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Disciplines
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Walking through a virtual environment improves perceived size within and beyond the walked space

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Abstract

Distances tend to be underperceived in virtual environments (VE's) by up to 50% whereas distances tend to be perceived accurately in the real world. Previous work has shown that allowing participants to interact with the VE while receiving continual visual feedback can reduce underperception. Judgments of virtual object size have been used to measure whether this improvement is due to rescaling of perceived space, but there is disagreement within the literature as to whether judgments of object size benefit from interaction with feedback. This study contributes to that discussion by employing a more natural measure of object size. This study also examines whether any improvement in virtual distance perception is limited to the space used for interaction (1-5 m) or extends beyond (7-11 m). Results indicate that object size judgments do benefit from interaction with the VE and this benefit extends to distances beyond the explored space.

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Virtual reality (VR) is an exciting technology with applications including research, entertainment, training, and therapy. For VR to be fully effective, it must accurately represent spatial properties of the environment. Previous work indicates that distances in virtual environments (VEs) are perceived to be about 70% of intended distance (Waller & Richardson, 2008). In contrast, real world distances are often perceived accurately, at least when measured through action-based tasks (Loomis & Knapp, 2003; but see Durgin & Li, 2011).

Some researchers have attempted to improve distance perception in VR using a bottom-up approach by determining whether technological shortcomings prevent accurate perception. Researchers have examined the impact of graphical quality (Thompson et al., 2004), field of view (Knapp & Loomis, 2004), and display weight (Willemsen, Colton, Creem-Regehr, & Thompson, 2009), but a clear bottom-up solution to underperception has yet to emerge.

The current project examines a top-down approach designed to adapt the user to the VE, which has the potential to improve distance perception immediately rather than waiting until technology improves sufficiently. One common approach to improving distance perception in VR allows participants to interact with the virtual environment while receiving visual feedback (Mohler, Creem-Regehr & Thompson, 2006; Richardson & Waller, 2005, 2007; Waller & Richardson, 2008; Kelly, Donaldson, Sjolund & Freiberg, 2013; Kelly, Hammel, Siegel, & Sjolund, 2014). In a prototypical study by Waller and Richardson (2008), participants performed pre-interaction distance judgments followed by interaction and then post-interaction distance judgments. For pre- and post-interaction judgments, participants viewed a virtual object before walking to the perceived object location without feedback, referred to as a blind-walking distance judgment. Interaction involved walking through the VE with continuous visual feedback. Pre-interaction judgments were around 50% of actual distance, whereas post-interaction judgments approached 100% of actual distance. However, it is unclear based on these methods whether improvement was due to improved distance perception or visuomotor recalibration.

Measurement of perceived size can be useful to discern whether walking interaction caused improvement in perceived distance. According to the size-distance invariance hypothesis (Sedgewick, 1986), perceived size and perceived distance are tightly coupled, and thus object size judgments can provide an alternate measure that is not susceptible to motor recalibration. However, Brenner and van Damme (1999) found that perceived object size, shape, and distance are largely independent. Although judgments of object size, shape, and distance were similarly affected by changes in perceived object distance, changes in perceived shape caused by motion parallax did not affect perceived size or distance, indicating their independence. Although the direct relationship between perceived size and distance has been questioned, judged distance and size have been shown to be highly correlated (Gogel, Loomis, Newman, & Sharkey, 1985; Hutchison & Loomis, 2006), presumably due to the impact of perceived distance on both perceptual variables (Brenner & van Damme).

Kelly et al. (2013) found that object size judgments increased after walking interaction, consistent with an increase in perceived distance. More recently, Kunz, Creem-Regehr, and Thompson (2015) tested the effects of visual feedback indicating faster- or slower-than-actual walking speed in a VE. Manipulation of visual speed impacted blind-walking but not size judgments. One explanation for the discrepant finding is that participants in Kelly et al. received feedback about true walked distance, whereas participants in Kunz et al. received false feedback about walking speed. Regardless, the equivocal results warrant further research to determine whether the effects of visual feedback during interaction cause rescaling of perceived space, visuomotor recalibration, or both.

