than the participants' actual feet. A second experiment explores whether any differences in affordance judgments may be driven by misperceptions of the size of the virtual foot in children and adults. Both findings are crucial to understanding how users across age groups interact with virtual environments. It is necessary to understand whether children perceive and act in virtual environments as adults do in order to use virtual reality for many other applications effectively. Such insights could inform the development of IVEs for children in the areas of education, entertainment, and research.

2 Related Work

2.1 Affordances are Body-Scaled in the Real World

Within our everyday environments, affordances shape the dynamic network of potential actions that we perceive that we can perform. Adults scale these affordances to their own body dimensions. Specifically, people scale affordance judgments with the property of their body that is relevant to the affordance [47]. For example, hand size is more relevant for grasping judgments. Previous research has shown that properties such as eye height [32] and arm length [38] are used to scale one's perception of what can be stepped over or reached. Obviously, the body part that is used for scaling necessarily changes depending on the affordance being perceived. When judging steppable distances, hand size is no longer relevant to the task, and leg length or eye height becomes more important. Evidence for this scaling mechanism is supported by studies that manipulated body part size, such as wearing a helmet, altering whether a barrier affords ducking under [50], or magnifying a hand to determine whether it affects the perception of what can be grasped [35, 36].

Despite the somewhat extensive research that shows the body is used to scale the perception of affordances in adults, the question of whether and how children scale affordances to their body size is mixed. Previous research suggests that children can scale affordances similar to adults in that 7-year-old children relied on their leg length when judging maximum stepping height [6]. Other research has shown that 8- to 10-year-old children required a larger aperture-to-shoulder width ratio to perceive the affordance of passing through [57] compared to adults who are relatively accurate [56]. There is also research that shows affordance judgments improve with age, such as fitting hands through openings [25] and passing through doorways [17]. Overall, across a variety of tasks, children grow to be more accurate in judging affordances with age [60, 59]. Unlike research on adults, there is a lack of evidence to show that children adapt their affordance judgments when body size is manipulated. The current paper will test this question in an immersive virtual environment.

2.2 Affordances in Immersive Virtual Environments

Current VR technologies provide a convenient and reliable way of studying affordances. But for findings in VR to be generalized to other scenarios, including the real-world, it is important to consider if the perception of affordances is similar across real and virtual environments. Adults were generally consistent in judging affordances for passing through an aperture in both an IVE and a matched real-world environment [20]. Further, adults' affordance judgments remain consistent across different types of head-mounted displays [21]. We discuss further research on adults' abilities to judge affordances in the context of body manipulations below.

Children, on the other hand, do not always judge affordances in virtual environments to be similar to those of adults. Plumert and colleagues showed in a large, screen-based virtual environment that children's decisions about whether or not a road could be crossed with oncoming traffic (i.e., a *dynamic* affordance judgment) were riskier than adults [45, 46]. However, when both children and adults were given practice with the crossing task, their judgments improved but adults showed better improvement than children [46]. O'Neal et al. [42] extended this work to crossing roads on foot and showed that younger children (aged 6–10) were involved in more virtual collisions than those aged 14 and up. Children underestimated the affordance of stepping over a gap more so than adults in an immersive virtual environment [7]. Creem-Regehr et al. [7] also showed, though, that children's gap affordances did not differ from adults in the real world, suggesting that IVEs may uniquely contribute to differences in children's affordance judgments compared to adults.

2.3 Perceiving the Virtual Body

One question that the work on children's affordance judgments raises is whether they are accurately perceiving the size of their virtual bodies. In IVEs, the user's physical, real body is completely occluded so the user's actual body dimensions cannot be seen. Instead, self-avatars serve as a digital representation of the user's presence within a virtual environment and can provide body-based information, including the size of body parts. But, do adults and children accurately perceive the size of these parts? This is an important question to address given the scaling of affordances in virtual environments could be biased by the accuracy of the perception of the virtual body itself.

Much of the work on the perception of virtual body size has been done in adults. Early work on this topic showed that when a virtual avatar was presented, people localized themselves at the location of the visual avatar [31]. More recently, others found that people were more willing to adopt avatars that were similar in ethnicity to guide self-location in the virtual environment but that avatars with matched genders garnered higher reports of embodiment [12]. People are often willing, though, to accept a quite differently sized avatar as their own, suggesting that their perception of the size of the avatar may not be totally accurate [44]. In extreme scenarios, some have shown that adults will adopt a virtual avatar that is the size of a small child as their own [1], especially when that avatar speaks in a voice similar to theirs, but altered to sound more child-like [52]. Also, when women were asked to recognize their own body size in a virtual avatar that was a 3D scan of their actual body, but adjustable in body mass index (BMI), they accepted a margin of error of up to a 6% change in their actual BMI as representing themselves [43]. Estimates of the size of a generic virtual avatar viewed through a virtual optical see-through AR display (akin to a mirror) were also found to be larger for women compared to that obtained in virtual reality [58]. Keenaghan et al. [28] found that both adults and 5-year-old children can experience embodiment of self-avatars as well as size perception changes corresponding with their virtual body size; children showed embodiment even when the virtual avatar moved incongruently with their own body.

