Recalibration of Perceived Distance in Virtual Environments Occurs Rapidly and Transfers Asymmetrically Across Scale

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Abstract—Distance in immersive virtual reality is commonly underperceived relative to intended distance, causing virtual environments to appear smaller than they actually are. However, a brief period of interaction by walking through the virtual environment with visual feedback can cause dramatic improvement in perceived distance. The goal of the current project was to determine how quickly improvement occurs as a result of walking interaction (Experiment 1) and whether improvement is specific to the distances experienced during interaction, or whether improvement transfers across scales of space (Experiment 2). The results show that five interaction trials resulted in a large improvement in perceived distance, and that subsequent walking interactions showed continued but diminished improvement. Furthermore, interaction with near objects (1-2 m) improved distance perception for near but not far (4-5 m) objects, whereas interaction with far objects broadly improved distance perception for both near and far objects. These results have practical implications for ameliorating distance underperception in immersive virtual reality, as well as theoretical implications for distinguishing between theories of how walking interaction influences perceived distance.

Index Terms—Distance perception, virtual reality, recalibration

INTRODUCTION

Distances in virtual environments are commonly underperceived relative to the intended distance. According to a recent review of past research [1], which included results from a wide variety of display technologies and virtual environments, distances in virtual environments are perceived to be just 71% of the intended distance, on average (differences across individuals and across studies resulted in a 95% confidence interval of ±8.2%). This is in stark contrast to distance perception in the physical world, which is reported to be nearly 100% of actual distance, on average [2]. Underperception of distance could undermine the usefulness of virtual environments, especially those designed to train skills that are intended to transfer to the real world [3]. However, interaction with the virtual environment by walking with visual feedback has recently been shown to drastically improve perceived distance to within 90-100% of actual distance with sufficient interaction [1][4][5][6]. The goal of the current project was to evaluate specific characteristics of the walking interaction required to achieve this level of improvement.

1 BACKGROUND

Perception of egocentric distance—the distance from oneself to another location—in real environments is typically quite accurate. Action-based distance judgments produce more accurate responses than verbal judgments of distance, which tend to result in under-reporting [7]. The most commonly used form of action-based distance judgments is blind walking, in which the viewer looks at a location and then, without vision, attempts to walk to the previously viewed location [8][9][10][11]. Recent summaries of published experiments using blind walking indicate nearly perfect performance, on average, for distances up to 20 m in real environments [12][7]. Other action-based judgments such as blind throwing [13][14] or even imagined walking [15] produce similar results. Although average responses can be highly accurate, precision decreases approximately linearly with object distance [16], a finding that could be due to reduced precision in the percept and the response. In the case of blind walking, response precision could deteriorate for larger distances due to the precision of the open-loop walking response as well as degradation of the remembered object location during walking.

Perception of egocentric distance in virtual environments is commonly reported to be 50-85% of intended distance, even when measured using action-based judgments [1][2][12][17][18][19][20][21][22][23][24][25][26][27][28][29][30]. Research aimed at understanding and improving distance perception in virtual environments can be characterized by two main approaches: the bottom-up and top-down approach. The bottom-up approach is to identify missing or misleading distance cues in virtual environments, with the intention of improving distance perception by improving those distance cues responsible for underperception. Some of the cues that have been evaluated include the quality of computer graphics [26], display field of view [17][22][27], stereoscopic cues [28], mass and inertia of head-mounted displays (HMDs) [27], and immersion [31][32]. Unfortunately, none of the cues tested so far appears singularly responsible for distance underperception in virtual environments. Instead, underperception might be caused by a complex interaction between many cues, but more research is needed. Another unique example of the bottom-up approach is to present white light to the visual periphery in an HMD, which has been found to improve distance perception accuracy [12]. Although more work is required to identify the underlying mechanism, we consider this to be a bottom-up approach because it involves changes to the stimulus experienced by the observer when making distance judgments.

Whereas the bottom-up approach seeks to identify deficient cues to distance perception, the top-down approach seeks to develop alternative protocols for improving distance perception in order to overcome the deficient cues without changing the distance perception stimulus itself. One example of the top-down approach is research on transitional environments, in which a virtual replica of the physical environment in which one is standing has been found to

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produce more accurate distance judgments than different virtual environments that participants have never experienced [32]. Furthermore, this increased level of accuracy can be maintained by using the virtual replica as a transitional environment through which users access other virtual environments via a portal [25][33][34][35].