For a top-down approach to be truly useful, improvement in perceived distance should transfer beyond the distance walked during interaction. In an experiment by Kelly, Hammel, Siegel, and Sjolund (2014), participants made pre- and post-interaction blind walking distance judgments to objects 1-5 m away. During walking interaction, participants walked with feedback to near (1 and 2 m) or far (4 and 5 m) objects. Post-interaction judgments in the near condition only improved for near distances, whereas post-interaction judgments in the far interaction condition improved across near and far distances. It is possible that walking interaction improved perceived distance for all distances up to but not beyond the farthest experienced during interaction. Alternatively, it is possible that walking interaction improved perceived distance for all distances, but this broad improvement only occurred when participants received feedback on walked distances greater than 2 m. Feedback received during walking interaction is likely based on an error signal representing the difference between expected distance and walked distance. The error signal on near interaction trials may not have been sufficiently large to cause rescaling across all distances. For example, 20% underperception would cause a 1 m distance to be perceived as 0.8 m, whereas a 5 m distance would be perceived as 4m, leading to a larger error signal during interaction.

The two primary goals of the current project were to replicate past work showing that walking interaction causes improvement in perceived object size and to determine whether such improvement generalizes to distances beyond those experienced during interaction. This study utilized an intuitive size judgment task in which participants were first familiarized with a soccer ball in the real world. Once in VR, participants were shown a randomly sized virtual soccer ball and tasked with correcting its size using adjustments on a controller. Size judgments were then used to calculate perceived distance under the assumption of size-distance invariance. Compared to blind-walking, the resizing task serves as a measure of perceived distance that should be immune to sensorimotor recalibration during walking interaction. Compared to verbal size judgments (Kelly et al., 2013), the resizing task should not be affected by an individual's skill in assigning metric values, and therefore judgments should be less variable. In light of the equivocal reports on the relationship between walking interaction and perceived size (Kelly et al., 2013; Kunz et al., 2015), the same experiment was conducted twice. Experiment 1b directly replicated Experiment 1a. For ease of exposition, the two experiments are described together.

Method

Participants

Thirty-three (Exp. 1a) and fifty-three (Exp. 1b) undergraduate students from Iowa State University participated for course credit. Six (Exp. 1a) and four (Exp. 1b) participants were removed from all analyses due to equipment failure. One participant (Exp. 1a) was also removed from all analyses for reporting artificially shortened walking for fear of hitting physical objects.

Stimuli

The VE was displayed on an nVisor SX111 (NVIS, Reston, VA) with a 102° by 64° field of view. Vizard software (WorldViz, Santa Barbara, CA) was used to render graphics. The VE consisted of an endless plane with a grass texture and gray sky (Figure 1).

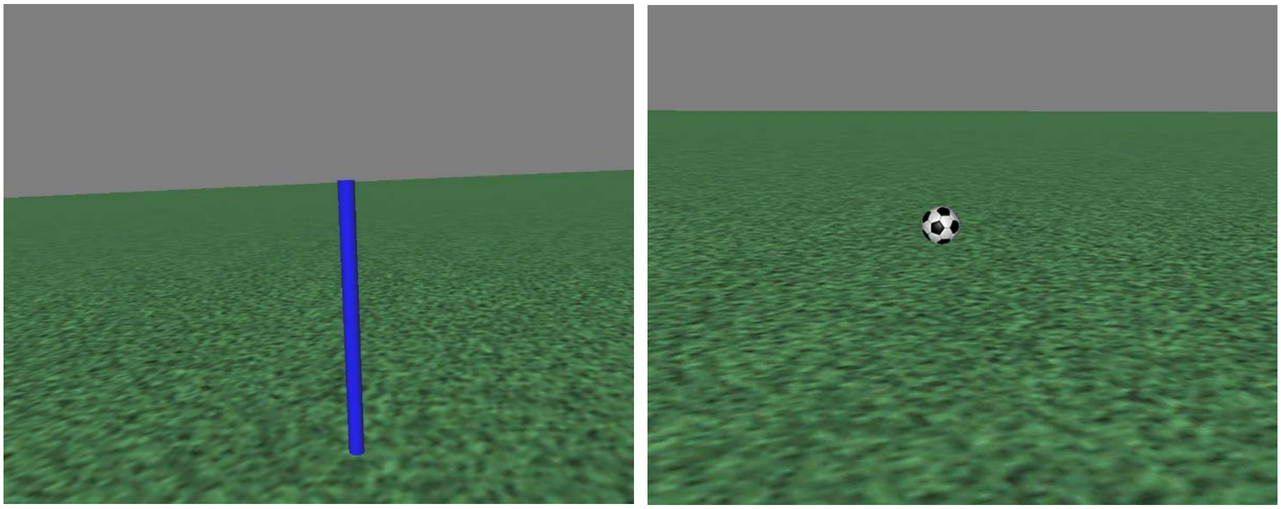

Figure 1. Virtual environment with stimuli used in the blind walking task (left) and resizing task (right).

