Comparison of Two Methods for Improving Distance Perception in Virtual Reality

JONATHAN W. KELLY, LUCIA A. CHEREP, BRENNA KLESEL, ZACHARY D. SIEGEL, and SETH GEORGE, Iowa State University

Distance is commonly underperceived in virtual environments compared to real environments. Past work suggests that displaying a replica VE based on the real surrounding environment leads to more accurate judgments of distance, but that work has lacked the necessary control conditions to firmly make this conclusion. Other research indicates that walking through a VE with visual feedback improves judgments of distance and size. This study evaluated and compared those two methods for improving perceived distance in virtual environments (VEs). All participants experienced a replica VE based on the real lab. In one condition, participants visually previewed the real lab prior to experiencing the replica VE, and in another condition they did not. Participants performed blind-walking judgments of distance and also judgments of size in the replica VE before and after walking interaction. Distance judgments were more accurate in the preview compared to no preview condition, but size judgments were unaffected by visual preview. Distance judgments and size judgments increased after walking interaction, and the improvement was larger for distance than for size judgments. After walking interaction, distance judgments did not differ based on visual preview, and walking interaction led to a larger improvement in judged distance than did visual preview. These data suggest that walking interaction may be more effective than visual preview as a method for improving perceived space in a VE.

Categories and Subject Descriptors: I.3.7 [Computer Graphics]: Three-Dimensional Graphics and Realism—Virtual reality; I.4.8 [Computer Applications]: Social and Behavioral Sciences—Psychology; H.5.1 [Information Systems]: Multimedia Information Systems—Artificial, augmented, and virtual realities; H.1.2 [Information Systems]: User Machine Systems—Human Factors

General Terms: Virtual environments, Experimentation

Additional Key Words and Phrases: Depth perception, stereoscopic displays, virtual environments

ACM Reference Format:

Jonathan W. Kelly, Lucia A. Cherep, Brenna Klesel, Zachary D. Siegel, and Seth George. 2017. Comparison of two methods for improving distance perception in virtual reality. *ACM Trans. Appl. Percept.* X, X, Article 1 (September 2017), 12 pages. DOI: http://dx.doi.org/10.1145/000000000000

1. INTRODUCTION

Virtual reality (VR) has proven to be a useful technology for applications such as education, training, industry, and entertainment. However, one consistent shortcoming of VR is the tendency for users to

© 2017 ACM 1544-3558/2017/September-ART1 \$15.00

DOI:http://dx.doi.org/10.1145/0000000.0000000

Author's address: Jonathan W. Kelly, Department of Psychology, Iowa State University, W112 Lagomarcino Hall, 901 Stange Rd, Ames, IA, 50011-1041; email: jonkelly@iastate.edu; Lucia A. Cherep, email: lacherep@iastate.edu; Brenna Klesel, email: bklesel@iastate.edu; Zachary D. Siegel, email: zsiegel@iastate.edu; Seth George, email: sethg13@gmail.com.

Permission to make digital or hard copies of part or all of this work for personal or classroom use is granted without fee provided that copies are not made or distributed for profit or commercial advantage and that copies show this notice on the first page or initial screen of a display along with the full citation. Copyrights for components of this work owned by others than ACM must be honored. Abstracting with credit is permitted. To copy otherwise, to republish, to post on servers, to redistribute to lists, or to use any component of this work in other works requires prior specific permission and/or a fee. Permissions may be requested from Publications Dept., ACM, Inc., 2 Penn Plaza, Suite 701, New York, NY 10121-0701 USA, fax +1 (212) 869-0481, or permissions@acm.org.

1:2 • J.W. Kelly, L.A. Cherep, B. Klesel, Z.D. Siegel, and S. George

underperceive distance in virtual environments (VEs). A recent review [Renner et al. 2013] (also see Creem-Regehr et al. [2015a]) indicates that judgments of distance in VR are approximately 75% of the intended distance. In contrast, similar judgments of distance in the real world are typically around 100% of actual distance [Loomis and Knapp 2004].

Underperception of distance in VEs manifests in a wide variety of measures. Some of the measures that have been used to study underperception in VEs include verbal judgments of distance [Kelly et al. 2017; Mohler et al. 2006], blind-walking judgments of distance [Thompson et al. 2004], judgments of imagined walking time [Grechkin et al. 2010], and judgments of object size [Kelly et al. 2013].

