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Rescaling of Perceived Space Transfers Across Virtual Environments

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Research over the past 20 years has consistently shown that egocentric distance is underperceived in virtual environments (VEs) compared with real environments. In 2 experiments, judgments of object distance (Experiment 1) and object size (Experiment 2) improved after a brief period of walking through the VE with continuous visual feedback. Whereas improvement of blind-walking distance judgments could be attributable to recalibration of walking, improvement in perceived size is considered evidence for rescaling of perceived space, whereby perceived size and distance increased after walking interaction. Furthermore, improvements in judged distance and size transferred to a new VE. Distance judgments, but not size judgments, continued to improve after additional walking interaction in the new VE. These results have theoretical implications regarding the effects of walking interaction on perceived space, and practical implications regarding methods of improving perceived distance in VEs.

Public Significance Statement
Perceived egocentric distance (distance from oneself to another location) is consistently underperceived in virtual reality (VR) compared with relatively accurate real world perception. In this study, a brief period of walking through the virtual environment (VE) with continuous visual feedback improved perceived distance as measured by a walking response and a size response. For both response measures, the improvement caused by walking interaction generalized to a new VE that had not been previously experienced. The finding that improvement generalized to a new VE is of practical significance, and also suggests that the perceptual deficiencies in VR are associated with the VR display rather than the VE itself.

Keywords: space perception, perceived distance, perceived size, recalibration, virtual reality

Virtual reality (VR) technology has proven to be a useful tool for industry (Berg & Vance, in press), training (Grantcharov et al., 2004), and entertainment (Badique et al., 2002). New head-mounted displays (HMDs) designed for video games have been sold to hundreds of thousands of households within the first months of availability, making the technology more widespread than ever. For virtual reality to be effective in these applications, it seems important that spatial properties of the virtual environment (VE) are perceived accurately. An architectural walk-through in virtual reality is an example in which perception of the VE would ideally be identical to perception of the real environment after it is built. In VEs that involve performance of actions such as shooting a projectile or throwing an object toward a target (actions found in many virtual reality games), accurate perception of size and distance may be less important because the user can calibrate actions to the perceived space. However, if those actions are expected to transfer to the real world, as in simulations designed for military training, then the actions calibrated within the VE may not transfer to the real world without further opportunity for recalibration in the real environment, thereby increasing training time and cost.

Research indicates that distance (Bodenheimer et al., 2007; Kuhl, Thompson, & Creem-Regehr, 2009; Messing & Durgin, 2005; Steinicke et al., 2009; Ziemer, Plumert, Cremer, & Kearney, 2009) and size (Kelly, Donaldson, Sjolund, & Freiberg, 2013; Kunz, Creem-Regehr, & Thompson, 2015; Siegel & Kelly, 2017; Stefanucci, Creem-Regehr, Thompson, Lessard, & Geuss, 2015) are underperceived in VEs, in contrast to relatively accurate perception in the real world (Loomis & Knapp, 2003). The current project examines a method of improving perceived distance in VR through recalibration of the user, and whether changes in perceived distance due to recalibration transfer across VEs.

One approach to improving perceived distance in VR seeks to identify whether deficient or missing distance cues are the source of underperception. Research following this approach has investigated the effects of reduced field of view (Knapp & Loomis, 2004), graphics quality (Grechkin, Nguyen, Plumert, Cremer, & Kearney, 2010; Thompson et al., 2004), and HMD weight (Grechkin et al., 2010; Willemsen, Colton, Creem-Regehr, & Thompson, 2009) on perceived distance, but has yet to completely identify the source(s) of underperception. Recent work suggests that modern, consumer-oriented HMDs such as the Occulus Rift DK2 produce

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more accurate distance perception compared with older displays (Creem-Regehr, Stefanucci, Thompson, Nash, & McCardell, 2015), although performance is still below that of real-world viewing (judged distance in the Rift DK2 was approximately 85% of actual distance when averaged across multiple virtual environments). Differences in perceived distance across displays are likely to be the result of differences in the displays themselves, but these results are preliminary and merit further study.

Another approach to improving distance perception in VR is to adapt the user to the VE. In one example of this approach, participants viewed a virtual replica of the physical room in which they stood (Interrante, Anderson, & Ries, 2006). Blind-walking distance judgments in the virtual replica showed no evidence of the distance underperception typically found in VR. In related work, distance judgments made within a virtual replica of a real outdoor environment were significantly more accurate after participants had recently made distance judgments in the real environment upon which the VE was based (Ziemer et al., 2009). In these studies, it seems likely that the observer recalled aspects of the real space which improved distance judgments within the virtual space. This technique is limited, however, to situations in which a fictional or distant environment is not critical to the purpose of the simulation.

Another example of this approach is to provide participants with an opportunity to interact with the VE by walking through it with continuous visual feedback. This method has been shown to improve judgments of distance to levels similar to real world performance. In a prototypical study by Waller and Richardson (2008), participants made blind-walking judgments of egocentric distance before and after interacting with the VE. Blind-walking judgments involved viewing a virtual object before walking to the perceived object location without visual guidance or feedback. Interaction involved walking to the same virtual object with continuous visual feedback, thereby providing an opportunity for correction. Preinteraction blind-walking judgments averaged approximately 50% of actual distance, whereas postinteraction judgments averaged approximately 100% of actual distance. The effect of walking interaction on judgments of egocentric distance has been demonstrated several times (Mohler, Creem-Regehr, & Thompson, 2006; Richardson & Waller, 2005, 2007), although some studies report smaller improvements as a result of walking interaction (Kelly et al., 2013; Kelly, Hammel, Siegel, & Sjolund, 2014).

