Perceived Space in the HTC Vive

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Underperception of egocentric distance in virtual reality has been a persistent concern for almost 20 years. Modern head-mounted displays (HMDs) appear to have begun to ameliorate underperception. The current study examined several aspects of perceived space in the HTC Vive. Blind-walking distance judgments, verbal distance judgments, and size judgments were measured in two distinct virtual environments (VEs)—a high-quality replica of a real classroom and an empty grass field—as well as the real classroom upon which the classroom VE was modeled. A brief walking interaction was also examined as an intervention for improving anticipated underperception in the VEs. Results from the Vive were compared to existing data using two older HMDs (nVisor SX111 and ST50). Blind-walking judgments were more accurate in the Vive compared to the older displays, and did not differ substantially from the real world nor across VEs. Size judgments were more accurate in the classroom VE than the grass VE and in the Vive compared to the older displays. Verbal judgments were significantly smaller in the classroom VE compared to the real classroom and did not significantly differ across VEs. Blind-walking and size judgments were more accurate after walking interaction, but verbal judgments were unaffected. The results indicate that underperception of distance in the HTC Vive is less than in older displays but has not yet been completely resolved. With more accurate space perception afforded by modern HMDs, alternative methods for improving judgments of perceived space—such as walking interaction—may no longer be necessary.

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1 INTRODUCTION

Virtual reality (VR) systems are valuable instruments that have been utilized in industry (Berg and Vance 2017), education (Winn et al. 1999), and entertainment (Badique et al. 2002). For VR systems to be effective, it is

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important that these systems accurately represent the intended environment. A recent review of 33 independent studies found that users, on average, judge distances in virtual environments (VEs) to be only 73% of intended distance (Renner et al. 2013) (also see Creem-Regehr et al. (2015a)). In contrast, similar distance judgments in real environments are often 100% of actual distance (Loomis and Knapp 2004). Recently, the VR industry has experienced unprecedented growth tied to the development and mass-production of new head-mounted displays (HMDs) aimed at video game consumers. The current project examined multiple aspects of perceived space in the HTC Vive, one of the most popular modern HMDs, by comparing multiple perceptual judgments in the Vive to real-world judgments as well as previous published and unpublished data using two older HMDs. Furthermore, this project evaluated whether a walking interaction task known to improve judged distance in VEs displayed on older HMDs (Kelly et al. 2013, 2014; Mohler et al. 2006; Richardson and Waller 2005, 2007; Waller and Richardson 2008) would also improve judgments of perceived space in the Vive.

Underperception of distance in virtual reality was documented almost 20 years ago (Witmer and Sadowski Jr. 1998), yet the phenomenon persists and remains poorly understood. One common approach to understanding and potentially resolving this persistent problem is to identify which perceptual cue(s) to distance are missing or deficient in the VE compared to the real world. For example, researchers have investigated whether underperception is caused by low-quality graphics (Thompson et al. 2004), incorrect stereo cues (Willemsen et al. 2008), limited display field-of-view (Creem-Regehr et al. 2005; Knapp and Loomis 2004), or display weight and inertia (Willemsen et al. 2009). However, none of those deficiencies appears to be singularly responsible for underperception of distance.

1.1 Measures of Perceived Space

Common measures of perceived space include blind-walking (Messing and Durgin 2005; Thompson et al. 2004) and blind-throwing (Rieser et al. 1995; Sahm et al. 2005) to previously viewed targets, time-to-walk judgments (Plumert et al. 2005; Grechkin et al. 2010), verbal reports of distance (Kelly et al. 2004; Knapp and Loomis 2004; Mohler et al. 2006), and judgments of size (Hutchison and Loomis 2006; Kelly et al. 2013; Siegel and Kelly 2017). Although most investigations of perceived space use a single dependent measure, it appears that not all dependent measures are equally influenced by manipulations of the VE. In one study (Kunz et al. 2009), participants viewed a virtual environment created with high-quality photorealistic graphics or low-quality repeating textures. Blind-walking distance judgments exhibited the same degree of underperception, regardless of graphics quality, whereas verbal distance judgments exhibited greater underperception in the low-quality VE compared to the high-quality VE (though underperception occurred in both VEs). It is unclear exactly why verbal but not walking judgments of distance were affected by graphics quality. One possibility that the authors considered is that different judgments rely on different perceptual representations, which differ based on the perceptual cues that are attended to when creating the representation. For example, angle of declination from the horizon is thought to be particularly important for blind walking judgments (Ooi et al. 2001). Verbal judgments also depend on the angle of declination but might additionally be affected by contextual cues that could provide necessary scale for the units of measurement (feet, meters, etc.) used in the participant's response. Using perceived size as a dependent measure, Murgia and Sharkey (2009) found that judgments were smaller in a cue-impoverished VE compared to a VE with more pictorial depth cues, pointing to the possibility that size judgments, like verbal judgments of distance, are also subject to context effects. To summarize, considering multiple dependent measures can provide additional insights into users underlying perceptual experience when viewing a VE.