Design

There were two different measures of perceived distance: object resizing and blind walking. Both measures were performed before and after walking interaction (object resizing was performed before blind walking). Experiment 1b also included a verbal measure, but results were inconclusive and are not discussed further.

In the resizing task, participants manipulated the size of a virtual soccer ball (Figure 1) until it appeared correct. On each trial, initial soccer ball size was randomly selected between 30% and 300%. Resizing was performed three times at five distances, resulting in 15 trials. Distances 1, 3, and 5 m (near) overlapped with distances used in walking interaction. Distances 7 and 11 m (far) extended beyond distances used in walking interaction.

In the blind walking task, participants judged the distance to a vertical post (Figure 1; 10 cm diameter and scaled to participant's eye height) at each of five distances (1, 2, 3, 4, and 5 m). Three repetitions of each distance resulted in 15 trials.

Participants interacted with the VE by walking with continuous visual feedback to a vertical blue post (the same post used in the blind walking task). Interaction was performed three times at five distances (1, 2, 3, 4, and 5 m), resulting in 15 trials.

For all experimental tasks (resizing, blind walking, and interaction), only one object at a time was visible within the VE, preventing comparison across trials. Furthermore, trials within a task were presented in a random sequence.

In summary, the dependent variables were size and blind walking judgments. The independent variables were egocentric object distance and whether the perceptual judgments occurred before (pre) or after (post) interaction. Both independent variables were manipulated within participants.

Procedure

Participants were given verbal instructions on the blind walking and resizing tasks. They were also shown a real soccer ball and allowed to hold it for the duration of the instructions. Participants then donned the HMD and were led to the viewing location.

In the resizing task, participants viewed a soccer ball and used joystick buttons to increase or decrease the ball size until it appeared correct. Resizing was always performed while standing at the viewing location (participants never walked to the virtual ball).

In the blind walking task, participants viewed a blue target post for five seconds, after which the scene vanished and they attempted to walk to the perceived location. After each blind walking trial, participants were guided by the experimenter back to the viewing location.

Participants interacted with the VE by walking, with vision, to a blue post. Upon reaching the target, the scene vanished and participants were guided back to the viewing location.

Analysis

Distance judgments were analyzed as a ratio of judged/actual distance, consistent with much past work (Kelly et al., 2013, 2014; Kunz et al., 2015; Mohler et al., 2006; Richardson & Waller, 2005, 2007; Waller & Richardson, 2008). Furthermore, the effect of walking interaction on judged distance can be described as a constant ratio change from pre- to post-test (Kelly et al., 2014).

Size judgments showed evidence of anchoring, whereby responses were biased toward initial object size on a given trial. To correct for anchoring, judged size was first expressed as the ratio of judged-to-correct size. Next, the mean ratio was subtracted from all size judgment ratios, which were then regressed against initial size (see supplemental Figure S1). The resulting linear equations generally fit the data well (R^2 ranging from .72 to .89), and were used to adjust size judgment ratios in order to correct for the anchoring bias. Correction was done by applying the linear equation (relating size judgment bias to initial object size) to size judgments based on initial ball size for that trial. Correction was done separately for each experiment, and for pre- and post-interaction judgments.

After correcting for anchoring, size judgments were converted into ratios of judged-to-actual distance based on the size distance invariance hypothesis (Sedgewick, 1986). According to the size-distance invariance hypothesis, perceived object distance (D') is directly related to perceived object size (S') and object angular size (α):

(1) $$D' = S'/\tan(\alpha)$$

Perceived size was always 22 cm (the participant's task was to adjust the virtual ball until it appeared to be the same size as a real soccer ball, which is 22 cm in diameter). Angular size (α) was determined by the adjusted size of the soccer ball (S) along with the actual distance of the soccer ball (D):

(2) $$\alpha = \text{atan}(S/D)$$

Perceived distance was then divided by actual distance to produce a ratio of judged-to-actual distance.