Real-world recalibration experiments reported by Rieser, Pick, Ashmead, and Garing (1995) could shed light on the mechanism underlying the improved postinteraction distance judgments in VR. Across several experiments, participants completed various target-directed actions without feedback before and after walking on a treadmill pulled behind a tractor, herein referred to as recalibration. During recalibration, the treadmill and tractor speeds were adjusted such that the biomechanical walking speed was faster or slower than the visual movement speed. The researchers proposed that walking recalibration could be functionally specific, anatomically specific, or global. According to the functionally specific account, recalibration of an action such as forward walking should generalize to any other action involving change in self-location directed toward the target, which is the function achieved by forward walking. For example, recalibration of forward walking should generalize to side-stepping toward a previously viewed location, but should not generalize to throwing a beanbag toward a target. According to the global account, recalibration should transfer broadly across actions, even if those actions do not share the same functional properties. For example, recalibration of forward walking should generalize to any target-directed action, such as throwing a beanbag toward a target or shooting an arrow from a bow, even though those actions do not involve changing self-position. Lastly, the anatomically specific account predicts that recalibration will be specific to movements of the effectors, and so recalibration of forward walking should not generalize to peddling a bike or side-stepping, because the relationship between effector movement and self-motion is distinct from walking.

Rieser et al. (1995) found that biomechanically faster recalibration resulted in blind-walking actions that were too far relative to the actual distance to the target, whereas biomechanically slower recalibration resulted in blind-walking actions that were too short. Similar changes characterized side-stepping actions, but not throwing actions nor rotating actions. A related study by Withagen and Michaels (2002) showed that recalibration of forward walking also affected crawling actions directed toward a previously viewed target. Together these results support the functionally specific account of action recalibration over the global or anatomical accounts.

Other research is inconsistent with the functional account of recalibration. For example, Durgin et al. (2005) reported that recalibration of forward walking only weakly transfers to side-stepping. Furthermore, recalibration from hopping on one leg is limb-specific (Durgin, Fox, & Hoon Kim, 2003). Based on these and other similar results, Durgin et al. (2005) proposed an organismic recalibration account, whereby recalibration involves change to the internal model of how limb movement dynamics affect perceived self-motion. The organismic account is similar to the anatomically specific account proposed by Rieser et al. (1995), and emphasizes the internal model relating movement of the effector to self-motion of the individual. Kunz, Creem-Regehr, and Thompson (2013) reported that recalibration of forward walking only weakly transferred to forward movement in a wheelchair, and that recalibration of forward wheelchair movement did not transfer at all to forward walking, results which also seem to support organismic recalibration rather than functional recalibration. Based on results from reaching recalibration experiments, Bingham, Pan, and Mon-Williams (2014) have argued that recalibration is both functionally and anatomically specific. In the context of the current project, both the functional and organismic accounts of recalibration make identical predictions, and so the distinction is not addressed further.

The biomechanically faster condition reported by Rieser et al. (1995) and the walking interaction in VR reported by Waller and Richardson (2008) both caused an increase in subsequent blind-walking judgments. However, only the biomechanically faster condition modified the coupling between visual movement speed and biomechanical movement speed. In contrast, visual movement speed was consistent with biomechanical movement speed during walking interaction in VR. Therefore, it is not clear whether recalibration also characterizes walking interaction in VR, regardless of whether we adopt the functional recalibration account of Rieser et al. (1995) or the organismic recalibration account of Durgin et al. (2005). In fact, walking interaction in VR has been shown to cause an increase in verbal judgments of distance

(Mohler et al., 2006) and judgments of object size (Kelly et al., 2013; Siegel & Kelly, 2017; but see Kunz et al., 2015). Because judgments of size and verbal judgments of distance are not associated with specific actions within the environment, they should be immune to sensorimotor recalibration effects during walking interaction. These findings led Kelly et al. (2013), to propose that walking interaction in VR caused rescaling of perceived space, such that the VE was perceived as larger after walking interaction. This conclusion of rescaling is quite different than functional or organismic recalibration, because rescaling of perceived space should affect all distance judgments that are based on the rescaled percept. Rescaling is also subtly different than the global recalibration account described by Rieser et al. (1995). Whereas global recalibration proposes that recalibration of one action should generalize to all possible actions, rescaling proposes that the perceived space is modified, and so all actions and all judgments that occur within the rescaled space will be modified. Therefore, only the rescaling account predicts that nonaction judgments of space, such as verbal judgments of egocentric distance or judgments of object size, should be affected.

It is possible that the effect of walking interaction in VR reflects a combination of both rescaling and recalibration (functional or organismic). For example, Kelly et al. (2013) reported that blind-walking judgments increased by a larger amount after walking interaction than did verbal judgments of size. Similarly, Waller and Richardson (2008) reported that real world blind-walking judgments increased slightly after walking interaction in VR, a finding that seems consistent with recalibration of the sensorimotor system.

Perceptual learning has been proposed as one possible mechanism to explain the rescaling caused by walking interaction (Kelly et al., 2013; Waller & Richardson, 2008). Space perception is informed by myriad cues which can be combined in a weighted manner, such that more reliable cues are assigned higher weight (e.g., Hillis, Watt, Landy, & Banks, 2004). Virtual reality gives the illusion of three-dimensional (3D) space by reproducing several of the distance cues that are present in real world viewing. However, not all of those distance cues are reproduced properly, and some cues may be missing or in conflict with other cues. For example, most HMDs use collimating lenses that cause the human lens to accommodate near optical infinity, which could also disrupt other distance cues such as binocular convergence through the accommodation-convergence reflex. Therefore, feedback provided through walking interaction could lead to perceptual learning whereby cue weights are modified based on their predictive value. In the example of lens accommodation, this distance cue might eventually receive zero weight after sufficient experience in the VE indicating that the cue has no predictive value. Such experience is likely to arrive in the form of feedback about actual object distance which can be compared with perceived distance.