1.2 Effects of Feedback

Recent studies have shown that walking through a VE with visual feedback improves subsequent blind-walking distance judgments (Kelly et al. 2013, 2014; Mohler et al. 2006; Richardson and Waller 2005, 2007; Waller and Richardson 2008). In one study (Waller and Richardson 2008), participants made blind-walking judgments in response to virtual objects placed 1–4m away in an otherwise sparse virtual environment. After completing the distance judgments, participants were given an opportunity to walk to the same virtual object at similar distances with continuous visual feedback (herein referred to as walking interaction) before making additional blind-walking distance judgments. Pre-interaction distance judgments exhibited underperception typical of studies in VR, whereas post-interaction distance judgments were quite accurate. This effect has been demonstrated several times, and although post-interaction judgments typically show improvement, they do not always reach veridical performance (e.g., Kelly et al. (2014)). Surprisingly, the improvement in post-interaction blind-walking judgments is not entirely due to recalibration of the visual-motor system during walking interaction, as walking interaction has also been shown to cause an increase in verbal judgments of distance (Mohler et al. 2006) as well as judgments of object size (Kelly et al. 2013; Siegel and Kelly 2017; Siegel et al. 2017). An increase in perceived size is considered to be a result of an increase in perceived distance, as described by the size-distance invariance hypothesis (Sedgewick 1986). This has led Kelly and colleagues to propose that walking interaction also causes rescaling of perceived space, whereby distances are perceived as farther away and objects are perceived as larger after walking interaction.

1.3 Perceived Space in Newer HMDs

Recent research using newer HMDs marketed toward video game players indicates that distance perception in VR may be improving when compared to older displays. Creem-Regehr et al. (2015b) examined distance perception in the Oculus Rift (DK2), a 2014 development edition of the newer Oculus display, and compared it to distance perception in the nVisor SX60, an older high-end display intended for research and military use, released in 2007. Blind-walking judgments in high-quality VEs (indoor and outdoor) revealed that participants were more accurate when using the Rift DK2 than the SX60. Although a real-world comparison was not included, performance in the Rift DK2 was approximately 90% of intended distance in the indoor VE and 75% in the outdoor VE, both of which are shy of the near-100% accuracy typical of blind-walking judgments in the real world under full-cue viewing (Loomis and Knapp 2004). Another study using the DK2 with an indoor VE also reported that blind walking judgments were approximately 90% of intended distance (Li et al. 2015). In contrast, two other studies have reported that distance judgments when using the Oculus Rift (DK1), a 2013 development edition, are near 100% of actual distance (Li et al. 2014; Young et al. 2014). It is unclear why distance judgments when using the Rift DK1 would be better than those using the more recent DK2, but there were several significant hardware changes that occurred between the two development kits. There are also methodological differences between labs that could prove important, but the distinction between performance in the DK1 and DK2 has also been reported within a single lab (Li et al. 2014, 2015).

1.4 Study Goals and Predictions

The purpose of this study was to investigate space perception in the HTC Vive. To date, there is no published research documenting the extent to which the Vive supports accurate perception of space. Of particular interest was to (1) compare perceived distance in the Vive and the real world, (2) compare perceived distance in the Vive and older HMDs, and (3) evaluate whether potential underperception in the Vive could be ameliorated through walking interaction. To address these issues thoroughly, this study employed three measures of perceived space: verbal distance judgments, blind-walking distance judgments, and size judgments, which were used to infer perceived distance. Furthermore, two distinct VEs were selected for this experiment: a high-quality classroom modeled after a real classroom on campus and an empty grass field. Blind-walking and size judgments made in the grass VE were compared with previously published and unpublished data using the same VE with two older displays, the nVisor ST50 (Kelly et al. 2014) and the nVisor SX111 (Siegel and Kelly 2017). No new data were collected using the older displays. Comparable verbal judgments using older displays were unavailable, and so no comparison was made. Responses made in the classroom VE were compared to responses made in the real classroom, but only verbal distance judgments and blind-walking distance judgments were collected in the real classroom. Last, all judgments in the two VEs were made before and after a brief walking interaction to evaluate the effectiveness of this protocol when using the Vive.