2.4 Virtual Bodies Influence Affordances

Understanding the size of the virtual self-avatar is critical for judging virtual affordances. The mere presence of a virtual self-avatar (not necessarily matched in size) improves the accuracy of affordance judgments for stepping over or ducking under a bar [33] and for stepping off a ledge [34]. More recently, Bhargava et al. found that the mere presence of an avatar improved judgments for street crossings, but that manipulations of the eye height of the avatar did not interact with the effects [5]. Performance on a task that required reaching into a box while avoiding obstacles was also shown to be easier when participants wore a virtual glove and saw a virtual hand in comparison to a condition where they held a controller, but saw a virtual hand [55]. Augmented reality (AR) avatars are also starting to be investigated, as in [54] where participants who saw a visualized avatar in AR were better able to retrieve an object from a box while avoiding obstacles. Other recent work has investigated affordances for reaching [11, 19], passing through [4, 3, 18], and grasping of objects [35]. Given that many of these investigations included manipulations of the size of the virtual body, we will discuss these more below. It is important to note, though, that the effect of avatars on affordance judgments tends to be influenced by whether the user actually feels ownership over the virtual body [53]. In other words, virtual avatars are more likely to be used for affordance judgments when the user has greater perceived ownership of their virtual body.

If body dimensions play a role in perceiving affordances, then altering the size of body parts should notably affect users' perception of affordances. Body manipulations, such as adjustments in size or positioning, are readily achievable with the latest VR technologies, a feat often difficult or impossible in real-world settings. For instance, modifying eye height has been shown to impact the accuracy of distance perception [32], while altering the overall size of a self-avatar's body leads to changes in the perception of object size with smaller self-avatars tending to result in overestimation of object sizes [1]. But certain tasks, such as reaching or stepping, have body parts that are of particular importance (for review, see [47]). For example, hand size is important for judging grasping so manipulating virtual hand size changes how people judge grasping affordances in VR [36] or the size of virtual objects [41]. Similarly, when participants saw an extension of their virtual arm length, through the use of a tool or by just extending the length of the virtual arm to be greater than the actual length, they overestimated what could be reached in the horizontal plane [11]. Interestingly, they had to 'see' the extended length of the virtual arm for this effect to occur because when only virtual controllers were rendered, reaching judgments resembled those made in the real world [15]. For passing through affordances, holding an object also led to conservative estimates of what could be passed through, but feedback about the possibility of collision improved the accuracy of these judgments [4, 18]. Participants who saw a self-avatar were also better able to judge lateral passability of apertures when holding virtual objects of various sizes [3]. Most relevant for the current study is that virtual feet that are larger than actual foot size made users overestimate their ability to step over gaps [26]. While there is a breadth of evidence supporting the claim that virtual body manipulations influence affordance judgments in adults, it is unknown if children's perception of affordances also changes in IVEs due to manipulations of virtual body size.

2.5 Overview of Experiments

Given the lack of consistency of an influence of virtual body size on the perception of affordances in children in virtual reality, the current experiments were designed to address two open questions. Much of the prior work suggests that children will differ from adults when making affordance judgments, but the open question is whether and how the manipulation of virtual body size will affect these judgments in children. Given that Creem-Regehr et al. [7] showed that children underestimated their ability to step over a gap, we expected to replicate their effect. In our first experiment, we extended their work by testing whether children's affordance judgments for stepping over gaps were also affected by the depicted size of their virtual feet. We tested children aged 8-12 years because they were in a period of development where body size can change rapidly. This change in body size could lead to two potential hypotheses: 1) children could rely on their body size for making judgments about affordances *less* than adults due to the unreliability of their natural body size for scaling the perception of space during this period of development or 2) children could rely *more* on their body size than adults due to a heightened sensitivity because of the rapid changes occurring. This unreliability of physical body size could also lead to misperceptions of virtual body parts that, in turn, could affect affordance judgments for stepping over. Thus, in a follow-up experiment, we explicitly tested the second open question in the literature, which is whether the perception of the size of virtual feet is accurate in both adults and children. Taken together, the two experiments allow us to understand whether children perceive the size of the virtual body accurately and whether this perception plays a role in their understanding of the actions they can perform in immersive virtual reality.

3 Experiment 1

In Experiment 1, children and adults provided affordance judgments about stepping over a gap in an immersive virtual environment. To determine the effect of body dimension on such judgments, participants either saw smaller than actual or larger than actual virtual feet. We also assessed (after all affordance judgments were made) participants' perception of the size of the virtual gaps by asking them to report their extents verbally. While we expected overestimation of perceived gap-stepping capabilities for all participants, we predicted that **(H1)** children would underestimate relative to adults regardless of the virtual foot size, similar to [7]. We extended prior work on adults [26], predicting that **(H2)** larger virtual feet would cause children to overestimate gap affordances, based on the rationale that bigger feet should be able to cover more distance when stepping. Further, we predicted that **(H3)** the magnitude of the effect of the foot manipulation would be different between children and adults, thereby producing a foot size by age group interaction. However, as discussed previously, the effect size could be either smaller or larger for children relative to adults due to rapid changes in body size. Finally, we hypothesized that **(H4)** manipulation of foot size would influence perceptual estimates of gap widths in that larger feet would result in smaller estimates [26].