The goal of the current project was to determine whether the effect of walking interaction on perceived space generalizes to other VEs. Based on past work showing that walking interaction leads to increases in verbal judgments of distance (Mohler et al., 2006) and judgments of object size (Kelly et al., 2013; Siegel & Kelly, 2017), it was expected that walking interaction would lead to rescaling of perceived space, rather than action recalibration. The rescaling account does not make specific predictions about whether rescaling should generalize to other situations, including other VEs. However, the perceptual learning mechanism proposed to explain rescaling does make specific predictions about whether rescaling should generalize to another VE depending on the relevant perceptual cues. If the relevant distance cues in the perceptual learning process are specific to the HMD or other fixed aspects of the simulation that are shared between multiple VEs, then it is reasonable to expect that rescaling will transfer across VEs. However, if the relevant cues are specific to the environment, then rescaling may not transfer if the VEs are sufficiently distinct. Furthermore, it is of greater practical value if rescaling caused by walking interaction generalizes to other virtual environments. Otherwise, walking interaction would need to occur upon entering every new VE, which could be tedious in many applications. Experiment 1 tested whether improvement in blind-walking judgments caused by walking interaction transfers to a new VE. Blind-walking judgments were chosen because they are the most commonly used measure in studies testing the effects of walking interaction. However, direct evaluation of the rescaling hypothesis requires alternative measures of perceived space unrelated to specific actions. Therefore, Experiment 2 tested whether improvement in judged size transfers to a new VE.

Experiment 1

Participants in Experiment 1 performed four blocks of blind-walking distance judgments. The first two blocks of distance judgments were separated by walking interaction. Following the second block of distance judgments, half of participants switched to a different VE where they performed the third and fourth block of distance judgments, which were separated by another walking interaction. The other half of participants followed the same procedure but stayed in the same VE throughout the experiment to serve as controls. One VE was an endless grassy field, and the other VE was a brick-walled room. Because different VEs can produce different baseline levels of perceived distance (Creem-Regehr et al., 2015), the environment variable was crossed with whether participants stayed or switched environments.

Method

Participants. Sixty-four undergraduate students from Iowa State University participated in exchange for course credit. Participants were randomly assigned to one of four conditions with equal numbers in each condition. Gender was approximately balanced across conditions.

Stimuli and design. The virtual environment was displayed on a HMD (nVisor SX111, NVIS, Reston, VA). Stereoscopic images were presented at 1,280 × 1,024 resolution with 102° horizontal × 64° vertical field-of-view. Vizard software (WorldViz) was used to render graphics on a desktop computer. Images were refreshed at 60 Hz and updated based on sensed head position (PPT, WorldViz) and orientation (InertiaCube2, InterSense) as the participant moved.

The field environment consisted of an endless, flat plane with a grass ground texture and featureless gray sky (Figure 1, left). The room environment consisted of a rectangular room with a tile floor, brick walls, and a light gray ceiling devoid of texture (Figure 1, right).

The primary aspects of the study design are illustrated in Figure 2. In all conditions, there were four blocks of blind-walking

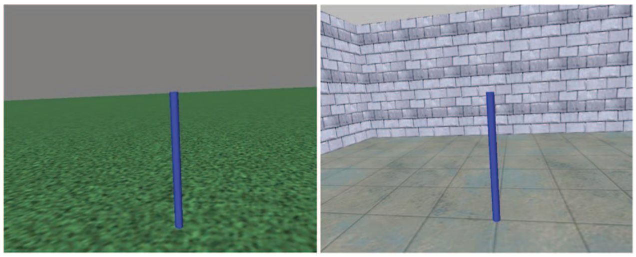

Figure 1. Participant's view of the field environment (left) and room environment (right). Also shown is the blue post used for blind-walking trials and walking interaction. See the online article for the color version of this figure.

distance judgments and two blocks of walking interaction, one between the first and second block of distance judgments and the other between the third and fourth block of distance judgments. Furthermore, there were four between-participants conditions: "Stay: Field," "Stay: Room," "Switch: Field-Room," and "Switch: Room-Field." In the Stay conditions, all distance judgments and walking interactions were completed within a single environment. In the Switch conditions, the environment was switched between the second and third block of distance judgments. In the Switch: Field-Room condition, participants started in the Field environment before switching to the Room environment, and vice versa in the Switch: Room-Field condition.

A vertical blue post (see Figure 1) was used as the target object for blind-walking judgments. The post was 10 cm in diameter and scaled to participant eye height. Walking interaction involved walking to the same blue post with continuous visual feedback. Blind-walking and walking interaction trials were presented in blocks consisting of three repetitions of five distances—1 m, 2 m, 3 m, 4 m, or 5 m—with trial sequence randomized within blocks. After each trial, the screen turned a uniform blue color except for an infinitely long gray line on the ground pointing in the direction of the viewing location. On walking interaction trials, 100 vertical gray posts, 3 cm in diameter and 250 cm tall, were placed randomly around the environment to enhance optic flow.

The dependent variable on blind-walking trials was the position of the participant's head after completing the blind-walking response. Head position was recorded using the VR tracking system.

Procedure. After signing the informed consent, the participant donned the HMD and stood at the viewing location. On blind-walking trials, the blue post appeared for 5 s before the entire environment disappeared and the participant was instructed to walk to the previous location of the post. Upon completion of the blind-walking response, the experimenter logged the participant's head position before leading the participant back to the viewing location. Only upon return to the viewing location did the VE become visible again and the next trial ensued.