Given the relatively large number of independent and dependent variables, the primary experimental predictions are described separately below.

(1) Blind-walking and size judgments in the grass VE viewed through the Vive were expected to be more accurate compared to older displays. This prediction was based on past work reporting superior blind-walking judgments in the Oculus development editions compared to older displays (Creem-Regehr et al. 2015b; Li et al. 2014; Young et al. 2014).
(2) It was unknown whether verbal and blind-walking judgments in the classroom VE would be comparable to performance in the real classroom, as there is no published comparison between judgments made in the real world and in a matched VE using a more modern, consumer-oriented HMD.
(3) Blind-walking distance judgments were expected to be equivalent in the classroom and grass VEs, but verbal and size judgments were expected to be more accurate in the classroom than the grass VE. This prediction was based on the finding that verbal report, but not blind walking, is affected by manipulation of graphics quality (Kunz et al. 2009), and the finding that judged size is affected by environmental context (Murgia and Sharkey 2009).
(4) All three measures of perceived space in the Vive were expected to be more accurate after walking interaction, but only if underperception occurred prior to interaction. This prediction was based on past work, indicating that blind-walking judgments (Waller and Richardson 2008), verbal judgments (Mohler et al. 2006), and size judgments (Kelly et al. 2013) improve after feedback received during walking interaction.

2 METHOD

2.1 Participants

Seventy-six undergraduate students from Iowa State University participated in exchange for course credit. Twenty-eight participants experienced the classroom VE, 26 experienced the grass VE, and 22 experienced the real-world classroom. Gender was approximately balanced across conditions.

2.2 Stimuli and Design

VEs were displayed on an HTC Vive HMD, and graphics displayed in the Vive were generated on a Windows 10 computer with an Intel 6700K processor and Nvidia GeForce GTX 1070 graphics card. Head position was tracked in three dimensions and orientation was tracked in three dimensions using the Lighthouse tracking system sold with the Vive. Vizard (Santa Barbara, CA) software was used to display projectively correct stereoscopic images of the VE based on sensed head position and orientation.

The classroom VE (Figure 1) was a replica of a real classroom and included photographs of the real classroom applied to a 3D model that was created based on careful measurement of the real space. The VE included several pieces of furniture present in the real classroom, such as tables and chairs and a media console for classroom presentations, and all were scaled based on the sizes of real objects in the classroom. The grass VE was an infinite ground plane with a grass texture and gray sky (Figure 1). An orange traffic cone was used as the target for blind-walking distance judgments and verbal distance judgments. A soccer ball of adjustable size was used for size judgments. A blue vertical post (0.1m radius and scaled to participants' eye height) was used as the target for the walking interaction task. One hundred gray vertical posts (2m tall, 0.05m radius) were scattered within the VE during walking interaction to provide additional optic flow. The same approach has been used in other studies involving walking interaction (Kelly et al. 2013; Richardson and Waller 2005; Siegel and Kelly 2017; Waller and Richardson 2008).