3.1 Method

3.1.1 Participants

Two age groups participated in the study: children (8-12 years) and adults (18 years and older). Thirty-six children (M_{age} = 10.22, SD_{age} = 1.33; 14 female, 21 male, one other) were recruited from the local community and were compensated with $10. As the children's age group tends to experience differences in developmental stages and stages of puberty, the distribution of the children's ages is as follows: four 8-year-olds, eight 9-year-olds, eight 10-year-olds, eight 11-year-olds, and eight 12-year-olds. Forty adults (M_{age} = 21.20, SD_{age} = 5.46; 22 female, 18 male) were recruited from the [anonymized] undergraduate population and received course credit for their participation. The participants were pseudorandomly assigned to one of two foot size conditions, large or small, by alternating assignment to condition. The body dimensions of each group are presented in Table 1. All participants provided consent, and the [anonymized] institutional review board approved the study.

3.1.2 Materials & Apparatus

The virtual environment (VE) for both the gap affordance and distance estimation task was an outdoor Italian piazza with a non-repetitive grass pattern as the floor (see Figure 2), originally designed by WorldViz and adapted in Unity version 2018.2.19. The VE was presented to participants through an HTC Vive Pro HMD with an AMOLED display with a resolution of 1440 × 1600 pixels per eye and a 100° horizontal field of view. Vive motion trackers were used to track participants' feet so that the movement of the virtual shoes in the VE matched that of the participants' actual movements in the real world. The trackers were affixed to Croc shoes that participants wore for the duration of the experiment. Participants were given the Crocs that were the best fit (given their foot measurements) before the trackers were attached.

3.1.3 Design & Procedure

After providing informed consent, participants' shoes were measured from heel to toe using a shoe measuring device, along with their height, eye height, and leg length. Then, participants were pseudorandomly assigned through alternative assignment to one of two foot size conditions to maintain equal numbers per foot condition: large or small (see Figure 1). In the small foot size condition, participants' virtual feet were 0.75 times the size of their actual shoe size. In the large foot condition, the participants' virtual feet were 1.5 times larger than their actual shoe size.

In the antechamber of the VR lab, participants were asked to wear a pair of Croc shoes. Vive motion trackers were secured to the top of the shoe to track participants' movements. The data from these trackers were used to synchronize the movements of the virtual feet with those of the participants' actual feet, ensuring a realistic animation within the virtual environment. The feet were tracked for all tasks conducted in VR.

The first task in VR was a gap affordance task where participants provided yes/no affordance judgments as to whether they believed they could step across variously sized gaps on the floor without taking an actual step. Eight different widths of gaps between a red and blue line (0.45m, 0.60m, 0.75m, 0.90m, 1.05m, 1.20m, 1.35m, and 1.50m) were presented three times each for a total of 24 trials. The order of trials was pseudo-randomized so participants never saw the same gap consecutively.

The second task in VR was a distance estimation task. Four different gap widths between a red and blue line (0.50m, 0.90m, 1.30m, and 1.70m) were presented three times each for a total of 12 trials and were pseudo-randomized so participants never saw the same gap consecutively. Participants aligned their toes to the far edge of the red line and estimated the distance to the near edge of the blue line. The participants verbally estimated the distance using a metric of their choice (e.g., feet or inches). After the distance estimation task, participants were asked to look at the virtual feet and report if they felt shorter than, taller than, or the same as their actual height on a scale from -3 to 3 (-3 = a lot shorter, -2 = somewhat shorter, -1 = a little shorter, 0 = actual, 1 = a little taller, 2 = somewhat taller, 3 = a lot taller).

Figure 2: A rendering of the virtual environment.

After completing both VR tasks, the participants' actual farthest step was measured three times in the laboratory after they had taken off the HMD. Then, they completed a body ownership questionnaire [13] adapted to focus on the feet. The questionnaire asks questions about participants' sense of self-localization, agency, and ownership of the virtual feet during the experimental tasks. Participants also completed a task-demand questionnaire and reported prior VR experience and video game frequency.

3.1.4 Analyses

Data were analyzed using R version 4.3.1. A series of regressions and the intraclass-correlation coefficient (ICC) of gap width estimates were run using the *lme*4 [2] and *stats* packages [48]. Planned comparisons within age groups were conducted using two-sample t-tests from the *stats* package [48]. As frequentist statistics cannot provide evidence in favor of the null hypothesis, JZS Bayes factors (BF_{10}) were computed using the *BayesFactor* package [40].