Results

Distance judgment ratios for blind walking and size judgments in Experiments 1a and 1b are shown in Figure 2 (supplemental Figure S2 shows distance and size judgments as a function of actual object distance). Planned comparisons were conducted to evaluate whether walking interaction improved blind walking distance judgments and whether walking interaction improved size judgments in near space and in far space.

In Experiment 1a, blind walking judgments improved from pre-test (M=.63, SD=.10) to post-test (M=.76, SD=.17), $t(25)=4.77$, $p<.001$, $\eta_p^2=.48$, and this effect was replicated in Experiment 1b, where blind walking judgments improved from pre-test (M=.71, SD=.15) to post-test (M=.80, SD=.13), $t(48)=5.70$, $p<.001$, $\eta_p^2=.40$. In Experiment 1a, near (1, 3, and 5 m) resizing judgments improved from pre-test (M=.57, SD=.08) to post-test (M=.63, SD=.10), $t(25)=2.55$, $p=.017$, $\eta_p^2=.21$, and this effect was replicated in Experiment 1b, where near resizing judgments improved from pre-test (M=.70, SD=.12) to post-test (M=.73, SD=.12), $t(48)=3.44$, $p=.001$, $\eta_p^2=.20$. In Experiment 1a, far (7 and 11 m) resizing judgments improved from pre-test (M=.61, SD=.14) to post-test, (M=.69, SD=.20): $t(25)=2.68$, $p=.013$, η_p^2=22., and this effect was replicated in Experiment 1b, where far resizing judgments improved from pre-test (M=.77, SD=.21) to post-test (M=.80, SD=.22), $t(48)=2.01$, $p=.050$, $\eta_p^2=.19$.

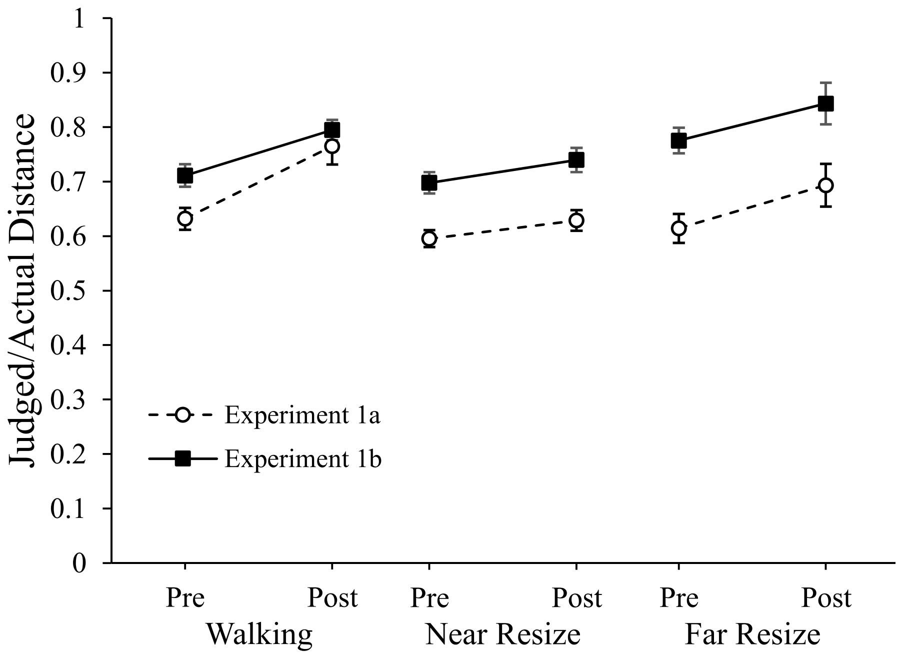

Fig2. Ratios of judged-to-actual distance in Experiments 1a and 1b. Error bars represent +/- 1 standard error based on between-participant variance.

Discussion

Walking through the VE with continuous visual feedback caused improvement in blind walking distance judgments and object size judgments. Furthermore, size judgments improved for object distances experienced during walking interaction and for distances beyond the interaction space. These findings were consistent across both experiments and serve to replicate past research as well as extend the understanding of space perception in VEs.