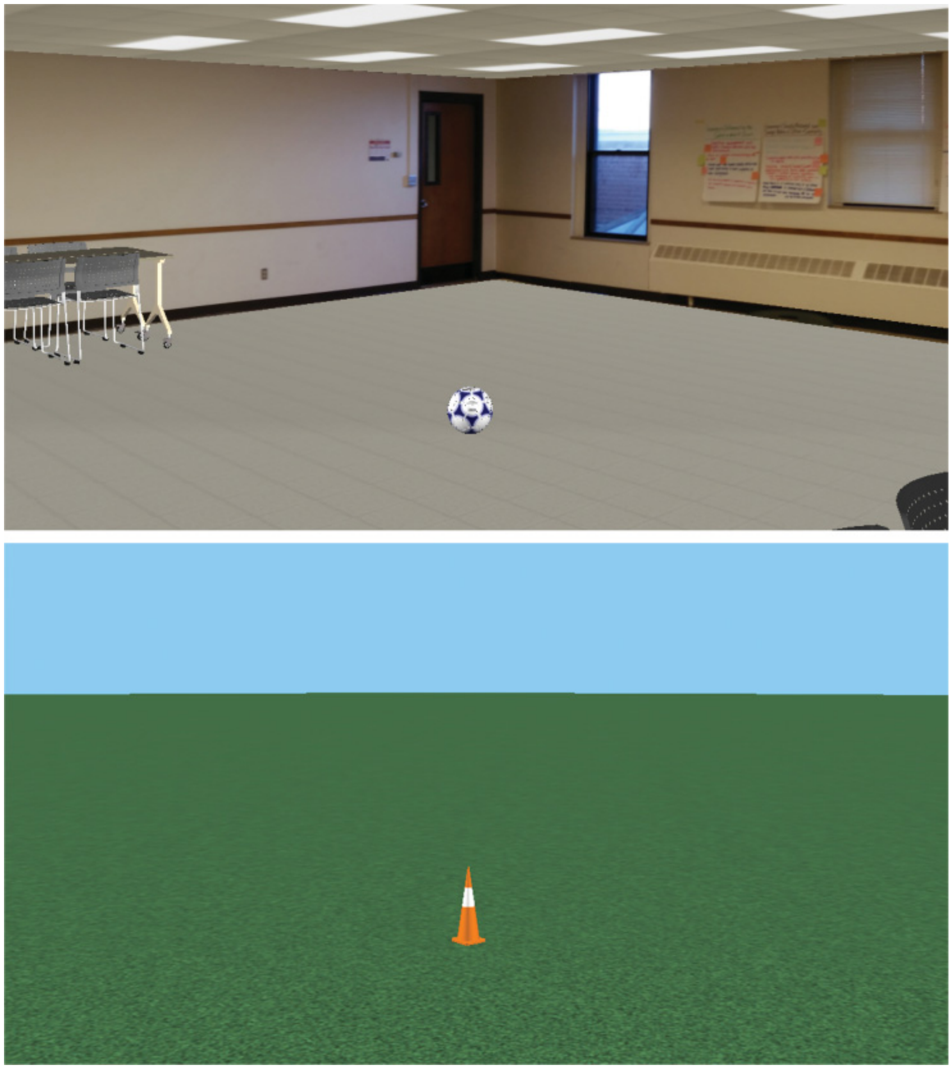

Fig. 1. Screen shots of the classroom VE and grass VE. Also pictured are the soccer ball used for size judgments and the traffic cone used for blind-walking and verbal distance judgments.

The Vive system includes a "chaperone" that consists of lines in the virtual space that represent boundaries of the physical environment, and they appear when the HMD approaches the room boundaries. Three steps were taken to avoid intrusion of the chaperone system on the current study. First, the chaperone space was set to the same size as the physical room. In this way, participants walking to a visible target during the walking interaction would never get near enough to the chaperone borders for it to become visible. Second, the chaperone line color was set to the background color in the HMD, such that if the chaperone lines were activated on a blind-walking trial they would not be visible to the participant. Third, the chaperone settings were changed such that the boundaries were displayed as only a single line on the floor, rather than the default display of a line grid representing wall and floor surfaces.

Considering the effects of display minification and magnification on judged distance (Li et al. 2014, 2015), we followed the procedures of Li et al. (2014) to determine whether the Vive HMD produced such distortion. Two vertical pieces of tape were placed on a laboratory wall, separated by 0.9m. Two vertical posts of the same width as the tape and at the same locations as the tape were placed in the virtual world. When standing at distances of 1 and 2m from the wall, no magnification or minification was observed. This was determined by repeatedly lifting the HMD to verify the agreement between the tape lines in the real environment and the vertical posts in the virtual environment.

Participants in the VE conditions completed separate blocks of verbal distance judgments, size judgments, and blind-walking distance judgments (in that order) before and after a period of walking interaction. Each judgment block contained 15 trials corresponding to three repetitions of five egocentric distances (1, 2, 3, 4, and 5m) presented in a random sequence. Walking interaction also entailed 15 trials, each a unique distance between 1 and 5m, in a random sequence. Participants in the real classroom condition completed one block of verbal distance judgments followed by one block of blind-walking judgments, and within-block trial composition was identical to the VE conditions.