3.2 Results

3.2.1 Gap Affordances

Gap affordance differences between age groups were examined by first calculating crossover points, which is the point of inflection where a participant's affordance judgment switches from "Yes, I can step over" to "No, I cannot." Crossover points were calculated using an average of the farthest distance participants judged as step-able (a minimum of two "yes" responses out of three trials) and the

	Children			Adults			
	Small Feet	Large Feet	$t(34)$	Small Feet	Large Feet	$t(38)$	$t(74)$
Foot Size	22.0 (2.8)	22.9 (1.9)	1.12	24.3 (2.3)	24.7 (1.9)	0.50	3.95**
Leg Length	84.5 (8.2)	88.2 (8.6)	1.33	100.2 (7.8)	98.0 (7.8)	0.89	6.82**
Height	142.3 (13.5)	148.0 (11.9)	1.34	169.9 (11.2)	167.7 (8.5)	0.71	9.05**
Eye Height	131.2 (13.7)	136.7 (11.9)	1.29	158.7 (10.8)	156.0 (8.3)	0.86	8.99**
Step Length	96.6 (15.4)	106.2 (14.8)	1.91	117.8 (14.5)	109.8 (18.0)	1.53	3.32*

Table 1: The mean (standard deviation) body dimensions of the age groups under the two randomized foot manipulations, presented in cm. Two-sample t-tests were conducted within age groups and between children and adults (last column), collapsed across foot manipulation. Note: **p-value < .001, *p-value < .05

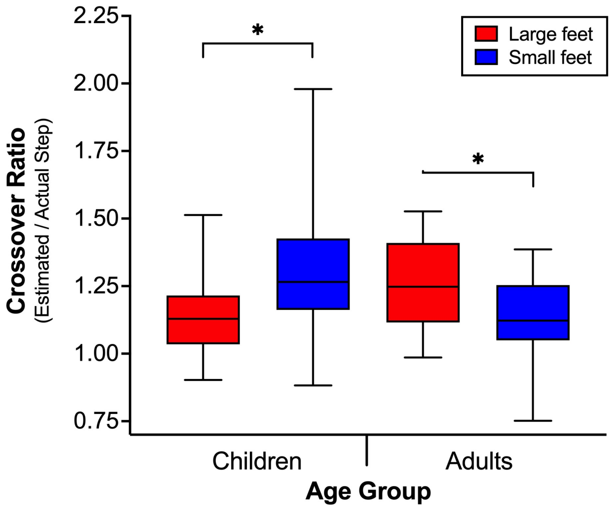

Figure 3: Crossover ratio for age groups by virtual foot size. Whiskers represent minimum and maximum ratios. A ratio of one represents accurate perception. *p < 0.05

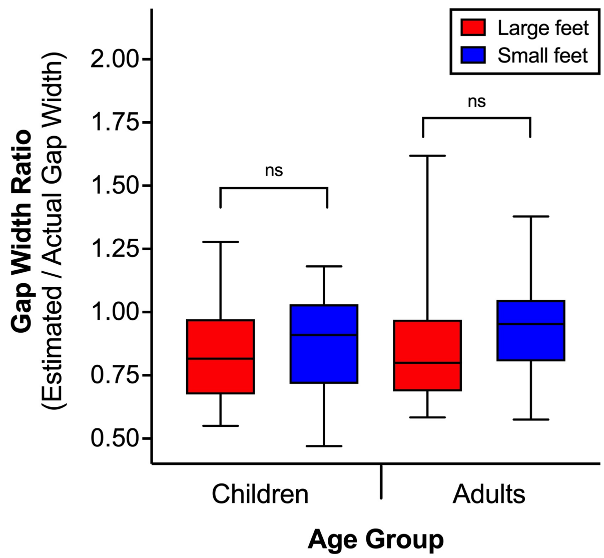

Figure 4: Gap width estimate ratios for age groups by virtual foot size. Whiskers represent minimum and maximum ratios. A ratio of one represents accurate gap width perception. ns = not significant

shortest distance participants judged as not step-able (a minimum of two "no" responses out of three trials). For example, if a participant judged 1.05m as step-able and 1.20m as not, their crossover point would be 1.125m. Then, crossover points were divided by the farthest participants could actually step. This creates a crossover ratio where a value over one indicates an overestimation in step ability, and a value under one indicates an underestimation. Foot size (small or large) and age group (children or adults) was regressed onto crossover ratios. Planned comparisons were conducted via independent-sample t-tests between the foot size conditions within the age groups.