Another example of the top-down approach is recalibration of distance perception through walking interaction, which is the focus of the current project. Walking through the virtual environment with continuous visual feedback causes dramatic improvement of post-interaction distance judgments within the virtual environment [1][4][5][6][36]. In one example [1], participants made blind walking distance judgments in response to virtual objects located approximately 1-4 m in front of them. Distance judgments were made before and after a period of interaction in which participants walked, with continuous visual feedback, to virtual objects that were also located approximately 1-4 m away. After 18 such interaction trials, distance judgments improved from approximately 50% of intended distance pre-interaction to 100% of intended distance post-interaction. A similar study [4] using larger egocentric distances (3-7 m) and 15 interaction trials reported that distance judgments improved from approximately 70% pre-interaction to 90% post-interaction.

2 Distance perception and distance judgments

Distance perception cannot be measured directly. Instead, distance judgments are commonly used to make inferences about distance perception. Convergence of multiple measures can provide supporting evidence that one is actually measuring perceived distance [37]. For example, a recent study evaluated the effects of walking interaction on perceived distance using direct blind walking judgments and size judgments [36]. Size can be used as an indirect measure of distance under the assumption of size-distance invariance. Walking interaction caused significant increases in blind walking and size judgments, and the two measures were highly correlated with one another, suggesting that they both tapped into the same underlying percept.

In the current experiments, participants completed direct blind walking judgments, and we acknowledge that blind walking judgments might not directly reflect perceived distance. However, based on previous work indicating that multiple measures of perceived distance converge [37], and that walking interaction has similar effects on blind walking judgments and size judgments [36], we interpret the blind walking judgments in the current studies as evidence of distance perception.

3 Project Overview and Hypotheses

Interaction by walking through the virtual environment holds great promise as a technique for quickly recalibrating perceived distance in virtual reality. The current project was designed to evaluate two important but unanswered questions regarding recalibration. The goal of Experiment 1 was to determine how quickly recalibration occurs. Past studies on the effects of walking interaction have typically provided a large number of interaction trials in a single block and then measured distance perception after completion of all interaction trials [1][4][5][6]. From a practical perceptive, it is important to know how many interaction trials are necessary to achieve the desired amount of recalibration. From a theoretical perspective, the function relating the amount of recalibration to the amount of walking interaction could be useful for evaluating theories about the underlying mechanism of recalibration (for a detailed description of possible mechanisms, see [1] and [36]). For example, one theory is that walking interaction leads to the development of an explicit strategy, whereby the viewer recognizes that the environment is actually twice as large as it appears and that he/she must therefore walk twice as far. Such explicit rule learning is likely to lead to a step function (or nearly so) relating interaction trials and distance judgments, whereby distance judgments improve nearly completely once the strategy is adopted. Another theory is that walking interaction recalibrates the coupling between the perceptual input and the action output [38][39][40][41], herein referred to as perception-action recalibration. The perception-action recalibration that occurs when reaching for a target while wearing prism glasses occurs gradually over tens of trials, although the largest increases tend to occur during early trials [42]. Therefore, evaluating the function relating the amount of recalibration to the amount of walking interaction could help to distinguish the explicit strategy theory from the perception-action recalibration theory.

Experiment 2 was designed to determine whether recalibration is specific to the distances experienced during interaction, or whether recalibration transfers across scales of space. For example, does recalibration after walking to near objects with visual feedback improve perceived distance to near objects and far objects alike, or to near objects only? This question has practical implications for recalibration in virtual environments, since most virtual reality systems have physical constraints that limit walking to relatively smaller distances. The theoretical implications include the specificity of recalibration, and whether walking interaction causes widespread recalibration that includes other distances, as has been found with recalibration of reaching [43][44].

4 Experiment 1: Time-Course of Recalibration

Participants performed four blocks of distance judgment trials in an immersive virtual environment, separated by three blocks of five walking interaction trials.