The source of distance underperception in VR remains unclear. Past research has investigated whether underperception is caused by technical deficiencies associated with head-mounted displays (HMDs) and the VEs themselves. Deficiencies in graphics quality [Thompson et al. 2004], display field of view [Creem-Regehr et al. 2005; Knapp and Loomis 2004], and display weight and inertia [Willemsen et al. 2009] do not appear to be singularly responsible for underperception. Modern HMDs produce more accurate judgments of distance compared to older HMDs, but the problem of distance underperception generally persists even in modern displays [Creem-Regehr et al. 2015b; Li et al. 2014; Young et al. 2014].

1.1 Improving perceived distance in virtual environments

Considering the challenges of identifying deficiencies in virtual displays, several alternative approaches to studying distance underperception emphasize the interaction between the user and the VE. The current project focuses on two such approaches: providing the user with an opportunity to walk through the VE, referred to as walking interaction, and displaying a replica VE based on the real room in which the user is located.

Research on walking interaction indicates that a brief period of walking through the VE with continuous visual feedback leads to more accurate blind-walking distance judgments [Kelly et al. 2014; Richardson and Waller 2005; 2007; Waller and Richardson 2008], as well as verbal judgments [Mohler et al. 2006] and size judgments [Kelly et al. 2013]. Improvements in perceived space also generalize to other distances [Siegel and Kelly 2017] and other VEs [Siegel et al. 2017]. The fact that walking interaction generalizes to non-motoric judgments of visual space (especially size judgments and verbal judgment of distance) indicates that walking interaction does more than simply recalibrate the walking response. This prompted Kelly and colleagues to propose that walking through the VE with visual feedback causes rescaling of perceived space, such that objects actually appear farther away after interaction. Walking interaction improves size judgments, but to a lesser degree than blind-walking judgments (e.g., Siegel et al. [2017]). It is possible that the improvement in size judgments represents rescaling of perceived space while the improvement in blind-walking judgments is the result of rescaling plus recalibrating the walking response. On the other hand, it is also possible that it reflects a violation of the size-distance invariance hypothesis, which states that perceived size is directly related to perceived distance [Gilinsky 1951; Sedgewick 1986]. Some researchers have challenged the direct relationship between perceived distance and perceived size [Brenner and van Damme 1999; Epstein et al. 1961], whereas others report that the two measures to be highly correlated [Gogel et al. 1985; Hutchison and Loomis 2006: Kelly et al. 2013].

Displaying a VE that is a replica of the real room in which the user is located has been shown to produce relatively accurate blind-walking distance judgments [Interrante et al. 2006]. Furthermore, a replica VE has been used as a transitional environment leading to a novel VE via a virtual portal, and at least some of the benefits of the replica VE appear to be conveyed to the novel VE [Steinicke et al. 2009]. In a related study, distance judgments in a virtual replica of a real environment were found to be more accurate when preceded by distance judgments within the real environment upon which the

VE was based [Ziemer et al. 2009]. Collectively, these findings suggest that distance judgments in a VE are facilitated when the user is able to leverage knowledge about the real environment. One theory of space perception [Durgin and Li 2011] is that distance in the real world is also underperceived, but that humans are finely calibrated to the real environment and therefore produce relatively accurate action-based judgments of distance such as blind-walking. Distance may be underperceived in virtual environments relative to the real world due to lack of calibration, but a virtual replica may allow users to transfer previous calibration from the real world to the VE.

1.2 Interpreting past research

Although research on displaying a replica VE provides intriguing ideas about improving distance perception in VR, past research on the topic has lacked the necessary experimental controls to determine whether a replica VE truly improves perceived distance. A definitive test to determine whether a replica VE improves distance perception would be to compare performance across individuals who have or have not seen the real VE upon which the replica was based. Other methods that have been used in the past are subject to alternative explanations. For example, in the studies reported by Interrante et al. [2006], blind-walking judgments in the replica VE were relatively accurate (only 10% shorter than actual distance) and no different from real world performance. However, that study did not include a control condition in which participants did not preview (i.e., visually experience beforehand) the real environment prior to entering the replica VE, thereby raising the possibility of alternative explanations for the relatively accurate judgments. Distance underperception varies across display technology and VE characteristics [Creem-Regehr et al. 2015b]. It is therefore possible, if unlikely, that the same VE and equipment used by Interrante et al. [2006] would have produced identical performance even if participants had not previewed the real lab. For example, other researchers have reported accurate distance judgments in a photographic VE even when visual preview of the real environment was not allowed [Riecke et al. 2009], indicating that some systems, for mostly unknown reasons, can lead to accurate distance judgments. Although uncommon, reports of accurate distance judgments within a high-quality VE are not unprecedented and therefore the results of Interrante et al. [2006] should be considered with caution.