Overall, participants overestimated their step ability by approximately 20% (M = 1.21 (SD = 0.21). The linear regression revealed a significant interaction between foot condition and age group ($F(1{,}72) = 8.99$, $p < 0.01$, $\eta_p^2 = 0.11$) (see Figure 3). Planned comparisons revealed that adults with large virtual feet (M = 1.25, SD = 0.17) overestimated their step ability significantly more than adults with small virtual feet (M = 1.14, SD = 0.16; $t(38) = 2.19$, p = 0.03, d = 0.69). However, children demonstrated the opposite effect. Children with large virtual feet (M = 1.15, SD = 0.17) overestimated their step ability significantly less than children with small virtual feet (M = 1.31, SD = 0.27; $t(34) = 2.07$, p = 0.04, d = 0.69). The main effects of age group and foot condition were not significant due to this crossover interaction.

3.2.2 Gap Width Estimates

It is possible that the difference in gap affordance judgments between foot sizes within age groups was due to foot size affecting the perception of gap width as was observed in [26]. To assess this in the current data, gap width estimates were scaled by dividing an average of the three estimates for each gap distance by the actual gap width. A ratio less than one indicates an underestimation of distance, and a ratio over one indicates overestimation. Then, gap width (0.50m, 0.90m, 1.30m, and 1.70m), foot size (small or large), and age group (children or adults) were regressed onto gap width ratios and fit using maximum likelihood. Across the estimates, approximately 13% of the variance was explained by between-subject variability (ICC = 0.13). Thus, we included a random intercept by a participant in the regression to account for this inter-individual variability.

The mixed model showed that the accuracy of gap width ratios did not differ by gap size ($F(3, 72) = 2.21$, p = 0.10). Overall, participants underestimated the gap widths by approximately 12% (M = 0.88, SD = 0.23). Planned comparisons showed that the accuracy of gap width estimation did not significantly differ between the two sizes of virtual feet in adults ($t(38) = 1.16$, p = 0.25, BF_{10} = 0.53) or children ($t(34) = 0.71$, p = 0.48, BF_{10} = 0.39) (see Figure 4).

3.2.3 Perceived Eye Height

Different sizes of virtual feet may have influenced participants' perception of their proximity to the ground. If this were the case, then smaller feet could have indicated to participants that they were taller and, therefore, potentially able to step farther. To examine if foot size manipulation altered height perception, eye height estimates (on a scale from -3 to 3) were compared between foot sizes within each age group. Overall, adults perceived their eye height in VR to be taller than their actual eye height (M = 2.58, SD = 1.72). There was no significant difference between adults with small and large virtual feet ($t(38) = 0.82$, $p = 0.42$, $BF_{10} = 0.40$). Children also perceived their virtual eye height to be taller than their actual eye height (M = 2.39, SD = 1.63). Like adults, there was no significant difference, though, between children who saw small and large virtual feet ($t(34) = 0.41$, $p = 0.69$, $BF_{10} = 0.34$). These results suggest that differences in perceived eye height may not cause differences in affordance judgments due to foot size, though we revisit this finding in the General Discussion section.

3.2.4 Subjective Reports of Ownership

It is also possible that the difference in gap affordance judgments between foot sizes within age groups was due to a sense of ownership of the avatar. One group might have felt a stronger sense of ownership over the virtual feet, which could have influenced their estimates of what the feet could do. Participants completed a body-ownership scale questionnaire in which participants rated (on a scale from 1 to 10) three components involved in the ownership of a virtual avatar: self-identification, self-localization, and sense of agency [13]. Foot size (small or large) and age group (children or adults) were regressed onto averaged body-ownership ratings, with each ownership component represented in a separate regression.

Overall, participants rated self-identification 6.30 out of 10 on average (SD = 2.04), indicating that they consciously experienced the virtual feet as their own. The main effects of foot size, age group, and interaction on self-identification were not significant (p > 0.38). Participants rated self-localization as 7.41 out of 10, on average (SD = 2.00), indicating that they felt their feet were in the location where the virtual feet were displayed in the VE. The main effects and interaction of foot size and age groups were not significant (p > 0.26). Finally, participants rated their sense of agency as 8.54 out of 10 (SD = 1.47), indicating they felt they had control over the virtual feet's movement and position. Again, the main effects of foot size, age group, and interaction were not significant (p > 0.49). Given these results (Figure 5), the differences in gap affordance judgments for large and small virtual feet size within age groups were not likely due to differences in subjective feelings of ownership.

3.3 Discussion

Using an IVE, adults, and children determined whether they could step over various gaps with large or small virtual feet. Overall, adults and children overestimated their ability to step over a gap by approximately 20%. As expected, adults with large virtual feet overestimated gap affordance judgments more than adults with small virtual feet. This pattern of results is consistent with previous work conducted on adults [26], which partially supports **H2**. However, manipulating virtual feet size had the opposite effect in children. Children with smaller virtual feet overestimated judgments more than children with larger virtual feet. Thus, we found an interaction between foot size and age group, supporting **H3**, but in an unexpected direction. There was no overall age effect as predicted in **H1**, likely due to this interaction. Finally, **H4** was unsupported in that the foot manipulation did not affect the perceptual estimates of gap width. The implications of these findings are discussed further in the General Discussion.