These experiments replicate past work showing that walking interaction causes improvement in judgments of distance (Waller & Richardson, 2008) and size (Kelly et al., 2013). The finding that size judgments increased after interaction indicates that walking interaction leads to rescaling of perceived space rather than simple recalibration of walked distance. However, the size judgment results also appear contradictory to results reported by Kunz et al. (2015). Possible explanations are discussed later in this section.

In addition to the aforementioned replications, these experiments add new data showing that walking interaction causes improvement in judged size for objects located beyond the walking space. This is somewhat surprising in light of research reported by Kelly et al. (2014) in which bind walking judgments did not improve for distances beyond those experienced during walking interaction. However, in that study, participants only received feedback while walking to distances of 1-2 meters compared to 1-5 meters in the current study. It is therefore possible that longer distances are necessary to produce improvement beyond the interaction space. It is also possible that such broad improvement is specific to size perception and would not be found in blind walking judgments, but this possibility was not tested in the current project due to physical space limitations.

The finding that size judgments improved after walking interaction appears contradictory to results reported by Kunz et al. (2015). In their experiment, participants performed blind walking and object size judgments before and after interaction in which visual walking speed was manipulated. Slower-than-actual visual movement caused longer blind walking judgments, and faster-than-actual visual movement caused shorter blind walking judgments. These same manipulations had no effect on size judgments, suggesting that visual feedback provided during walking does not cause perceptual rescaling. Although there are several methodological differences across these studies, we believe the critical difference is that participants in the current experiments and in Kelly et al. (2013) received feedback about walked distance rather than walking speed. The method used by Kunz et al. is conceptually similar to experiments reported by Rieser, Pick, Ashmead and Garing (1995), in which participants walked on a treadmill pulled behind a tractor, allowing independent manipulation of body-based and visual cues to walking speed. In those experiments, the effect of manipulating visual speed was specific to walking judgments, and did not generalize to other measures of perceived space such as ball throwing. It is therefore possible that the discrepancy between findings reported here and by Kunz et al. is due to differences in interaction: manipulation of visual walking speed may only recalibrate walked distance, whereas feedback regarding walked distance causes rescaling of perceived space.

The resizing task was chosen over verbal size judgments used in past work (e.g., Kelly et al., 2013) because resizing should not be affected by individual skill in assigning metric values, making judgments less variable. To evaluate this, within-participant standard deviations of size judgments were calculated for each participant at each test distance. Standard deviations were then averaged across these distances. Within-participant standard deviations in the resizing task (M=.072, SD=.050) were smaller than those in the verbal task (M=.14, SD=.07) used by Kelly et al. (2013)[1]. Between-participant standard deviations of overall size judgments were calculated by first determining the between-participant standard deviation of distance judgment ratios for each test distance and then averaging those standard deviations. Between-participant standard deviation in the resizing task (.16) was 47% smaller than in the verbal task (.30).

Kelly et al., 2013 proposed that walking interaction leads to perceptual learning, whereby the visual system assigns higher weights to distance cues that are more predictive of actual distance in the VE. For example, texture gradient can be reliably reproduced in the VE, whereas collimating lenses in the HMD fix the accommodative state of the lens at a specific distance, rendering it useless as a distance cue. According to this theory, the effect of walking interaction on perceived distance will only transfer to another VE or HMD if the predictive value of the distance cues remains the same across contexts.

[1] $t(97)=3.14$, $p=.002$

Experiment 1b was a direct replication of Experiment 1a, in that the tasks and lab equipment were identical, as was the population from which the participant samples were recruited. Despite those similarities, walking[2] and size judgments[3] were overall larger in Experiment 1b compared to 1a. Although some things varied across experiments (e.g., time of year, the researchers conducting the study), none provide insight into the overall difference across experiments.

The experiments reported here weigh in on disparate findings in the literature regarding perceptual changes caused by interaction with the VE. These results indicate that continuous visual feedback regarding walked distance causes rescaling of perceived space. Additionally, rescaling can extend beyond the range of space experienced during interaction. Underperception of distance in virtual reality continues to be a problem for users and researchers alike, but improvements through interacting with the VE show potential as a solution until technology advances sufficiently.

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[2] $F(1,73)=3.17$, $p=.08$, $\eta_p^2=.04$

[3] Near: $F(1,73)=12.78$, $p=.001$, $\eta_p^2=.15$; Far: $F(1,73)=11.19$, $p=.001$, $\eta_p^2=.13$

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