The studies reported by Steinicke et al. [2009] are also susceptible to alternative explanation. Those studies showed that experience with the replica VE improved subsequent distance judgments in a novel VE, compared to participants who did not experience the replica VE first. The novel VE was accessed by walking through a portal connecting it with the replica VE. However, after experiencing the replica VE, participants performed target-directed walking through the portal with visual feedback. That is, participants stood in the replica VE and walked with visual feedback through the portal until reaching an object in the novel VE, and they repeated this walk six times to establish the connection between the two VEs. It is well known that walking through a VE with visual feedback improves blindwalking distance judgments (e.g., [Waller and Richardson 2008]). Therefore, additional walking with feedback could account for the advantage when participants experienced the novel VE via the replica VE, compared to those who experienced the novel VE directly.

In the studies reported by Ziemer et al. [2009], half of participants in the VE condition had previously made blind-walking distance judgments in the real environment upon which the VE was based, and half had not. Although this seems like an ideal method for evaluating the benefit of a replica VE, the same regularly spaced target distances (20 feet, 40 feet, 60 feet, etc.) were used in both environments. Therefore, superior performance in the VE after experiencing the real environment could have been caused by memory for the distances tested rather than the replica VE per se. The study authors also favor this memory explanation, which seems even more plausible when considering that participants

1:4 • J.W. Kelly, L.A. Cherep, B. Klesel, Z.D. Siegel, and S. George

who experienced the VE before the real environment produced shorter real world distance judgments than those participants who had not previously experienced the VE.

1.3 Study overview

In light of the methodological concerns with past research using a replica VE, the current study experimentally evaluated whether a replica VE improves perceived distance. All participants performed judgments of perceived distance and perceived size in a virtual replica of the surrounding lab. Half of participants visually experienced the lab prior to experiencing the replica VE, whereas half of participants experienced the replica VE directly without visual preview of the real lab. In this way, any performance difference between groups can only be attributable to the prior experience in the real lab. To better contextualize any improvement caused by visual preview of the real environment, all participants completed both measures of perceived space before and after a brief period of walking interaction. This allowed for direct comparison of two different techniques designed to improve perceived distance in VR, as well as an initial exploration of the potential interactions between visual preview and walking interaction.

2. METHOD

2.1 Participants

Fifty-eight undergraduate students at Iowa State University participated in exchange for course credit. The preview and no preview conditions were run on alternating weeks during the semester, making assignment of participants to condition non-random. However, there is no reason to think that recruitment on alternating weeks had a systematic effect on the samples in each condition. The no preview condition included 28 participants and the preview condition included 30 participants. Gender was approximately balanced across conditions.

2.2 Stimuli and Design

VEs were displayed on an nVisor SX111 (NVIS, Reston, VA) HMD with $102^{\circ} \times 64^{\circ}$ field of view. Graphics were rendered stereoscopically using Vizard software (WorldViz, Santa Barbara, CA) generated on a Windows 7 computer with Intel Core2 Quad processors and Nvidia GeForce GTX 285 graphics card. Head position was tracked optically in three dimensions (PPTX4 by WorldViz) and head orientation was tracked using a three-axis orientation sensor (InertiaCube2+ by Intersense). Graphics displayed in the HMD were dynamically updated based on sensed head position and orientation.

The VE (Figure 1) was a replica of the lab where testing occurred, and was created based on measurements of the actual lab space with photographs applied to a 3D model. The VE included all major pieces of furniture present in the actual lab (e.g., tables, chairs, computers, and cabinets, plus minor objects such as light switches and door knobs). A black and white soccer ball (see Figure 1, center) of adjustable size was used for the resizing task. A blue vertical post (0.1 m radius and scaled to participant eye height; see Figure 1, right) was used as the target for the blind-walking task and the walking interaction task.

All participants completed separate blocks of resizing and blind-walking judgments before and after a period of walking interaction. Task order was counterbalanced, such that half of participants completed blind-walking before resizing and half completed resizing before blind-walking. Each judgment block contained 15 trials corresponding to three repetitions of five egocentric distances (1, 2, 3, 4, and 5 m) in a random sequence. Walking interaction entailed 18 trials, each a unique distance between .75 and 5 m in increments of .25 m, in a random sequence.