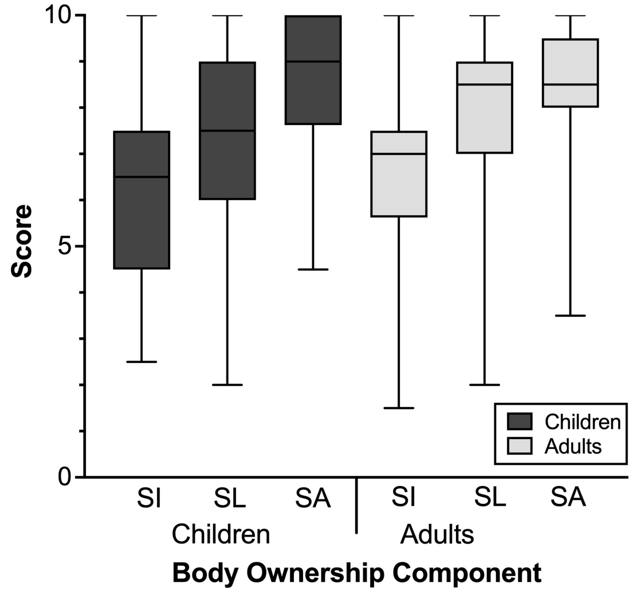

Figure 5: Subjective reports of body ownership by age group and component. SI = self-identification, SL = self-localization, SA = sense of ownership.

4 Experiment 2

An additional factor that could have produced the results observed in Experiment 1 is the accuracy of the perception of the virtual feet across age groups. Adults and children may have perceived the size of the virtual feet differently, which could have led to differences in affordance judgments for stepping over a gap. For example, if children perceived their "small" feet to be the actual size of their shoes , then they might have felt more capable of stepping with small feet compared to large feet. We explored potential age-related differences in the size perception of virtual feet in Experiment 2. To determine if children perceived the size of virtual feet differently than adults, a new group of participants (including both adults and children) estimated the size of virtual shoes by choosing the virtual shoes that they thought would best fit their actual shoes . Their estimates were compared to their actual shoe size to determine age-related differences in perceptual accuracy.

4.1 Method

4.1.1 Participants

A new subset of participants were recruited to participate in this experiment across two age groups: children (8-12 years) and adults (18 years and older). Eighteen children (M_{age} = 9.72, SD_{age} = 1.45; 10 female, 8 male) were recruited from the local community and were paid $10 for their participation in the context of a larger study. Twenty-six adults (M_{age} = 24.04, SD_{age} = 7.20; 20 female, 6 male) were recruited from the [anonymized] undergraduate population and received course credit for their participation. The children's average foot size was 22.94 cm (SD = 1.26). Adult's average foot size was 25.53 cm (SD = 1.63). All participants provided informed consent and the experiment was approved by the [anonymized] institutional review board.

4.1.2 Materials & Apparatus

The virtual environment was a 10 m x 10 m room with a ceiling height of 5 m. The floor was a wood grain pattern (see Figure 6). The VE was presented using an HTC Vive Pro HMD and used

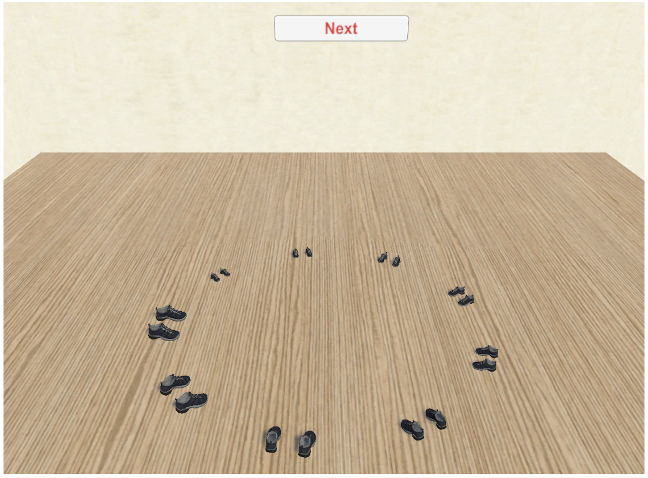

Figure 6: A rendering of the virtual environment for Experiment 2 with the nine shoe size options.

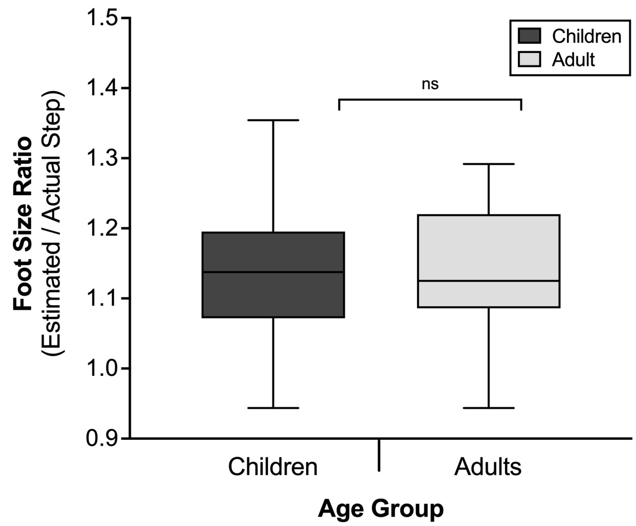

Figure 7: Foot size ratio for age groups. A ratio of one represents accurate perception.