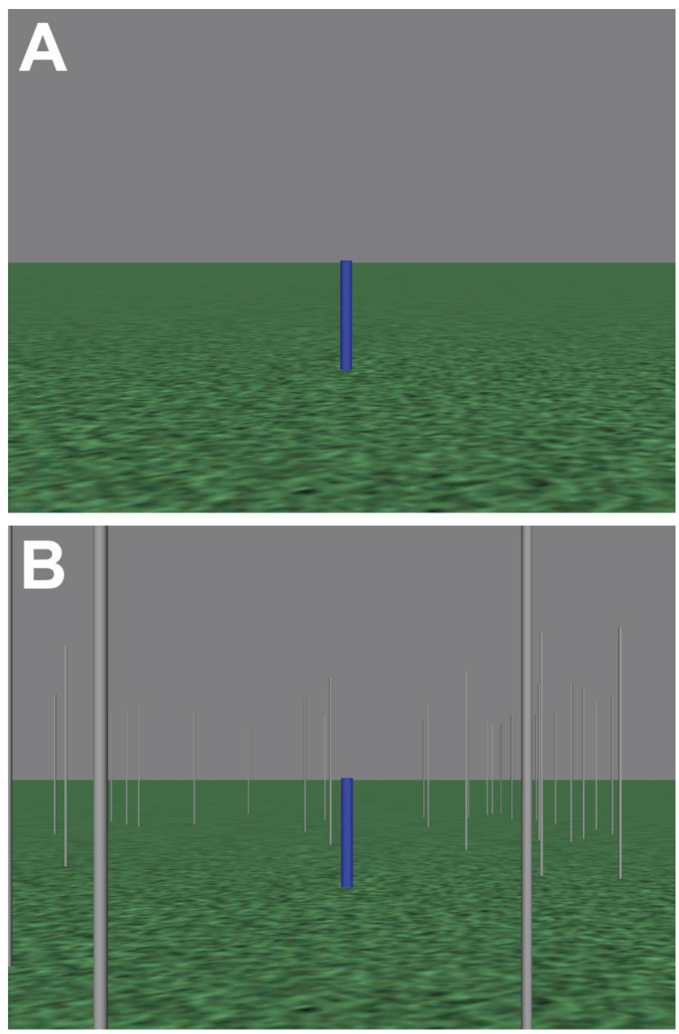

Fig. 1. Images of the virtual environment used in Experiments 1 and 2 during blind walking judgments (A) and walking interaction (B).

4.1 Method

4.1.1 Participants

Eighteen undergraduate students (nine male, nine female) from Iowa State University participated in exchange for course credit.

4.1.2 Stimuli and Design

Participants performed four blocks of direct blind walking distance judgments: one block before interacting with a virtual environment and one block after each of three interaction blocks. No feedback was provided during distance judgment trials, but continuous visual feedback was provided during interaction trials. The virtual environment (Figure 1) contained an infinite ground plane with a grass texture. Although the ground plane was infinite, the far clipping plane limited distance of the plane to 10,000 meters, which caused a downward shift of the horizon of approximately .01°. A blue cylinder (0.1 m diameter) served as the target for distance judgment trials (Figure 1a) and interaction trials (Figure 1b). The height of the cylinder was continuously scaled to the participant's eye height. During interaction trials, 150 vertical gray cylinders were randomly placed in a 30 × 30 m area to enhance optic flow.

Each distance judgment block included 15 distance judgment trials, composed of 3 repetitions of 5 egocentric distances: 1.1, 1.95, 3.1, 3.9, and 4.9 m. Each interaction block included 5 interaction trials in which participants walked egocentric distances of 1, 2, 3, 4, and 5 m.

The virtual environment was viewed on an HMD (nVisor ST50, NVIS, Reston, VA; see Figure 2), which provided binocular images presented at 1,280 × 1,024 pixel resolution within a 40º horizontal × 32º vertical field of view. Graphics were updated at 60 Hz and reflected moment-to-moment changes in the participant's head position and orientation. Head orientation was tracked using a 3-axis orientation sensor (InertiaCube2+ by Intersense, Bedford, MA), and head position was tracked optically (PPTX4 by WorldViz, Santa Barbara, CA). Graphics were rendered using Vizard software (WorldViz, Santa Barbara, CA) running on a Windows computer with Intel Core2 Quad processors and Nvidia GeForce GTX 285 graphics card.

4.1.3 Procedure

The participant was given a brief description of the blind walking procedure and was then led to the viewing location, which was marked by a rubber strip on the floor that could be felt through shoes. The participant then donned the HMD and the room lights were extinguished. The darkened room along with occluding fabric attached to the edge of the HMD prevented peripheral visual stimulation external to the HMD.

Fig. 2. Photograph of the HMD as worn by participants. The room lights were extinguished during the actual experiment.