Fig. 1. Images of the real and virtual lab taken from the viewing location. Left: Real lab environment. Middle: Virtual lab with soccer ball used for resizing task. Right: Virtual lab with blue vertical post used for blind walking task and walking interaction.

The primary independent variables were whether or not the participant visually previewed the real lab before entering the VE, and whether judgments were made before or after walking interaction.

2.3 Procedure

In the preview condition, the participant walked into the lab and was seated in chair that provided a full view of the lab. While seated, the participant completed the informed consent process and was then provided with verbal instructions on the blind-walking task and the resizing task. When explaining the resizing task, the experimenter showed the participant a real soccer ball and gave the participant an opportunity to hold the ball in order to become familiar with its true size. Next, the participant stood and the experimenter led the participant to the viewing location, which was marked by a rubber pad that could be felt when standing on it. Once in position, the participant donned the HMD and adjusted it to fit tightly yet comfortably before the room lights were turned off.

The procedure was similar for the no preview condition, except that the participant stood behind a black curtain that partitioned a small area between the hallway and the lab. The curtain blocked the participant's view of the lab, a small carpet hid the lab floor pattern, and the hallway door remained visible and open to allow light to come in. The lights inside the lab were turned off to further prevent accidental viewing of the lab. The consent process and instructions were identical to the preview condition except that they occurred in the partitioned space behind the curtain. The participant then donned and adjusted the HMD while still standing behind the curtain. Once the HMD was in place, the curtain was removed, the hallway door was closed, and the participant was guided by the experimenter to the viewing location.

For the resizing task, the participant was instructed to use joystick buttons to adjust the size of the virtual soccer ball until it appeared to be the same size as an actual soccer ball. Four buttons provided the ability to resize the soccer ball larger or smaller by 1% and 10% increments. The initial size of the soccer ball on each trial was randomly selected from a range of 30% to 300% of actual size in increments of 10%. The participant then adjusted the size of the soccer ball until satisfied, at which point the experimenter pressed a key to record the response and advance to the next trial.

For the blind-walking task, the participant viewed the blue post for five seconds, after which the entire VE disappeared and was replaced with a uniform light blue display. The participant was then asked to walk to the location of the blue post. The participant verbally indicated when he/she had reached the intended location and the experimenter pressed a key to record the response. A gray line then appeared on the ground plane, guiding the participant back to the viewing location. The experimenter assisted with finding the viewing location when necessary.

J.W. Kelly, L.A. Cherep, B. Klesel, Z.D. Siegel, and S. George 1:6



Fig. 2. Size judgment bias as a function of initial ball size, illustrating the anchoring effect.

For walking interaction, the vertical blue post appeared within the VE. The participant then walked toward the blue post with continuous visual feedback. Upon reaching the blue post location, the VE disappeared and the same gray line used in blind walking trials appeared to guide the participant back to the viewing location.

3. **ANALYSIS**

Size judgments showed evidence of anchoring, such that adjusted ball size was biased toward the initial ball size, which varied randomly across trials. To correct for this bias, a two-step process was used to describe the anchoring effect and then to remove the bias prior to analysis (the same process was used by [Siegel and Kelly 2017]). To describe the anchoring bias, judged size was expressed as a ratio of judged-to-correct size. The mean of that ratio (averaged across all size judgments) was subtracted from each individual size judgment and regressed against initial ball size. Figure 2 shows that this relationship was well-described by a linear equation (R^2 =.904). As seen in Figure 2, judged ball size was anchored by (i.e., biased toward) initial ball size on a given trial. To compensate for anchoring, the initial ball size on a given trial was passed through the linear equation relating initial ball size to judgment bias in order to calculate presumed bias on that trial. The resulting bias value was then subtracted from the judged ball size on that trial.

Size judgments and blind-walking judgments were converted into ratios of judged-to-actual distance prior to analysis. Prior to calculating judgment ratios, size judgments had to be converted into judgments of perceived distance. Following past work involving size judgments as a measure of perceived distance [Gogel et al. 1985; Hutchison and Loomis 2006; Kelly et al. 2013; Siegel and Kelly 2017; Siegel et al. 2017], the size-distance invariance hypothesis was used to compute perceived distance (D') based on perceived size (S') and object visual angle (α):

$$D' = \frac{S'}{\tan(\alpha)}.\tag{1}$$

Perceived ball size (S') was always 22 cm, because the participant's task was to adjust the ball until it appeared to be the size of a real soccer ball (which is 22 cm in diameter). Visual angle (α) was based on the adjusted ball size (S) and the actual distance from the participant to the ball (D):



Fig. 3. Blind-walking distance judgment ratios. Error bars represent +/- 1 SEM.

$$\alpha = atan(\frac{S}{D}). \tag{2}$$

The resulting value for α was then used in Equation 1 to calculate perceived distance.