2.3 Procedure

2.3.1 Virtual Reality. After signing the informed consent, the participant was given verbal instructions on verbal distance judgments, size judgments, and blind-walking judgments. The participant was asked to choose the distance units (metric or imperial) for the verbal judgment task. The participant was then shown examples of egocentric distances (1, 2, and 4m or 1, 2, 3, 6, and 12ft) pre-measured and marked on the floor of the real lab in an area not visible from the stimulus viewing location. The participant then moved to the viewing location and was allowed to hold and view a real soccer ball as reference for the size judgment task. During this time, the participant was also instructed on how to increase and decrease the virtual soccer ball size using a hand-held controller before donning the HMD.

In the verbal distance judgment task, the participant viewed the virtual traffic cone from a static location and verbally stated how far away the cone appeared to be. The experimenter wrote down the response and pressed a key to start the next trial. The VE was visible throughout the task but the cone disappeared from view after the key press and reappeared 2s later.

In the size judgment task, the participant viewed the virtual soccer ball from a static location. Initial ball size on each trial was randomly selected from a range of 30% to 300% of actual ball size in 10% increments. The participant's task was to adjust the size of the soccer ball using buttons on a remote control until; the ball appeared to match the true size of a soccer ball. The experimenter pressed a key to record the adjusted ball size after the participant verbally indicated satisfaction with the response.

In the blind-walking distance judgment task, the participant viewed the traffic cone for 5s. The entire VE then disappeared and the participant was instructed to walk to the location of the cone. The experimenter pressed a key to record the participant's stopping location and then led the participant back to the viewing location. Upon returning to the viewing location, the VE became visible again and the next trial began. Other studies have unlimited viewing time (Thompson et al. 2004), but 5s was chosen because it seemed to provide sufficient opportunity to evaluate object distance and has been used in other studies from our lab (Kelly et al. 2013, 2014; Siegel and Kelly 2017; Siegel et al. 2017).

Walking interaction trials began after the first block of verbal judgments, size judgments, and blind-walking judgments were completed. The blue vertical post served as the walking destination and remained visible (along with the rest of the VE) as the participant walked to it. Once the participant arrived at the blue post, the environment disappeared and the participant was led back to the viewing location for the next trial.

After completion of the walking interaction trials, the participant completed one additional block of verbal judgments, size judgments, and blind-walking judgments. Upon completion of the experiment, the participant was debriefed by the experimenter.

2.3.2 Real World. The procedure for verbal and blind-walking judgments (size judgments were not performed) was similar to the virtual reality trials, with the following exceptions. A blindfold was used while the experimenter moved the traffic cone during verbal judgment trials, and when the participant walked during blind-walking trials. On blind-walking trials, walked distance was measured using a laser measure[1] and was recorded on paper by the experimenter.

3 ANALYSIS

All three judgment types were converted into ratios of judged-to-actual distance prior to analysis. For blind-walking and verbal judgments, this conversion was straightforward. Size judgments first had to be converted into judgments of perceived distance, and this was done using the size-distance invariance hypothesis, which states that perceived distance (D′) is linearly related to perceived size (S′) and object visual angle (α):

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

Although many researchers have used the size-distance invariance hypothesis to infer perceived distance from judged size (Gogel et al. 1985; Hutchison and Loomis 2006; Kelly et al. 2013; Siegel and Kelly 2017), the direct relationship between perceived size and perceived distance has been questioned. For example, Epstein et al. (1961) found that manipulation of perceived distance to an object of constant angular size resulted in a larger change in perceived size than predicted based on the size-distance invariance hypothesis. Despite concerns about the causal relationship between perceived size and perceived distance (e.g., Brenner and van Damme (1999)), the two variables have been found to be tightly coupled, presumably due to the effect of perceived distance on both judged distance and judged size.

Size judgments demonstrated an anchoring effect, whereby the adjusted ball size on a given trial tended to be biased toward the initial ball size on that trial. To account for this, a two-step process was used to mathematically describe the anchoring bias and then remove the bias prior to converting size judgments into distance judgments. The same process has been described and used elsewhere (Siegel and Kelly 2017; Siegel et al. 2017). To describe the anchoring bias, the mean of all size judgments was subtracted from each individual size judgment and then regressed against initial ball size. Figure 2 shows that this relationship was well-described by a linear equation ($R^2 = 0.797$). To compensate for the anchoring bias, the initial ball size on a given trial was passed through the linear equation relating initial ball size to judgment bias to calculate presumed bias on that trial. The resulting bias value was then subtracted from the judged ball size on that trial. Size judgments were then converted into estimates of perceived distance using Equation (1), and subsequently converted into ratios by dividing perceived distance by actual object distance. This process was completed using data from both VEs together. The difference between anchoring equations when considering the VEs separately was within rounding error and did not change the results or conclusions in any way.