On walking interaction trials, the environment was made visible and the blue post appeared and remained visible while the participant walked to it. Upon arrival at the blue post, the environment disappeared and the experimenter led the participant back to the viewing location for the next trial.

After participants in the Switch conditions completed the first two blocks of blind-walking distance judgments separated by one block of walking interaction, the VE automatically switched. The participant was told that they were in a new VE and the experiment continued.

Results

Blind-walking distance judgments were converted into ratios of judged-to-actual distance by dividing walked distance by target distance on each trial. Ratios of judged-to-actual object distance are shown in Figure 3 for all four distance judgment blocks. Planned contrasts were used to evaluate the effect of walking interaction and environment change on rescaling of perceived space. The effect of the first walking interaction was evaluated using a two (Block 1 and Block 2) by four (condition) contrast. Distance judgment ratios in Block 2 (M = .83, SE = .02) were significantly larger than those in Block 1 (M = .69, SE = .02), indicating that walking interaction caused blind-walking distance judgments to increase, $F(1, 60) = 64.12$, $p < .001$, $\eta_p^2 = .52$. Neither the main effect of condition nor the interaction between block and condition were significant.

Comparison of distance judgment ratios between Block 3 and Block 1 in the Switch conditions was conducted to evaluate whether any rescaling caused by walking interaction transferred across VEs. Distance judgment ratios in Block 3 were significantly larger than those in Block 1 for both Switch conditions, indicating that at least some of the rescaling caused by the first walking interaction transferred to the new VE (Switch: Field-Room, $t(15) = 4.84$, $p < .001$; Switch: Room-Field, $t(15) = 2.66$, $p = .018$).

To evaluate whether transfer of rescaling across VEs was complete, distance judgments were evaluated using a two (Block 2 and Block 3) by four (condition) contrast. The only significant effect was the interaction between block and condition, $F(3, 60) = 6.10$, $p = .001$, $\eta_p^2 = .23$. Distance judgments in the Switch: Field-Room condition increased from Block 2 to 3, $t(15) = 2.53$, $p = .023$, whereas distance judgments in the Switch: Room-Field condition

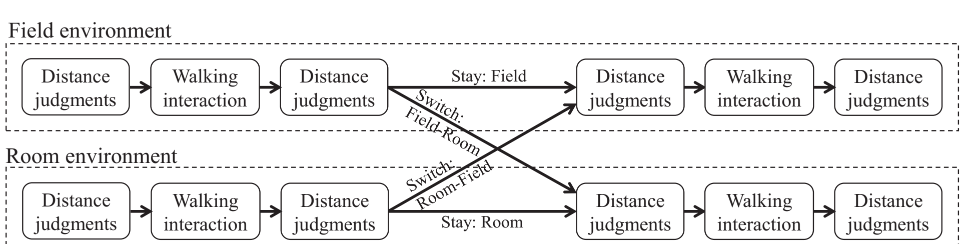

Figure 2. Illustration of the design used in Experiment 1.

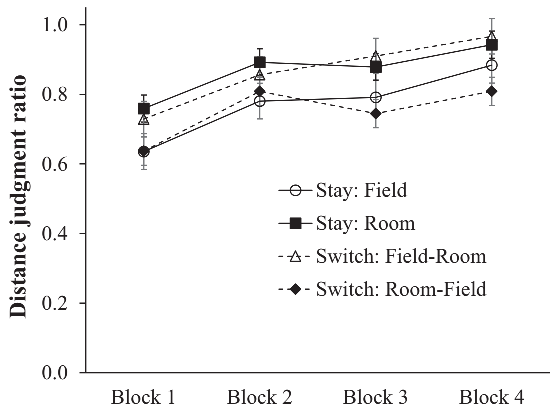

Figure 3. Distance judgment ratio (judged/actual object distance) based on blind-walking judgments as a function of distance judgment block in each of the four conditions.

decreased from Block 2 to 3, $t(15) = 3.20$, $p = .006$. Distance judgments in the two stay conditions were unchanged from Block 2 to Block 3 ($t < .7$, $p > .5$).

As a further test of the transfer of rescaling across VEs, the Block 3 data for each VE were compared when participants switched or did not switch prior to Block 3. For the field VE, Block 3 performance did not significantly differ between the Stay: Field and Switch: Room-Field conditions, $t(30) = .66$, $p = .516$. For the room VE, Block 3 performance did not significantly differ between the Stay: Room and Switch: Field-Room conditions, $t(30) = .57$, $p = .572$. In addition to standard null-hypothesis testing, further evaluation using Bayesian analysis revealed that the odds in favor of the null were 3.70:1 (field VE) and 3.72:1 (room VE), providing "substantial" evidence in favor of the null (Gallistel, 2009).

The effect of the second walking interaction was evaluated using a two (Block 3 and Block 4) by four (condition) contrast. Distance judgment ratios in Block 4 ($M = .90$, $SE = .02$) were significantly larger than those in Block 3 ($M = .83$, $SE = .02$), $F(1, 60) = 27.66$, $p < .001$, $\eta_p^2 = .32$, and the effect of block did not interact with condition.

To evaluate whether blind-walking performance changed with experience, the slope relating distance judgment ratio to trial number (1–15) was calculated separately for each participant for each block. Slope in Block 2 was significantly negative ($M = -.0049$, $SE = .0015$), indicating that the distance judgment ratio became smaller as trials progressed in that block, $t(63) = 3.24$, $p = .002$). Slopes in Blocks 1, 3, and 4 did not significantly differ from zero.

Discussion

The main findings from Experiment 1 are that walking interaction caused an increase in blind-walking distance judgments and that the effect of walking interaction transferred across VEs. Across all four conditions, including the two Switch conditions, blind-walking judgments in Block 3 were larger than those in Block 1, providing evidence that improvement caused by walking interaction transferred across environments.