4. RESULTS

Blind-walking distance judgment ratios are shown in Figure 3. Ratios were analyzed in a $2 \times 2 \times 2$ mixed ANOVA with terms for visual preview (preview vs. no preview), walking interaction (pre- vs. post-interaction), and order (blind-walking first or resizing first). Significant main effects of visual preview, F(1,54)=4.096, p=.048, $\eta_p^2=.071$, and walking interaction, F(1,54)=70.115, p<.001, $\eta_p^2=.565$, were qualified by a significant interaction between visual preview and walking interaction, F(1,54)=13.181, p=.001, $\eta_p^2=.196$.

Visual preview led to significantly more accurate pre-interaction blind-walking judgments (M=0.834, SE=0.028) compared to the no preview condition (M=0.711, SE=0.025), t(56)=3.265, p=.002. Walking interaction led to significantly more accurate post-interaction blind-walking judgments for both the preview condition, t(29)=3.70, p=.001 and the no preview condition, t(27)=7.74, p<.001. After walking interaction, blind-walking judgments did not differ between the preview (M=0.919, SE=0.018) and no preview (M=0.925, SE=0.119) conditions, t(56)=.234, p=.816. Although there was no significant difference in post-interaction blind walking between the preview and no preview conditions, it is difficult to make theoretical conclusions based on non-significant null-hypothesis tests. Therefore, we also conducted Bayesian analysis, which revealed that the odds in favor of the null were 6.14:1, providing substantial evidence in favor of the null [Gallistel 2009].

Blind-walking judgments were more accurate after compared to before walking interaction. However, walking interaction was confounded with experience with the blind-walking task. That is, the more accurate post-interaction judgments could have been caused by the walking interaction or by the 15 pre-interaction judgments made prior to the walking interaction. If practice with the blind-walking task caused more accurate blind-walking judgments, then the slope relating trial number (1-15) to distance judgment ratio should be positive, reflecting improved performance as a function of progression through the 15-trial block. To evaluate this, slope of the best-fitting line relating judgment ratio to





Fig. 4. Blind-walking distance judgment ratios and best-fitting lines as a function of within-block trial.

trial number was calculated separately for each participant in each of the four combinations of walking interaction (pre- vs. post-interaction) and visual preview (preview vs. no preview). Slopes were then compared to zero using one-sample t-tests (no statistical correction was applied for the multiple comparisons). Slopes were not different from zero (p>.41). Relevant data are shown as scatterplots with best-fitting lines in Figure 4.

Size judgment ratios are shown in Figure 5. Ratios were analyzed in a $2 \times 2 \times 2$ mixed ANOVA with terms for visual preview (preview vs. no preview), walking interaction (pre- vs. post-interaction), and order (blind-walking first or resizing first). Only the main effect of walking interaction was statistically significant, F(1,54)=19.86, p<.001, $\eta_p^2=.269$, reflecting the fact that size ratios were larger (more accurate) after walking interaction (M=0.894, SE=0.014) than before walking interaction (M=0.863, SE=0.012). In the preview condition, judged size significantly improved from pre-interaction (M=0.844, SE=0.014) to post-interaction (M=0.870, SE=0.015), t(29)=2.78, p=.009. In the no preview condition, judged size significantly improved from pre-interaction (M=0.882, SE=0.019) to post-interaction (M=0.918, SE=0.023, t(27)=3.59, p=.001.



Fig. 5. Size judgment ratios. Error bars represent +/- 1 SEM.

5. DISCUSSION

In a tightly controlled experiment, blind-walking distance judgments in a replica VE were better after visual preview of the real environment upon which the replica was based. This finding confirms past work suggesting that a virtual replica produces relatively accurate distance judgments [Interrante et al. 2006; Steinicke et al. 2009], and builds on that work by accounting for potential methodological concerns.