4 RESULTS

Results are presented in terms of the predictions described in the Introduction. Data from blind-walking judgments are displayed in Figure 3, data from size judgments are displayed in Figure 4, and data from verbal judgments are displayed in Figure 5. Data from the two older HMDs are from previous studies and always reflect pre-interaction judgments.

[1]The Vive tracking system was used to measure walked distance in the VE, whereas a laser measure was used to measure walked distance in the real environment. To ensure that these were comparable measures, a person wearing the HMD stood on top of virtual targets placed at 1, 2, 3, 4, and 5m from the viewing location, while the laser measure was used to measure the same distance. Across repeated measurements, the laser measure produced values that were within 8cm of the intended distance in the VE and showed no systematic bias.

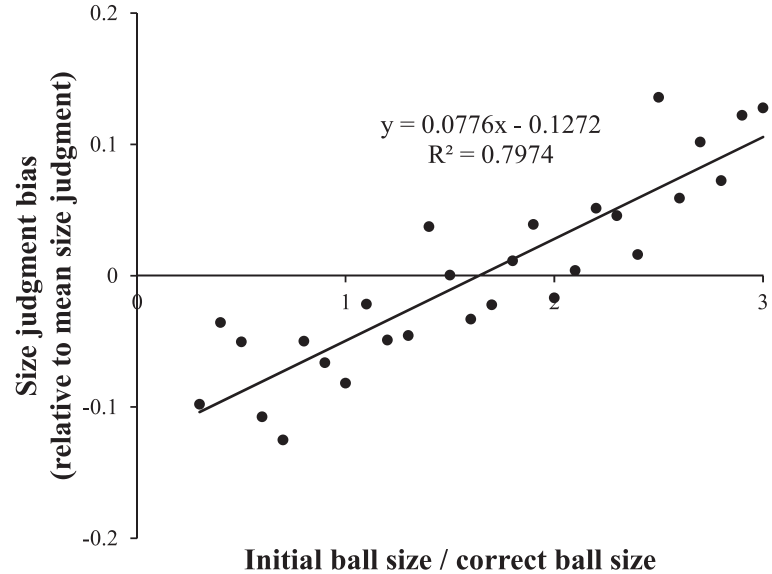

Fig. 2. Size judgment bias as a function of initial ball size, illustrating the anchoring effect.

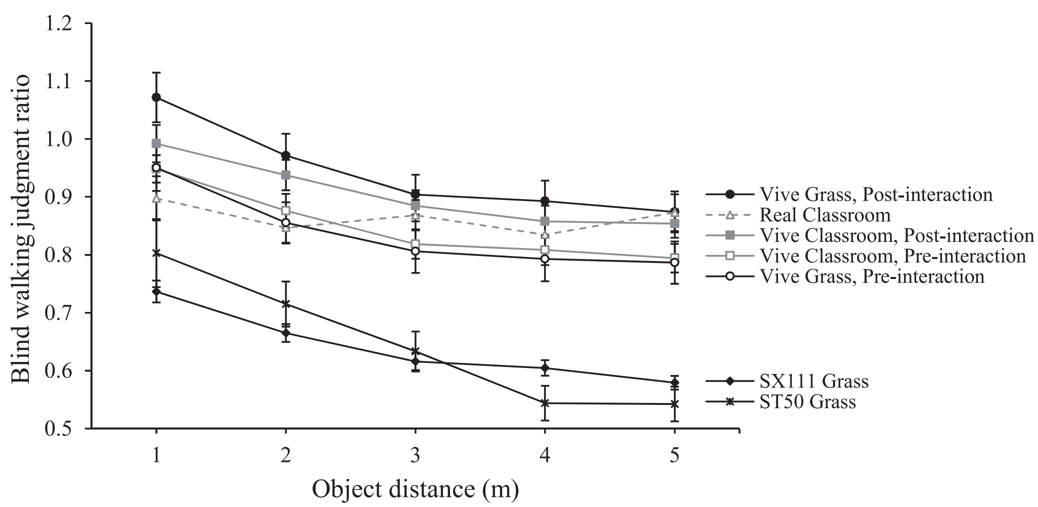

Fig. 3. Judgment ratios based on blind-walking distance judgments, relative to actual object distance. Error bars represent +/− 1 SEM.