For distance judgment trials, the blue cylinder appeared on the ground plane in front of the participant for five seconds, after which the HMD screens went blank (i.e., the cylinder and ground plane disappeared), indicating that the participant should walk to the location of the cylinder. The participant walked to the perceived cylinder location without vision, and the experimenter pressed a button on a joystick to log the participant's head position after completion of the blind walking response. A black line then appeared at the participant's feet, which the participant could use to guide him/herself back to the viewing position before the next trial began. This black line was infinitely long and without texture, so as to prevent any feedback about the participant's accuracy or walked distance.

On each interaction trial the blue cylinder and small gray cylinders appeared on the ground plane and remained visible until the participant walked to the location of the blue cylinder. Upon reaching the blue cylinder the HMD screens went blank and a black line appeared at the participant's feet in order to guide him/her back to the viewing position for the next interaction trial.

The experiment lasted approximately 45 minutes, and participants were actually wearing the HMD for approximately 40 minutes. Simulator sickness was not explicitly measured, but participants were told to inform the experimenter if they felt symptoms of motion sickness. A small number reported minor symptoms, but none reported severe symptoms and none withdrew from the study.

4.2 Results

Blind walking distance judgments were converted into ratios of judged-to-actual distance in order to more easily examine the effects of actual egocentric distance and walking interaction on distance perception. Mean judgment ratios are shown in Figure 3 as a function of actual object distance and distance judgment block (Block 0 is pre-interaction, Block 1 is after one interaction block, etc.). Each interaction block resulted in larger distance judgment ratios on the subsequent distance judgment block compared to the prior block, but the largest increase occurred after the first interaction block compared to subsequent interactions. Furthermore, judgment ratios were larger for near distances than far distances, indicating greater underestimation for farther distances. These conclusions were supported by statistical analyses.

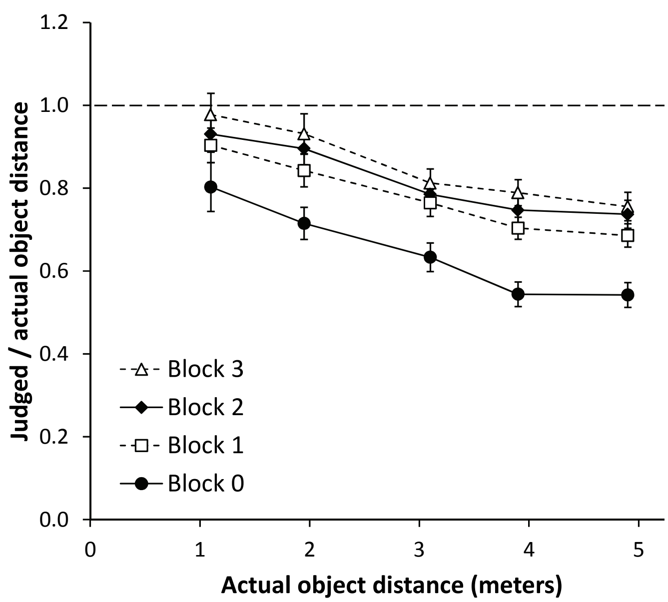

Fig. 3. Distance judgment ratios (judged distance divided by actual distance) in Experiment 1 as a function of actual object distance and test block (Block 0 corresponds to pre-interaction judgments, Block 1 corresponds to judgments made after a single interaction block, etc.). Error bars indicate +/- 1 standard error.

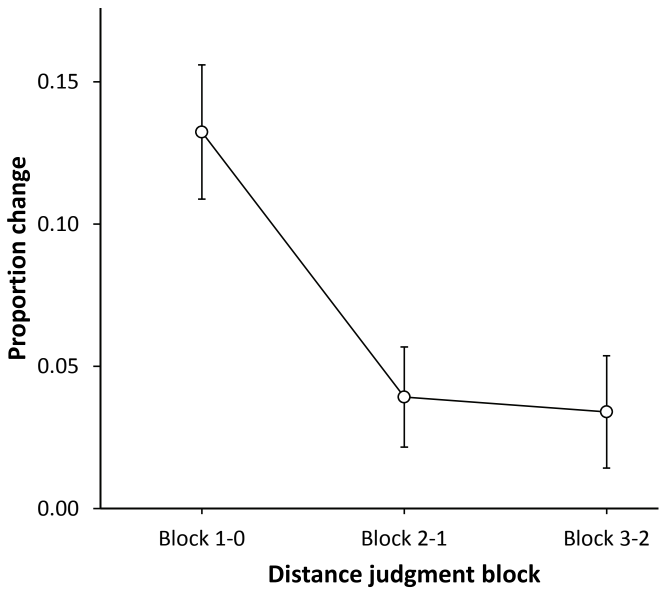

Fig. 4. The proportion change in distance judgment ratios as a function of distance judgment block. "Block 1-0" indicates the change in distance judgment ratio for distance judgment Block 1 relative to Block 0 (calculated as Block 1 minus Block 0), and so on. Error bars indicate +/- 1 standard error.