Blind-walking judgments were affected by visual preview, but size judgments were not. This result appears to contradict the size-distance invariance hypothesis (Equation 1). In particular, change in perceived distance (assessed by blind-walking) caused by visual preview did not lead to change in perceived size. Other researchers have previously questioned the size-distance invariance hypothesis [Brenner and van Damme 1999; Epstein et al. 1961]. For example, Brenner and van Damme [1999] found that judgments of perceived size, shape, and distance were largely independent of one another. After completion of the current experiment, participants were asked to report strategies they used when completing the two tasks. Fourteen participants (24%) reported relying on room-based cues, especially nearby virtual objects, when making size judgments. None mentioned such a strategy when making blind-walking judgments. Likewise, 46 participants (79%) reported using a step-counting strategy and 3 participants (5%) reported using a tile-counting strategy when making blind-walking judgments, but none reported such strategies when making size judgments. It is therefore possible that participants relied on different sets of cues when making the two judgment types, which could explain why judged size and distance were not similarly affected by visual preview. A similar theory was proposed by Kunz et al. [2009] (also see Kelly et al. [2017]) to explain why manipulation of graphics quality affected verbal judgments of distance but not blind-walking judgments of distance. Although numerous participants reported step-counting strategies for the blind-walking task, it is unclear whether or how this strategy would succeed in this experiment. The only opportunity for feedback came during the walking interaction, but walked distances during testing were 1, 2, 3, 4, and 5 meters, whereas walked distances during walking interaction ranged from .75-5 meters in equal small increments. In this way, most distances experienced during walking interaction were not included during pre- and post-interaction test blocks. For a step-counting strategy to be effective, a participant would have needed to identify the number of steps required on interaction trials with the same distance used

1:10 • J.W. Kelly, L.A. Cherep, B. Klesel, Z.D. Siegel, and S. George

on blind-walking trials, and this strategy seems cumbersome and unlikely. It's therefore unclear how participants actually deployed a step-counting strategy, and what effect such a strategy had on their responses. Future work using indirect blind-walking judgments could circumvent this issue, since step counting would not help in that task.

The current results do not directly address the reason why visual preview led to more accurate blind-walking judgments. One possible explanation is that users enter VEs in a relatively uncalibrated state, but that experiencing a replica VE allows users to more easily apply calibrations acquired in the real environment. Such calibrations reflect perception-action couplings, and thus affect blind-walking judgments of distance but not size judgments. Another possible explanation is that experiencing a virtual replica causes users to focus on specific cues that would facilitate performance of the same task in the real environment. To that end, one possible alternative explanation for the effect of visual preview in this experiment is that participants in the preview condition were instructed on the blindwalking and resizing tasks while standing in a medium-sized, cue-rich environment (i.e., the real lab), whereas participants in the no preview condition stood in a small curtained space that contained relatively fewer cues. It is possible that the small and sparse environment used for training in the no preview condition led participants to focus on a different set of distance cues than those in the preview condition. Future work could include a no preview condition in which participants are trained in a visually rich environment distinct from the lab room (e.g., training could occur in a neighboring room instead of the curtained space). Unlike the study by Ziemer et al. [2009] in which participants showed improved blind-walking judgments after making similar judgments in the real world, the current study only exposed participants passively to the real lab, and no blind-walking trials were conducted in the real environment. Therefore, the effect of visual preview in the current study could not be due to memory for walked distances experienced in the real space, but is more likely due to memory for the real space per se.

The walking interaction task significantly improved both judged distance and judged size. However, the effect of walking interaction on judged size was rather small compared to the effect on judged distance, replicating past work [Kelly et al. 2013; Siegel and Kelly 2017]. The effect of visual preview on blind-walking judgments disappeared after walking interaction, and post-interaction blind-walking judgments were better than pre-interaction judgments even for participants in the preview condition. These data suggest that walking interaction may be more useful than visual preview as a method for improving perceived space in a VE. Walking interaction, as compared to visual preview, resulted in a numerically larger improvement in judged distance and also resulted in an improvement in judged size. Furthermore, walking interaction is effective in VEs that are distinct from the real environment (e.g., [Siegel and Kelly 2017]).

When choosing the appropriate method to use for improving perceived distance, it is important to consider the potential challenges associated with each method. There are situations in which walking interaction is impractical due to real world space constraints. For example, lack of a sufficiently large positional tracking space would limit walking interaction. Using a replica VE presents its own challenges, primarily the time and expertise required to create a 3D replica of the surrounding real environment.

Research with more modern consumer-oriented HMDs (e.g., the Oculus Rift and HTC Vive) indicates that distance underperception is less of a problem than in older displays [Creem-Regehr et al. 2015b; Kelly et al. 2017; Li et al. 2014; Li et al. 2015; Young et al. 2014]. However, distance perception in some of those displays still indicates deficiencies that can be improved through walking interaction [Kelly et al. 2017]. Presumably a replica VE would also benefit distance perception in modern HMDs, but further research is needed.