4.1 Comparison between HTC Vive and Older HMDs

The first hypothesis was that blind-walking and size judgments in the grass VE viewed through the Vive would be more accurate compared to older displays. To evaluate this prediction, separate ANOVAs were conducted testing blind-walking judgments and size judgments.

For blind-walking judgments (Figure 3), pre-interaction data collected using the Vive display were compared to previously collected data using the nVisor SX111 (Siegel and Kelly 2017) (unpublished data following the same protocol reported in Kelly et al. (2014)) and the nVisor ST50 (Kelly et al. 2014). Relevant data are displayed in

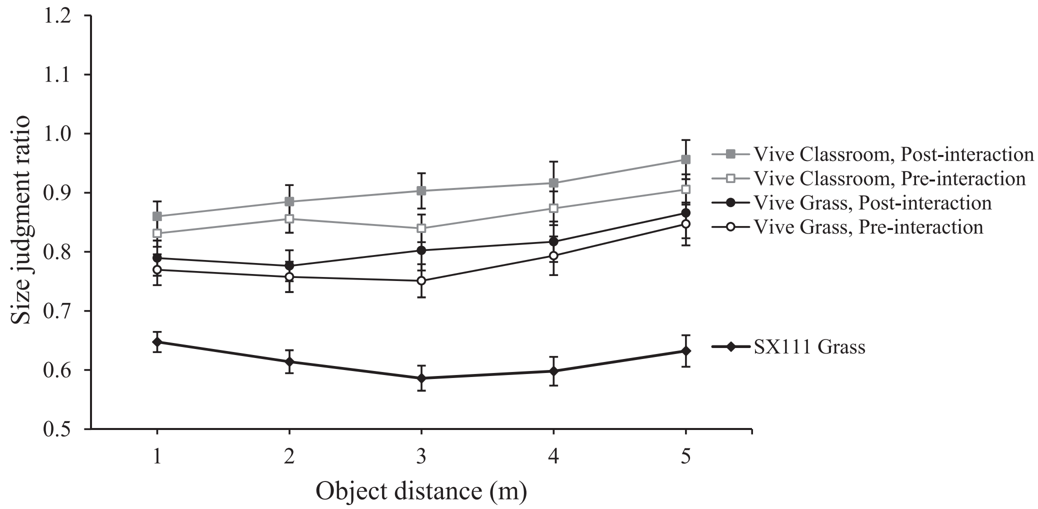

Fig. 4. Judgment ratios based on size judgments, relative to actual object distance. Error bars represent +/− 1 SEM.

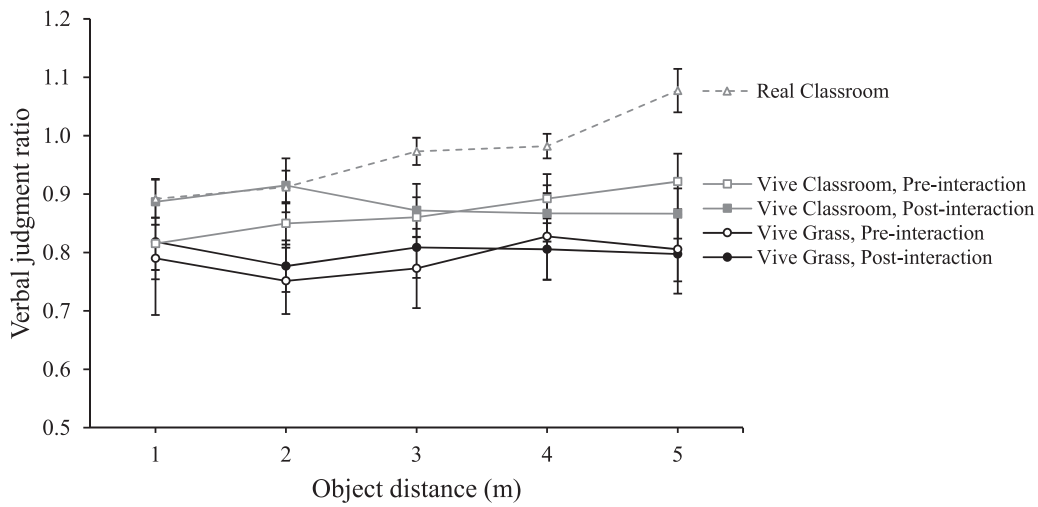

Fig. 5. Judgment ratios based on verbal judgments, relative to actual object distance. Error bars represent +/− 1 SEM.