Judgment ratios were analyzed in a repeated-measures ANOVA with terms for distance judgment block and actual object distance. Main effects of distance judgment block, $F(3,51)=26.35$, $p<.001$, $\eta_p^2=.61$, and actual distance, $F(4,68)=25.58$, $p<.001$, $\eta_p^2=.63$, were both significant. The interaction between distance judgment block and actual object distance was not significant, $F(12,204)=0.71$, *ns*. Contrasts comparing distance judgment ratios across blocks indicated that judgment ratios were larger in Block 1 that Block 0, $F(1,17)=31.46$, $p<.001$, $\eta_p^2=.65$, and larger in Block 2 than Block 1, $F(1,17)=4.98$, $p=.039$, $\eta_p^2=.23$, but there was no difference between Blocks 3 and 2, $F(1,17)=2.96$, *ns*.

To compare the relative effects of the three interaction blocks, changes in distance judgment ratios were calculated by subtracting the preceding block's distance judgment ratio from Blocks 1 through 3 (e.g., the effect of the first interaction block was calculated by subtracting distance judgment Block 0 from distance judgment Block 1), collapsing across actual object distance. These data are shown in Figure 4. The change in distance judgment ratio after the first interaction block was significantly larger than that of the second, $F(1,17)=8.61$, $p=.009$, $\eta_p^2=.34$, and third, $F(1,17)=8.901$, $p=.008$, $\eta_p^2=.34$, interaction blocks, which did not differ significantly from one another, $F(1,17)=0.04$, *ns*.

4.3 Discussion

Five interaction trials (a single interaction block) in which continuous visual feedback was provided during walking caused a 13% increase in perceived distance, as assessed by subsequent blind walking distance judgments. Additional walking interaction continued to improve distance perception, but the effect of later interactions greatly diminished compared to the effect of the first five interaction trials. These findings indicate that recalibration resulting from interaction with a virtual environment occurs rapidly, and tapers off with increased interaction. One possible reason for the diminishing effect of interaction is that interaction produces corrective feedback that is most salient during early interaction trials because the error signal (i.e., the difference between the perceived and actual distance experienced during interaction) is largest before recalibration has occurred. However, errors when walking to distant objects were still quite large (up to 24% for the farthest object) even after three interaction blocks, so it is surprising that the second and third interaction blocks produced such meager (3-4%) improvements.

Distance judgment ratios were larger for near than far object distances, both before and after walking interaction, which is consistent with previous research testing distance perception in virtual environments [2][29][30][45]. Another way to describe this trend is that judged distance is related to actual object distance by a linear function with slope less than one and intercept greater than zero. Pre-interaction data from Experiment 1 were well-fit by a line with slope equal to 0.45 and intercept equal to 0.46 (R^2=0.985). The non-zero intercept underlies the decrease in distance judgment ratios with increased object distance, and describes how distance judgment ratios could exceed 1.0 for short distances. Such underperception of far distances and overperception of near distances is consistent with studies that test distance perception under reduced-cue viewing conditions, in which some absolute distance cues are removed [46][47]. One theory that explains these findings is the specific distance tendency, whereby objects viewed in the absence of any distance cues appear to be located approximately 2 m away, regardless of the actual object distance [48][49]. Under reduced cue viewing, perceived distance is biased toward the specific distance, and virtual reality could be considered a reduced cue viewing environment because of the various deficiencies in the visual display, including reduced field of view, compressed ranges of color and brightness, pixilation of the display, and deficiencies in texture gradients.

In summary, the results of Experiment 1 show that the first block of five interaction trials produced the largest improvement in perceived distance, but that small improvements continued after the second and third trial blocks. In practical terms, these results indicate that just a few interaction trials could be sufficient to recalibrate distance perception to acceptable levels. In theoretical terms, these results are consistent with the perception-action recalibration theory and are inconsistent with adoption of an explicit strategy. Recalibration of perception-action coupling, as when learning to reach for a target while wearing prism glasses that displace visual information by a fixed angular amount, occurs gradually over tens of trials, with the largest increases occurring during early trials [42]. In contrast, explicit rule learning [1] is typically characterized by quick and complete change in responses once the rule is learned [50].