To summarize, judgments of distance in a replica VE were more accurate after visual preview of the real environment upon which the replica was based. However, size judgments were unaffected by visual preview. Walking interaction resulted in more accurate distance judgments and size judgments, although the effect on distance judgments was more pronounced. Neither walking interaction nor visual preview completely solved underperception, as judgments of size and distance did not reach veridical performance in any condition.

REFERENCES

E. Brenner and W. J. van Damme. 1999. Perceived distance, shape and size. Vision Research 39, 5 (1999), 975-986.

- S. H. Creem-Regehr, J. K. Stefanucci, and W. B. Thompson. 2015a. Perceiving absolute scale in virtual environments: How theory and application have mutually informed the role of body-based perception. In *The Psychology of Learning and Motivation*, B. Ross (Ed.). Academic Press: Elsevier Inc., Waltham, MA, 195–224.
- S. H. Creem-Regehr, J. K. Stefanucci, W. B. Thompson, N. Nash, and M. McCardell. 2015b. Egocentric distance perception in the occulus rift (DK2). In *Proceedings of the ACM Symposium on Applied Perception*. ACM, New York City, NY, 47–50.
- S. H. Creem-Regehr, P. Willemsen, A. A. Gooch, and W. B. Thompson. 2005. The influence of restricted viewing conditions on egocentric distance perception: Implications for real and virtual indoor environments. *Perception* 34, 2 (2005), 191–204.
- F. H. Durgin and Z. Li. 2011. Perceptual scale expansion: An efficient angular coding strategy for locomotor space. Attention, Perception, Psychophysics 73 (2011), 1856–1870.
- W. Epstein, J. Park, and A. Casey. 1961. The current status of the size-distance hypotheses. *Psychological Bulletin* 58, 6 (1961), 491–514.
- C. R. Gallistel. 2009. The importance of proving the null. Psychological Review 116 (2009), 439-453.
- A. S. Gilinsky. 1951. Perceived size and distance in visual space. Psychological Review 58, 6 (1951), 460-482.
- W. C. Gogel, J. M. Loomis, N. J. Newman, and T. J. Sharkey. 1985. Agreement between indirect measures of perceived distance. *Attention, Perception, Psychophysics* 37, 1 (1985), 17–27.
- T. Y. Grechkin, T. D. Nguyen, J. M. Plumert, J. F. Cremer, and J. K. Kearney. 2010. How does presentation method and measurement protocol affect distance estimation in real and virtual environments? *ACM Transactions on Applied Perception* 7, 4 (2010), 26.
- J. J. Hutchison and J. M. Loomis. 2006. Does energy expenditure affect the perception of egocentric distance? A failure to replicate Experiment 1 of Proffitt, Stefanucci, Banton, and Epstein (2003). The Spanish Journal of Psychology 9 (2006), 332-339.
- V. Interrante, L. Anderson, and B. Ries. 2006. Distance perception in immersive virtual environments, revisited. In *Proceedings* of the IEEE Virtual Reality Conference. IEEE Computer Society, Washington, D.C.
- J. W. Kelly, L. A. Cherep, and Z. D. Siegel. 2017. Perceived Space in the HTC Vive. ACM Transactions on Applied Perception 15, 1 (2017), 2:1–16.
- J. W. Kelly, L. S. Donaldson, L. A. Sjolund, and J. B. Freiberg. 2013. More than just perception-action recalibration: Walking through a virtual environment causes rescaling of perceived space. *Attention, Perception, Psychophysics* 75 (2013), 1473–1485.
- J. W. Kelly, W. W. Hammel, Z. D. Siegel, and L. A. Sjolund. 2014. Recalibration of perceived distance in virtual environments occurs rapidly and transfers asymmetrically across scale. Recalibration of perceived distance in virtual environments occurs rapidly and transfers asymmetrically across scale. *IEEE Transactions on Visualization and Computer Graphics* 20, 4 (2014), 588–595.
- J. M. Knapp and J. M. Loomis. 2004. Limited field of view of head-mounted displays is not the cause of distance underestimation in virtual environments. *Presence: Teleoperators and Virtual Environments* 13, 5 (2004), 572–577.
- B. R. Kunz, L. Wouters, D. Smith, W. B. Thompson, and S. H. Creem-Regehr. 2009. Revisiting the effect of quality of graphics on distance judgments in virtual environments: A comparison of verbal reports and blind walking. *Attention, Perception, Psychophysics* 71, 6 (2009), 1284–1293.
- B. Li, R. Zhang, and S. Kuhl. 2014. Minication affects action-based distance judgments in oculus rift HMDs. In Proceedings of the ACM Symposium on Applied Perception. ACM, New York City, NY, 91–94.
- B. Li, R. Zhang, A. Nordman, and S. Kuhl. 2015. The effects of minification and display field of view on distance judgments in real and HMD-based environments. In *Proceedings of the ACM Symposium on Applied Perception*. ACM, New York City, NY, 55–58.
- J. M. Loomis and J. M. Knapp. 2004. Visual perception of egocentric distance in real and virtual environments. In Virtual and Adaptive Environments, L. J. Hettinger and M. W. Haas (Eds.). Erlbaum, Mahwah, NJ, 21–46.