Although Block 3 judgments were larger than Block 1 judgments in both Switch conditions, indicating transfer of rescaling across environments, Block 3 judgments increased relative to Block 2 judgments in the Switch: Field-Room condition and decreased relative to Block 2 judgments in the Switch: Room-Field condition. The fact that there was no change in judged distance from Block 2 to Block 3 in the Stay conditions indicates that repeated testing did not affect blind-walking distance judgments. Rather, the increase and decrease in the two Switch conditions is likely attributable to the VE change. A difference in baseline distance perception within the field and room VEs could potentially produce such an interaction when switching environments. However, Block 1 data indicate that no such baseline difference existed between VEs.[1] Therefore, it remains unclear why distance judgments increased when switching from field to room but decreased when switching from room to field.

Experiment 2

Based on past work showing that walking interaction in a VE improves size judgments (Kelly et al., 2013; Siegel & Kelly, 2017) and verbal judgments (Mohler et al., 2006; Kelly et al., 2013) proposed that walking interaction causes rescaling of perceived space. Because size judgments and verbal distance judgments are independent of actions, they are likely to be immune from sensorimotor recalibration. The organismic (Durgin et al., 2005), functional, and global (Rieser et al., 1995) recalibration accounts predict that recalibration of forward walking should have no effect on judgments of perceived size, because judging size is not associated with a specific action. The rescaling account predicts that walking interaction changes perceived space, and therefore should affect all aspects of perceived space. In this way, size judgments are one example of a dependent measure that can potentially determine whether walking interaction in a VE leads to rescaling of perceived space.

Experiment 2 was designed to test whether improvement in size judgments caused by walking interaction transfers across VEs. Size judgments have been used to infer perceived distance based on the size-distance invariance hypothesis (Sedgewick, 1986), which states that perceived object size (S′) is directly related to perceived object distance (D′) and object angular size (α):

$$S' = 2D' \times \tan(\alpha/2) \quad (1)$$

Whether or not judgments of perceived size and distance strictly adhere to the size-distance invariance hypothesis has been debated (Epstein & Landauer, 1969). For example, Brenner and van Damme (1999) found that information about object shape provide by motion parallax did not affect perceived size or distance even though it was potentially informative. However, perceived object distance and size have been shown to be highly correlated (Gogel,

[1] An independent samples t test comparing Block 1 distance judgments in the field VE (Stay: Field and Switch: Field-Room conditions; $M = .68$, $SE = .03$) and room VE (Stay: Room and Switch: Room-Field conditions; $M = .70$, $SE = .03$) revealed no difference, $t(62) = .36$.

Loomis, Newman, & Sharkey, 1985; Hutchison & Loomis, 2006; Kelly et al., 2013), presumably due to the effect of actual object distance on both perceived object distance and perceived object size (Brenner & van Damme, 1999). In the current experiment, the primary advantage of using object size judgments as a measure of perceived space is that size judgments can provide an alternate measure that should be immune to motor recalibration effects during walking interaction, and therefore provide a more direct indication of rescaling.

Experiment 2 followed the same experimental design used in Experiment 1 but the dependent measure was judged size rather than judged distance. Participants judged size by manipulating a virtual soccer ball until it appeared to match the actual size of a soccer ball.

Method

Participants. Seventy-one undergraduate students from Iowa State University participated in exchange for course credit. Participants were randomly assigned to one of four conditions (the Switch: Room-Field condition had 17 participants and all other conditions had 18 participants) and gender was approximately balanced across condition.

Stimuli and design. The same VEs and equipment were used as in Experiment 1. A virtual soccer ball was provided on resizing trials. Four buttons on a joystick gave participants the ability to resize the soccer ball larger or smaller by 1% and 10% increments. For each resizing trial, initial soccer ball size was randomly selected to be between 30% and 300% of actual soccer ball size (22 cm in diameter). Resizing trials were performed in blocks consisting of three repetitions of five distances—1 m, 2 m, 3 m, 4 m, or 5 m—resulting in 15 trials per block presented in a randomized sequence. The dependent variable was the size of the soccer ball after participants indicated that they were satisfied with the size.

Procedure. After signing the informed consent, the participant was given verbal instructions on the size judgment and walking interaction task. The participant was allowed to hold a real soccer ball while being instructed on the resizing task, and was also instructed on how to increase or decrease the soccer ball size using the joystick before donning the HMD.

In the size judgment task, the participant viewed a soccer ball in the VE from a static location and resized the soccer ball until it appeared to match actual size. The experimenter recorded the soccer ball size on the computer after the participant verbally indicated that they were satisfied with the adjusted size. Participants never walked to the virtual ball.

The procedure for interaction trials was identical to Experiment 1.

Results

Size judgments showed evidence of anchoring, whereby judgments were biased toward the initial size of the virtual soccer ball on a given trial. A two-step process was used to correct for this anchoring bias before proceeding with further analyses, and this process was conducted using data aggregated from all participants and all conditions. The first step was to identify and describe the anchoring bias. To do this, judged ball size was expressed as a ratio of judged-to-correct size. The mean of that ratio was then subtracted from all size judgments, which were regressed against the initial ball size (see Figure 4). The resulting linear equation fit the data well ($R^2 = .96$). The second step was to use that linear equation to correct for the anchoring bias. To do this, the initial ball size on a given trial was passed through the linear equation relating initial ball size to size judgment bias, and this bias value was subtracted from judged ball size on that trial. This correction for anchoring bias was conducted for each size judgment trial.