Experiment 1 addressed the effect of interaction quantity (i.e., number of interaction trials) on distance perception in a virtual environment. Related to the goal of improving distance perception in virtual environments through walking interaction, it is also important to consider the effect of interaction quality on distance perception. In other words, which characteristics of walking interaction influence recalibration? For example, past research has shown that purely visual movement through the virtual environment is insufficient to produce recalibration, indicating that physical walking is required [1]. Experiment 2 considered whether the distance walked during interaction affects recalibration. In Experiment 1, distances walked during interaction were very similar (although not identical) to those tested during distance judgments. Therefore, it is unclear whether the recalibration that occurred in Experiment 1 transfers across distances. For example, does walking interaction over short distances cause recalibration of both short and long distances, or is recalibration of perceived distance specific to the distances experienced during interaction?

5 Experiment 2: Transfer of Recalibration across Distances

Experiment 2 was designed to explore the transfer of recalibration from distances experienced during walking interaction to distances tested during post-interaction distance judgments. In the Near interaction condition participants interacted by walking to objects that were 1 and 2 m away. In the Far interaction condition participants interacted by walking to objects that were 4 and 5 m away. All participants made pre- and post-interaction distance judgments for objects that were approximately 1-5 m away. If recalibration only occurs for distances experienced during walking interaction, then post-interaction distance judgments should show selective improvement (relative to pre-interaction judgments). However, if recalibration transfers across distances, then post-interaction distance judgments should show broad improvement across the full range of tested distances.

5.1 Method

5.1.1 Participants

Thirty-three undergraduate students (18 male and 15 female) from Iowa State University participated in exchange for course credit. Participants were randomly assigned to condition, and gender was approximately balanced across condition.

5.1.2 Stimuli, Design, and Procedure

Participants performed two blocks of direct blind walking distance judgments, one before and one after interacting with a virtual environment. The two distance judgment blocks were identical to the distance judgment blocks in Experiment 1. The interaction block included only two object distances: Participants in the Near interaction condition walked to objects at egocentric distances of 1 and 2 m, whereas participants in the Far interaction condition walked to objects at egocentric distances of 4 and 5 m. Each object distance was repeated nine times for a total of 18 interaction trials. The stimuli, design, and procedure were otherwise identical to those in Experiment 1.

The experiment lasted approximately 30 minutes, and participants were actually wearing the HMD for approximately 25 minutes. Simulator sickness was not explicitly measured, but participants were told to inform the experimenter if they felt symptoms of motion sickness. A small number reported minor symptoms, but none reported severe symptoms and none withdrew from the study.

5.2 Results

Mean distance judgment ratios are shown in Figure 5 as a function of interaction condition, actual object distance, and distance judgment block. Walking with visual feedback to near objects (Near condition)

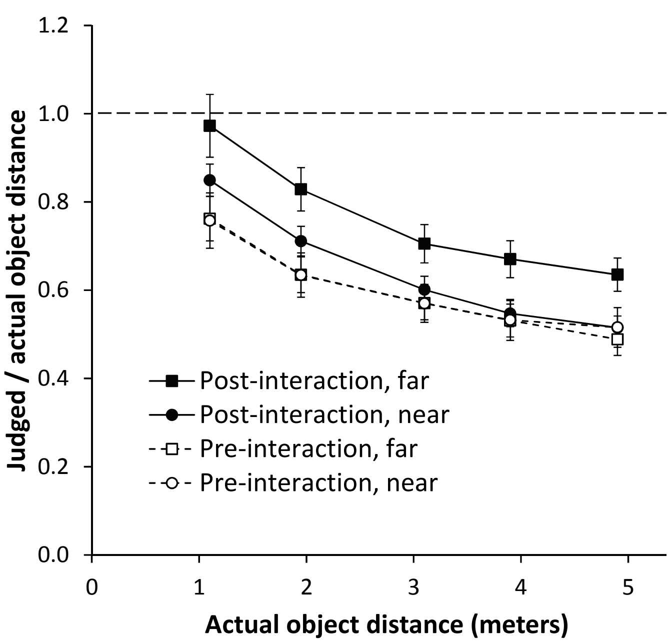

Fig. 5. Distance judgment ratios (judged distance divided by actual distance) in Experiment 2 as a function of actual object distance, test block (pre- or post-interaction) and interaction condition (Near or Far). Error bars indicate +/- 1 standard error.

caused selective improvement of subsequent distance judgments to near, but not far, objects. In contrast, walking with visual feedback to far objects caused uniform improvement on subsequent distance judgments, regardless of object distance. Not only did walking interaction in the Near condition fail to transfer across distances, but it also produced relatively less recalibration than the Far condition even for the shorter distances. These conclusions were supported by statistical analyses.