1:12 • J.W. Kelly, L.A. Cherep, B. Klesel, Z.D. Siegel, and S. George

- B. J. Mohler, S. H. Creem-Regehr, and W. B. Thompson. 2006. The influence of feedback on egocentric distance judgments in real and virtual environments.. In *Proceedings of the ACM Symposium on Applied Perception*. ACM, New York City, NY, 9–14.
- S. Renner, B. M. Velichkovsky, and R. Helmert. 2013. The perception of egocentric distances in virtual environments: a review. ACM Computer Surveys 46 (2013), 23:1–40.
- A. R. Richardson and D. Waller. 2005. The effect of feedback training on distance estimation in virtual environments. Applied Cognitive Psychology 19, 8 (2005), 1089–1108.
- A. R. Richardson and D. Waller. 2007. Interaction with an immersive virtual environment corrects users' distance estimates. Human Factors: The Journal of the Human Factors and Ergonomics Society 49, 3 (2007), 507–517.
- B. E. Riecke, P. A. Behbahani, and C. D. Shaw. 2009. Display size does not affect egocentric distance perception of naturalistic stimuli. In *Proceedings of the 6th Symposium on Applied Perception in Graphics and Visualization*. ACM, New York, NY, 15–18.
- H. A. Sedgewick. 1986. Space perception. In Handbook of Perception and Human Performance (Sensory processes and perception), J. P. Thomas K. R. Boff, L. Kaufman (Ed.). Wiley, New York, NY, 21.1–21.57.
- Z. D. Siegel and J. W. Kelly. 2017. Walking through a virtual environment improves perceived size within and beyond the walked space. *Attention, Perception, Psychophysics* 79, 1 (2017), 39–44.
- Z. D. Siegel, J. W. Kelly, and L. A. Cherep. 2017. Rescaling of perceived space transfers across virtual environments. *Journal of Experimental Psychology: Human Perception and Performance* (2017).
- F. Steinicke, G. Bruder, K. Hinrichs, M. Lappe, B. Ries, and V. Interrante. 2009. Transitional environments enhance distance perception in immersive virtual reality systems. In *Proceedings of the 6th Symposium on Applied Perception in Graphics and Visualization*. ACM, New York, NY.
- W. B. Thompson, P. Willemsen, A. A. Gooch, S. H. Creem-Regehr, J. M. Loomis, and A. C. Beall. 2004. Does the quality of the computer graphics matter when judging distance in visually immersive environments? *Presence: Teleoperators Virtual Environments* 13 (2004), 560–571.
- D. Waller and A. R. Richardson. 2008. Correcting distance estimates by interacting with immersive virtual environments: Effects of task and available sensory information. *Journal of Experimental Psychology: Applied* 14 (2008), 67–72.
- P. Willemsen, M. B. Colton, S. H. Creem-Regehr, and W. B. Thompson. 2009. The effects of head-mounted display mechanical properties and field of view on distance judgments in virtual environments. *ACM Transactions on Applied Perception* 6, 2 (2009), 8:1–14.
- M. K. Young, G. B. Gaylor, S. M. Andrus, and B. Bodenheimer. 2014. A comparison of two cost-differentiated virtual reality systems for perception and action tasks. In *Proceedings of the ACM Symposium on Applied Perception*. ACM, New York City, NY, 83–90.
- C. J. Ziemer, J. M. Plumert, J. F. Cremer, and J. K. Kearney. 2009. Estimating distance in real and virtual environments: Does order make a difference? *Attention, Perception, Psychophysics* 71 (2009), 1095–1106.

Received June 2017; revised September 2017; accepted September 2017