After correcting for the anchoring bias, size judgments were converted to size judgment ratios. This was done by dividing the size of an actual soccer ball by the adjusted soccer ball size on a resizing trial. According to the size–distance invariance hypothesis (Equation 1), underperception of egocentric distance should be associated with underperception of object size. Because participants viewed a soccer ball at a fixed distance and adjusted its size to match that of a real soccer ball, underperception of distance should result in responses (adjusted ball size) that are larger than actual ball size. In other words, a participant who underperceives the distance to a correctly sized virtual ball will underperceive the ball's size and subsequently adjust ball size by making it larger. According to the size-distance invariance hypothesis, a size judgment ratio of 1.0 would indicate veridical distance perception while a size judgment ratio of 0.5 would indicate underperception of distance by one half.

Size judgment ratios are shown in Figure 5 for all four size judgment blocks. Planned contrasts were used to evaluate the effect of walking interaction and environment change on rescaling of perceived space. The effect of the first walking interaction was evaluated using a two (Block 1 and Block 2) by four (condition) contrast. Size judgment ratios in Block 2 ($M = .68$, $SE = .14$) were significantly larger than those in Block 1 ($M = .61$, $SE = .11$), $F(1, 67) = 42.46$, $p < .001$, $\eta_p^2 = .39$. The main effect of condition was also significant, reflecting the overall larger size judgment ratios in the Stay: Field condition relative to all others, $F(3, 67) = 4.54$, $p = .006$, $\eta_p^2 = .17$.

Comparison of size judgment ratios between Block 3 and Block 1 in the Switch conditions was conducted to evaluate whether any rescaling caused by walking interaction transferred across VEs. Size judgment ratios in Block 3 were larger than those in Block 1 for both Switch conditions, indicating that at least some of the rescaling caused by the first walking interaction transferred to the new VE (Switch: Field-Room, $t(17) = 4.06$, $p = .001$; Switch: Room-Field, $t(16) = 3.37$, $p = .004$).

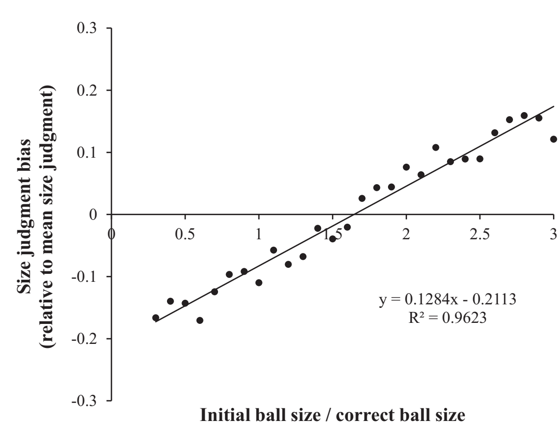

Figure 4. Size judgment bias as a function of initial ball size.

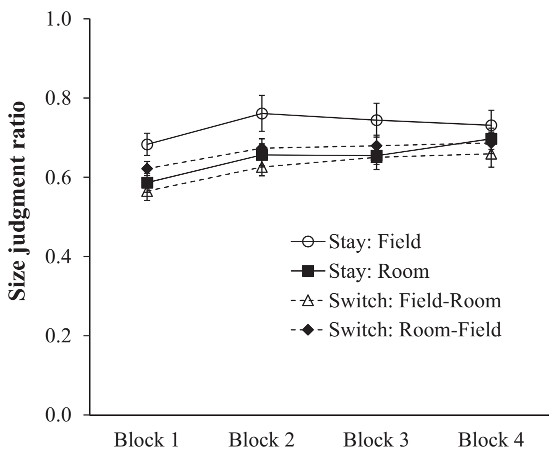

Figure 5. Size judgment ratio (actual/judged object size) as a function of distance judgment block in each of the four conditions.

To evaluate whether transfer of rescaling across VEs was complete, size judgment ratios were evaluated using a two (Block 2 and Block 3) by four (condition) contrast. Only the main effect of condition was significant, $F(3, 67) = 2.75$, $p = .049$, $\eta_p^2 = .11$, reflecting the overall larger size judgment ratios in the Stay: Field condition relative to all others. Neither the main effect of block nor the interaction was significant.

As a further test of the transfer of rescaling across VEs, the Block 3 data for each VE were compared when participants switched or did not switch prior to Block 3. For the field VE, Block 3 performance did not significantly differ between the Stay: Field and Switch: Room-Field conditions, $t(33) = 1.27$, $p = .213$. For the room VE, Block 3 performance did not significantly differ between the Stay: Room and Switch: Field-Room conditions, $t(34) = .04$, $p = .971$. In addition to standard null-hypothesis testing, further evaluation using Bayesian analysis revealed that the odds in favor of the null were 2.43:1 (field VE) and 5.37:1 (room VE), providing “weak” and “substantial” evidence in favor of the null, respectively (Gallistel, 2009).

The effect of the second walking interaction was evaluated using a two (Block 3 and Block 4) by four (condition) contrast. The main effect of block was significant, $F(1, 67) = 4.39$, $p = .04$, $\eta_p^2 = .06$, reflecting the overall larger judgment ratios in Block 4 ($M = .69$, $SE = .13$) compared with Block 3 ($M = .68$, $SE = .14$). The main effect of condition was not significant. The interaction was significant, $F(3, 67) = 4.46$, $p = .006$, $\eta_p^2 = .17$, reflecting the increase from Block 3 to Block 4 in the Stay: Room condition compared with all other conditions which showed no change in size judgment ratios.