Distance judgment ratios were analyzed in a mixed-model ANOVA with terms for condition (Near or Far), distance judgment block (pre- or post-interaction) and actual object distance. Significant main effects of distance judgment block, $F(1,31)=21.76$, $p<.001$, $\eta_p^2=.41$, and actual object distance, $F(4,124)=86.86$, $p<.001$, $\eta_p^2=.74$, were qualified by significant interactions between condition and block, $F(1,31)=7.55$, $p=.01$, $\eta_p^2=.20$, and between block and actual object distance, $F(4,124)=3.79$, $p=.006$, $\eta_p^2=.11$. No other main effects or interactions were significant.

Specificity of transfer was evaluated separately for Near and Far conditions using predicted pattern analysis [51][52], which tested for patterns in the data based on an *a priori* hypothesis about transfer of recalibration. This was accomplished by using actual distance contrast weights of -1, -1, 0, 1, 1 corresponding to the actual object distances of 1.1, 1.95, 3.1, 3.9, and 4.9 m. A significant interaction contrast between actual distance and distance judgment block would be consistent with selective influence of interaction distance on subsequent distance judgments for the condition tested (i.e., failure of transfer across distances). The interaction contrast was significant for the Near condition, $F(1,16)=5.02$, $p=.04$, $\eta_p^2=.24$, accounting for 93.5% of the variance associated with the interaction and leaving a non-significant amount of variance unaccounted for, $F(1,16)=0.23$, *ns*. The interaction contrast for the Far condition was not significant, $F(1,15)=3.33$, *ns*.

5.3 Discussion

Walking with visual feedback to near objects caused selective improvement on subsequent blind walking judgments to near objects compared to far objects. In contrast, walking with visual feedback to far objects caused widespread improvement on subsequent blind walking distance judgments, and was not specific to actual object distance. These results indicate that perception of large distances does not improve as a result of recalibration to smaller distances. This is somewhat disappointing from a practical perspective, because one important feature of virtual reality is the ability to display virtual environments that are larger than the containing physical environment. Unfortunately, it may not be possible to recalibrate perception of the regions beyond the confines of the physical space because physically walking to those regions is impossible.

Transfer of recalibration was asymmetric, whereby interacting with far objects recalibrated near distances, but not vice versa. One possible reason for the asymmetric transfer of recalibration is that walking to a far object necessarily involves walking both short and long distances. In other words, walking to an object 5 m away requires walking through distances of 1, 2, 3, and 4 m.

Even when only considering perception of smaller distances, the effect of interaction with near objects was less effective than interaction with far objects. One explanation could be that walking to near objects resulted in less distance traveled and therefore less visual feedback through optic flow over the course of the interaction, compared to walking to far objects. However, comparison with Experiment 1 suggests that total distance traveled is not a complete explanation of the difference between the Near and Far conditions. Participants in the Near condition walked a total of 27 m during interaction, compared with 81 m in the Far condition. However, participants in Experiment 1 walked a total of 15 m per interaction block. In that experiment, even a single interaction block resulted in substantial and widespread recalibration across all distances tested, despite the fact that the total distance walked during interaction was only half that in the Near condition of Experiment 2. Therefore, the object distance appears to be dissociable from total distance walked (in other words, walking to a 2 m object three times is not the same as walking to a 6 m object once). Another possible explanation that warrants future work is that walking speed could influence recalibration. It is possible that walking speeds were lower when participants walked to near objects during interaction, but these data were not recorded in the current project.

6 General Discussion

Egocentric distance in virtual environments is commonly underperceived relative to intended distance. However, interaction by walking through the virtual environment with visual feedback has been shown to drastically improve perceived distance [1][4][5][6]. Past work has typically provided a large number of walking interaction trials and measured distance perception after completion of all interaction trials. The goals of the current project were to determine how quickly improvement occurs as a result of walking interaction (Experiment 1) and whether recalibration is specific to the distances experienced during walking interaction, or whether recalibration transfers across scales of space (Experiment 2). To that end, the results show that five interaction trials resulted in a large improvement in perceived distance, and that subsequent interactions resulted in continued but reduced improvement. Furthermore, interaction by walking to near objects improved distance perception for near but not far objects, whereas interaction by walking to far objects broadly improved distance perception for near and far objects.