Unity version 2019.3.0f3. Participants held an HTC Vive Pro controller in order to be able to select virtual shoes.

4.1.3 Procedure & Design

After providing consent, participants' shoe size was measured from heel to toe using a shoe measuring device in the antechamber of the VR lab. The measured shoe size was not visible to the participant. This measurement was entered into the VR program so that the rendered virtual shoes were all a set percentage of the participants' actual shoe size. Then, the participant was led into the laboratory where the experimenter helped fit the HMD onto their head.

Within the VE, there were nine pairs of shoes presented in a circle (see Figure 6), four of which were smaller than the participant's actual shoe size, four pairs were larger, and one pair was the actual shoe size. The pairs of virtual shoes differed by 7.5% of their actual shoe size, resulting in the following relative sizes: 70%, 77.5%, 85%, 92.5%, 100%, 107.5%, 115%, 122.5%, and 130%. The participant started in the center of the circle and were free to walk around the VE. However, participants were instructed to not stand on the virtual shoes, so that they would have to view the shoes from several perspectives as well as multiple shoes at the same time in order to make the most informed judgment taking all shoes into account . For all participants, the first trial was a practice trial in which the shoe pairs were presented in size order.

Holding the controller in one hand, participants would point at the pair of shoes they believed matched the size of their actual, physical shoes. A virtual line was emitted from the end of the controller so that participants could see where it was pointed and they selected the pair of shoes by pulling the trigger on the controller. To advance to the next trial, participants would select the "Next" button presented on the wall of the VE which would randomize the pairs of shoes and start the next trial. After the practice trial, participants completed 5 experimental trials.

4.2 Results

Foot size estimation between age groups was examined by first calculating an accuracy ratio. Participant's estimated foot size (averaged across the experimental trials) was divided by their actual foot size. The results showed that children's foot size estimation (M = 1.14, SD = 0.10) was not significantly different from adult's foot size estimation (M = 1.13, SD = 0.10; $t(42) = 0.11$, $p = 0.91$, BF_{10} = 0.30) (see Figure 7). Both groups overestimated the size of their respective virtual shoes by approximately 13%. We discuss these findings further in the next section.

5 General Discussion

Our goal was to assess whether 8-to-12-year-old children differed from adults in gap-stepping affordance judgments due to scaling such judgments to body dimensions. We also assessed whether any differences in these judgments could be due to the perception of body size in virtual environments. In the first experiment, body dimensions were manipulated by providing participants with either larger or smaller than actual virtual feet that were motion-tracked to their actual foot movement. The results showed that larger virtual feet led to overestimation of gap-stepping affordance judgments in adults. Children, however, showed the opposite effect in that larger virtual feet led to *underestimation* of gap-stepping affordance judgments relative to the smaller virtual feet. Several alternative explanations were explored for this age-related difference in body scaling. First, both adults and children showed similar estimations of gap width regardless of seeing large or small virtual feet. This suggests that differences in how they judged affordances were not due to the virtual feet altering the perception of the size of the gap differently. Both age groups underestimated the size of the gap by approximately 12%. Second, virtual feet did not lead to differences in perceived height in either age group. Finally, manipulating foot size did not cause differences in subjective reports of ownership. In other words, both age groups felt an equal amount of ownership over the feet of the virtual self-avatar. No variables we collected in Experiment 1 explained the age-related differences in the effect of virtual foot size.

Our second experiment was run to determine if age-related differences in stepping affordances could be attributed to perceptual differences in the size of the virtual feet. Given that little (if anything) is known about whether and how children perceive the size of virtual bodies, we hypothesized that a misperception of the size of the feet could have led to differences in affordance judgments. Adults and children chose virtual shoe sizes that they believed matched their actual shoe sizes. Participants' estimates were scaled to their actual shoe size. Overall, participants overestimated their actual shoe size by approximately 13%, and there were no perceptual differences between children and adults. Previous research has shown that children's size perception in the real world matches that of adults at approximately 7 to 9 years of age [23, 27]. This suggests that the majority of our children, aged 8-to-12 years old, would have developed a size perception that closely matches that of adults. It is essential to consider that our age range for children was rather broad and may contain children in different developmental and puberty stages. Additionally, the instruction to participants to not stand directly on the virtual shoes may have resulted in a lower sense of ownership over the virtual shoes. With both experiments taken together, our findings suggest that the differences in how children use body dimensions to scale affordances may be due to disparities in the cognitive processes they engage in rather than their perception of foot or gap size.