To evaluate whether size judgments changed with experience, the slope relating size judgment ratio to trial number (1–15) was calculated separately for each participant for each block. Slope in Block 4 was significantly positive ($M = .0167$, $SE = .0074$), indicating that size judgment ratio became larger as trials progressed in that block, $t(70) = 2.25$, $p = .028$, but that result would not have survived a reduction in alpha to compensate for multiple comparisons absent a priori hypotheses. Slopes in Blocks 1, 2, and 3 did not significantly differ from zero.

Discussion

The main findings from Experiment 2 are that walking interaction caused an increase in size judgment ratios, and that the effect of walking interaction transferred across VEs. Across all four conditions, including the Switch conditions, size judgments in Block 3 were larger than those in Block 1, providing evidence that rescaling caused by walking interaction transferred across environments.

Compared with blind-walking responses in Experiment 1, the increase in size judgment ratios after the second walking interaction was meager, only reaching statistical significance in the Stay: Room condition. Although blind-walking judgments in Experiment 1 improved after the second walking interaction, improvement was smaller (6.9%) than that observed after the first walking interaction (14.4%). In a related experiment reported by Kelly et al. (2014; Experiment 1), participants performed four blocks of blind-walking distance judgments, each separated by a block of five walking interaction trials. For context, walking interaction blocks in the current project comprised 15 walking interaction trials. Kelly et al. (2014) found that the improvement in blind-walking distance judgments caused by first walking interaction block was three times larger than the improvement caused by the second walking interaction block. The third walking interaction block did not significantly improve performance, despite the fact that distance judgments were still less than veridical (85.3%, averaged across object distance). It therefore seems likely that the reason size judgments showed little increase after the second walking interaction was due to a combination of (a) the relatively small effect of walking interaction on size judgments and (b) the tendency for the effect of walking interaction to saturate.

General Discussion

Walking through a VE with continuous visual feedback caused an increase in perceived distance measured through blind-walking judgments (Experiment 1) and size judgments (Experiment 2). Furthermore, those improvements transferred to a new VE that was visually distinct from the VE in which walking interaction occurred. These results support the hypothesis that walking interaction causes rescaling of perceived space, and that rescaling transfers across VEs.

When averaged across the two VEs, blind-walking distance judgment ratios increased from .690 to .834, an improvement of 21%. In contrast, size judgment ratios increased from .614 to .679, an improvement of 11%. One possible explanation for this difference between the two dependent measures is that perceived size is not linearly related to perceived distance under some circumstances (Epstein & Landauer, 1969). However, Kelly et al. (2013) reported that perceived size and perceived distance were highly correlated (R = .97–.99 across different conditions) when tested in a VE similar to the field environment used in the current project, suggesting that failure of size-distance invariance is not likely to account for the different effects of walking interaction on the two dependent measures. Another possibility is that the effect of walking interaction on blind-walking judgments reflects a combination of rescaling of perceived space and recalibration of the walking response. The size judgments in Experiment 2 suggest that walking interaction causes rescaling, although an alternative explanation involving a compensation strategy is discussed later in this section.

Waller and Richardson (2008) reported that blind-walking distance judgments in the real world increased by 10% after walking interaction in a VE, and this aftereffect might reflect recalibration of the walking response. The sum of the effect of walking interaction on recalibration (10%; Waller & Richardson, 2008) and rescaling (11%; Experiment 2) is similar in magnitude to the effect of walking interaction on blind-walking judgments (21%) in Experiment 1. Therefore, the overall larger effect of walking interaction on blind-walking compared with size judgments could reflect the combined influence of rescaling and recalibration on blind-walking judgments.

In Experiment 2 and in experiments reported by Kelly and colleagues (Kelly et al., 2013; Siegel & Kelly, 2017), walking interaction in VR affected subsequent judgments of object size, which we interpret as rescaling of perceived space. This rescaling interpretation also fits well with results reported by Mohler et al. (2006), in which walking interaction in VR led to larger and more accurate verbal judgments of distance. In contrast, experiments in which participants walked while experiencing visual motion that was faster or slower than biomechanical motion have consistently shown that the effects are limited to walking responses (Durgin et al., 2005; Kunz et al., 2015) or responses that are functionally related to walking (Rieser et al., 1995; Withagen & Michaels, 2002). We believe that the crucial difference is that experiments showing evidence of rescaling of perceived space have provided feedback regarding walked distance, but visual speed was identical to walking speed. In contrast, experiments showing action-specific effects have modified visual speed to conflict with walking speed. One potentially complicating factor in this analysis is that perception of visual walking speed in VR may differ from biomechanical walking speed. Bruder and Steinicke (2014) found that participants were, on average, accurate in their judgment of the relationship between visual speed in VR and biomechanical walking speed when walking through a replica of the empty lab in which they were physically moving. Similarly accurate speed perception was reported by Durgin, Fox, Schaffer, and Whitaker (2005), but only when the VE contained nearby objects. When the VE was empty, participants required faster visual movement in order to match their perceived biomechanical walking speed. Perceived walking speed was not measured in the current experiments, but future work could evaluate the relationship between type of feedback (walked distance vs. walking speed) on judgments of distance and size.

The finding that recalibration and rescaling transfer across VEs is of practical significance because it indicates that walking interaction does not need to be performed in every VE experienced by an individual user. With sufficient interaction, blind-walking judgments can approach 100% (e.g., Waller & Richardson, 2008), and improvements can transfer across environments. However, for most VR applications, it would be more useful if rescaling of perceived space, not recalibration of a specific action, transferred to other VEs. For example, a VE designed to present an architectural rendering to an investor would ideally be perceived at the intended scale, and action-specific recalibration would not be of much use in evaluating the VE. Unfortunately, walking interaction resulted in a modest improvement in perceived size which may not be meaningful in most VR applications. However, modern consumer-oriented HMDs have been reported to produce perceived distance that is ~85% of actual distance (Creem-Regehr et al., 2015; averaged across the two VEs used in that study), and it is possible that walking interaction could serve to fill the gap and improve perception to levels near real-world accuracy.