Although interaction with virtual environments can be achieved through numerous actions (walking, reaching, touching, throwing, moving a joystick, etc.), it appears that walking may have privileged status for recalibrating perceived space. For example, reaching to nearby virtual objects was found to have no effect on distance judgments [36], and purely visual movement through the environment was also found to be insufficient for recalibrating distance judgments [1].

Whereas some previous studies have compared distance judgments in real and virtual environments [26][29], the current studies were designed to evaluate how walking through a virtual environment with visual feedback affects distance judgments in the virtual environment. Therefore, distance judgments in the real world were not conducted. However, this prevents comparison between virtual and real environments.

It is useful to compare the magnitude of the effect of walking interaction in the current studies with that reported by other similar studies. Table 1 shows the percentage improvement in distance judgment ratios caused by walking interaction in the current study and in other published studies on this topic. Percentage improvement was calculated as the change caused by walking interaction (post-interaction ratio minus pre-interaction ratio) divided by the pre-interaction ratio. The selected studies all used blind walking as the method of distance judgment and walking with visual feedback as the method of interaction, and all included 15-18 interaction trials. Furthermore, all studies used an HMD as the visual display, although the exact viewing characteristics of the HMD varied across studies. Despite the methodological similarities, there are vast differences in pre-interaction distance judgment ratios (from 0.47 to 0.73) and in the percentage influence of interaction (from 14% to 104%). In this context, the pre-interaction distance judgment ratios in the current experiments were in the middle range (0.65 and 0.60 in Experiments 1 and 2, respectively) and the percentage effect of interaction was somewhat low (31% and 27% in Experiments 1 and 2, respectively). These large differences across experiments suggest that other important factors influencing the effect of interaction have yet to be identified. Some possibilities include the display field of view, which directly influences optic flow in peripheral vision, and environmental complexity, which could also influence optic flow and also distance cues such as texture gradients and familiar size.

The results of the current project are useful for evaluating theories about the underlying mechanism through which walking interaction influences distance judgments. According to the explicit strategy theory, interaction allows the viewer to recognize that the environment is actual larger than it appears, and that he/she must therefore walk farther to successfully reach the target. In contrast, the recalibration theory proposes that interaction results in recalibration of the perception-action coupling [38][39][40][41]. The gradual effect of interaction on distance judgments in Experiment 1 is consistent with other studies on perception-action recalibration [42], and inconsistent with the quick and complete change in responses associated with explicit strategy learning [50]. The results of Experiment 2 are equivocal regarding the mechanism of recalibration, since it is unclear why an explicit strategy or perception-action recalibration would transfer asymmetrically across scale.

The two experiments reported here indicate that interacting with a virtual environment by walking results in rapid recalibration of perceived distance, which makes it a promising tool for improving the usefulness of virtual environments. Upon experiencing an unfamiliar virtual environment, users could be asked to walk to a sequence of virtual objects dynamically introduced into the environment as a method of improving perceived distance during subsequent tasks performed within that environment. Furthermore, walking to objects at farther distances will produce more widespread recalibration of perceived distance. However, the failure of recalibration to transfer from near to far distances is a limiting factor, since most virtual reality systems are contained in physical spaces that limit possible walking distance (but see [53]).

Table 1. Pre- and post-interaction distance judgment ratios and percent improvement, in the current studies and similar past studies.

Research study	Pre-interaction	Post-interaction	Improvement
Kelly et al. (2013)			
Experiment 1, blind walking condition	0.70	0.80	14%
Mohler et al. (2006)			
Continuous visual feedback condition	0.73	0.91	25%
Richardson & Waller (2005)			
Experiment 1, egocentric condition	0.59	1.02	73%
Experiment 2, direct walking condition	0.48	0.89	85%
Richardson & Waller (2007)			
Experiment 2, direct walking condition	0.56	0.94	68%
Waller & Richardson (2008)			
Experiment 2, body-based plus optic flow condition	0.47	0.96	104%
Experiment 3, primed search condition	0.54	0.99	83%
Current study			
Experiment 1	0.65	0.85	31%
Experiment 2, far condition	0.60	0.76	27%

Acknowledgments

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