Children did not use the information about the size of the virtual feet in the same manner as adults to estimate their action capabilities in a virtual environment. Prior work suggests that adults adjust their affordance judgments based on the body size information provided by virtual self-avatars [1, 15, 32, 41]. The current study is the first (to our knowledge) to investigate if children demonstrate similar behaviors in an immersive virtual environment. Given that they did not make judgments identical to adults, we questioned whether other measures could help to explain our results. We stated above that there were no differences in many variables we controlled for (ownership of avatar, perception of foot size). Still, it is possible that the measures themselves were not treated similarly by the children. To control for differences in avatar adoption in Experiment 1, we examined whether children felt differently about their ownership of the virtual feet through the body ownership questionnaire [13]. We did not find differences in reports of ownership between children and adults. In addition to body-scaled affordances, scaling to action capabilities is also important when judging potential action [16]. In Experiment 1, both age groups adjusted their affordance judgments to match their action capabilities in a similar manner, consistently overestimating their stepping abilities relative to their actual stepping ability, shown by the crossover ratios being over 1.0. Thus, an important implication to emerge from our study is that children fundamentally perceive potential actions differently from adults in IVEs. Although we found no perceptual differences between age groups, it is clear that there are still unknown variables that lead to children's distinct affordance judgments from their adult counterparts, at least in the current VR task. Notably, previous research in gap-stepping affordances [7] suggests that these differences between children and adults may be attributed to VR, as both age groups judge gaps similarly in the real world. As a result, the design and development of VR programs intended for a wide age range needs to recognize that differences exist in how these age groups interact with virtual environments. It should not be assumed that children perceive affordances the same way as adults, nor can they be treated as smaller versions of adults. Although we generally demonstrated that researching children's perception of affordances in VR is feasible, open questions remain about how children make judgments in virtual environments. Understanding the differences between children and adults is crucial for creating immersive experiences that cater to the abilities of both age groups in education, entertainment, or research applications.

One reason that children may judge affordances differently is due to the technological limitations of the current HMDs. First, children's interpupillary distance (IPD) is smaller than that of adults and is not always accommodated by the HMD. The average IPD for 8-year-olds is approximately 52mm, and for 12-year-olds, it is 57mm [14]. The average IPD for our young age group was lower than the smallest possible IPD for the HTC Vive Pro (61.7mm). A mismatch between a user's actual IPD and the set IPD within the HMD could have led to distortions that affected the accuracy of depth or size perception [10]. The mismatch in IPD in children may have also affected eye height perception. Further, the weight of the HMD is proportionally larger compared to a child's body weight and strength than when compared to adults. Previous research has shown that heavier HMDs result in lower accuracy in distance perception [29]. Additionally, it is possible that the proportionally heavier HMD limited children's ability to look directly down at their feet, which could have affected their ability to use the size of the virtual feet to judge affordances relative to the adults. The technological characteristics of VR may have resulted in the higher variability in the children's responses, but further work is needed to further parse potential individual differences.

This work has some limitations. In particular, the body ownership questionnaire has not previously been used with children. It is possible that children interpreted the questions differently from adults. Further, we only obtained subjective reports of ownership. Future work should consider collecting data on objective measures of ownership in children to be sure that they are experiencing control and agency over the avatars as expected. A similar problem may have occurred in how children answered the perceived eye height question. We only asked one question about perceived height in the virtual environment, and this question was answered after participants had removed the HMD. Thus, they may not have remembered how they perceived their height or did not understand what was meant by height perception. Future research should examine subjective reports, such as these, along with more objective measures across age groups and likely in larger samples [39] than were tested here to be sure that these parameters are not explanations for the change in effect across age.

Additionally, children may not have understood the size of the disembodied virtual feet as easily as adults. While previous research has manipulated the length of body parts, such as the arms [11], our experiment only manipulated the size of the foot and did not present corresponding legs with their respective lengths. It is possible that only manipulating the size of a disembodied foot led children and adults to use different strategies for judging affordances. For example, more realistic virtual hands resulted in higher accuracy in an object retrieval task [55]. Further, children have previously been shown to differ in strategies used to navigate around an object [24], which could imply that their strategy for judging affordances differs as well. Again, future work is needed to test for cognitive strategies that each group may have employed to make their judgments.

6 Conclusions

In this paper, we investigated whether children perceive affordances for stepping over a gap when viewing different sized virtual feet similarly to adults. In Experiment 1, children and adults were assigned either larger or smaller than actual virtual feet. Then, they estimated whether they could step over variously sized gaps. We found that adults with larger feet overestimated their stepping ability while children with larger feet underestimated their ability. To examine if this interaction was due to differences in perceiving the size of the virtual feet, a new set of participants matched virtual shoes to their actual shoe size in Experiment 2. We found that there were no perceptual differences between age groups as both children and adults overestimated their shoe size. Our findings suggest that age-related differences need to be considered when developing VR programs and technologies for a wide range of ages. By acknowledging and accommodating these distinctions, we can create more inclusive VR experiences that cater to the unique perceptual abilities of both children and adults.

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