Another important question regarding practical significance is whether the effects of walking interaction are durable over time. Richardson and Waller (2005) found that walking interaction affected blind-walking judgments 1 week later. This is somewhat surprising given that participants had 1 week to recalibrate to walking in the real environment. It would be valuable to determine whether walking interaction also affects size judgments 1 week later, and whether such long-term effects also transfer across VEs.

One theory for why walking interaction causes rescaling is that it leads to perceptual learning, whereby feedback about walked distance leads to modification of cue weights. This should lead to improved distance perception if some of the distance cues in VR are deficient. For example, lenses in the HMD cause the lens in the human eye to accommodate to a fixed distance, and so feedback received through walking interaction could cause the perceptual system to reduce the weight associated with the accommodation distance cue. The finding that postinteraction improvements in judged distance and judged size transferred to a new VE indicates that the deficient cues were constant across the two VEs, suggesting that characteristics of the HMD may be to blame for underperception. At least two other findings in related work support this conjecture. First, Willemsen et al. (2009) found that HMD weight and inertia can account for some of the underperception of distance that occurs in VR, indicating that the display itself is at least somewhat to blame. Second, modern HMDs produce distance perception that is better than in older displays (Creem-Regehr et al., 2015; Li, Zhang, & Kuhl, 2014; Young, Gaylor, Andrus, & Bodenheimer, 2014), although the critical differences between newer and older HMDs are unknown.

The finding that walking interaction in a VE leads to more accurate blind-walking judgments in the same VE has now been demonstrated several times (Kelly et al., 2013, 2014; Mohler et al., 2006; Richardson & Waller, 2005, 2007; Siegel & Kelly, 2017; Waller & Richardson, 2008). Across these demonstrations, the magnitude of the postinteraction improvement in blind-walking ranges from 14% (Experiment 1 of Kelly et al., 2013) to 104% (Experiment 2 of Waller & Richardson, 2008). For context, Experiment 1 of the current project produced a 21% improvement in blind-walking judgments from Block 1 to Block 2, averaged across VEs. The discrepancy between studies does not appear to be caused by a ceiling effect, whereby preinteraction distance judgments are nearly perfect and there is little room for improvement. Rather, preinteraction blind-walking distance judgment ratios (walked distance divided by actual target distance) in the aforementioned studies ranged from .54 to .73 (.69 in Experiment 1 of the current study, collapsed across VE). Furthermore, the study reporting the smallest improvement (Kelly et al., 2013) was modeled directly after the study showing the largest improvement (Waller & Richardson, 2008), although equipment was not matched. It is unclear which methodological differences could account for the differences across experiments. Differences in equipment and stimuli seem unlikely to be the cause, since our lab has produced similar results using different HMDs (compare Kelly et al., 2013 and Kelly et al., 2014) and different VEs (compare the Room and Field VEs in Experiment 1 of the current study). Future work could focus on procedural differences, such as experimenter instructions or real-world practice with blind-walking, but there is no reason to expect that these differences underlie the reported differences in the literature.

Experience with the blind-walking task has been shown to cause an increase in walked distance, and this effect appears to be at least partially due to recalibration caused by walking without vision (Philbeck, Woods, Arthur, & Todd, 2008). However, the slopes relating within-block trial sequence to blind-walking distance ratio (Experiment 1) were nonsignificant or negative, indicating that experience with blind-walking did not lead to longer blind-walking judgments. Therefore, the effect of block on blind-walking distance judgments cannot be explained by practice with the task. Size judgments were also unaffected by within-block trial sequence, and therefore were not likely affected by practice. Furthermore, the effect of practice demonstrated by Philbeck, Woods, Arthur, and Todd (2008) appeared to saturate after 15–20 trials. In contrast, blind-walking judgments in Block 4 (Trials 46–60 in the context of the entire experiment) were significantly larger than those in Block 3 (Trials 31–45), reinforcing the notion that the effect of block on blind-walking distance judgments was not caused by experience with the blind-walking task.

Research in developmental psychology has shown that children's judgments of object size depend on their understanding of the relationship between object distance and object size (both perceived size and image size; Granrud, 2009). Children with high knowledge of the relationship between distance and size demonstrate greater size constancy (and sometimes overconstancy) than those with low knowledge. Granrud (2009, 2012) argued that reports of size constancy in adults is due to compensatory strategies, rather than accurate perception of size. Such strategies might also explain reports of overconstancy in judgments of distant objects (Carlson, 1962; Kavšek & Granrud, 2012). It is therefore possible that improvement in size judgments after walking interaction is due to cognitive strategies rather than rescaling of perceived space. Walking interaction might reveal to participants that the objects are farther away than they had initially perceived them to be, which could lead participants to apply a compensatory strategy when making size judgments. Walking interaction could also reveal that the texture elements surrounding the target object become larger upon approach and those texture elements could be used to compensate for underperception of size. However, the latter explanation might also lead to the prediction that removal of learned texture cues would make size compensation impossible, yet participants in the Switch conditions showed no decrement in size distance judgments after switching to a new VE with new textures. In a similar, unpublished study from our lab, 51 participants made blind-walking, size, and verbal judgments before and after walking interaction. After completion of the experiment all participants were asked to report any strategies they used, and none reported capitalizing on the known relationship between size and distance.

In summary, judgments of distance and size improved (increased) after a brief period of walking through a VE with visual feedback, and improvements transferred to a new VE. The improvement in judged size reflects rescaling of perceived space, and was smaller than the improvement in judged distance, which most likely reflects both rescaling and recalibration of the walking response.

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