Figure 3. All data were collected using the same blind-walking protocol and the same grass VE. The only notable difference was the HMD. A 3 (display type: Vive, SX111, and ST50) by 5 (object distance: 1, 2, 3, 4, and 5m) ANOVA revealed significant main effects of display type, $F(2,111) = 22.52$, $p < 0.001$, $\eta_p^2 = 0.29$, and object distance, $F(4,444) = 79.98$, $p < 0.001$, $\eta_p^2 = 0.42$, as well as a significant interaction, $F(8,444) = 3.50$, $p = 0.001$, $\eta_p^2 = 0.06$. Blind-walking judgments in the Vive ($M = 0.838$, $SE = 0.026$) were more accurate than those in the SX111 ($M = 0.640$, $SE = 0.016$; $p < 0.001$) and ST50 ($M = 0.647$, $SE = 0.031$; $p < 0.001$), which did not differ from one another ($p = 0.836$). Blind-walking judgments were overall more accurate for near distances than for far distances. Although blind-walking judgments became less accurate at farther distances for all three displays, this effect appeared more linear in the SX111 and ST50 displays, whereas in the Vive the effect of distance appeared more pronounced from 1–3m than from 3–5m.

For size judgments (Figure 4), pre-interaction data collected using the Vive display were compared to previously collected data using the nVisor SX111 (Siegel et al. 2017). A 2 (display type: Vive and SX111) by 5 (object distance: 1, 2, 3, 4, and 5m) ANOVA revealed significant main effects of display type, $F(1,59) = 27.87$, $p < 0.001$, $\eta_p^2 = 0.32$, and object distance, $F(4,236) = 7.41$, $p < 0.001$, $\eta_p^2 = 0.11$, as well as a significant interaction, $F(4,236) = 3.67$, $p = 0.006$, $\eta_p^2 = 0.06$. Size judgments were overall more accurate in the Vive ($M = 0.784$, $SE = 0.024$) than in the SX111 ($M = 0.616$, $SE = 0.021$), and both displays appeared to show a non-linear pattern with more accurate judgments for near and far object distances compared to middle distances, but this pattern was exaggerated in the Vive compared to the SX111.

To summarize, size judgments and blind-walking judgments of distance were more accurate in the Vive compared to the older SX111 and ST50 displays. The blind-walking data add to previously published work indicating that a more modern HMD (Oculus Rift DK2) produced more accurate judgments than older displays (Creem-Regehr et al. 2015b). The size judgment data extend that knowledge by indicating that both perceived distance and perceived size are judged more accurately in the Vive than in older displays.

4.2 Comparison between HTC Vive and Real World

It was unknown whether blind-walking and verbal distance judgments in the classroom VE would be comparable to performance in the real classroom. To evaluate, separate ANOVAs were conducted for the two dependent measures comparing Vive classroom VE data to real-world classroom data.

Blind-walking judgments (Figure 3) were evaluated in a 2 (environment: virtual versus real world) by 5 (distance: 1, 2, 3, 4, and 5m) ANOVA. There was a significant main effect of distance, $F(4,188) = 11.58$, $p < 0.001$, $\eta_p^2 = 0.20$, and a significant interaction, $F(4,188) = 5.32$, $p < 0.001$, $\eta_p^2 = 0.10$, but the main effect of environment was not significant ($p = 0.66$), indicating that no overall difference existed between the classroom VE displayed in the Vive ($M = 0.849$, $SE = 0.022$) and the real classroom ($M = 0.864$, $SE = 0.026$). In both environments there was a tendency toward more accurate judgments for near compared to far object distances, and this trend was more pronounced in the virtual compared to real environment. Blind-walking judgments were numerically more accurate in the Vive than in the real classroom for the 1 and 2m object distances and numerically less accurate in the Vive than in the real classroom for the 3–5m object distances, which led to the significant interaction. However, judgments in the Vive did not significantly differ from those in the real classroom for any of the individual object distances.

To summarize, blind-walking distance judgments made in the Vive classroom VE did not differ appreciably from those made in the real classroom. This result indicates that blind-walking distance judgments in the Vive are similar in accuracy to those made in the real world. To date, no other study has directly compared blind-walking performance in a modern HMD to performance with unrestricted viewing in the real world (but see Li et al. (2015) for a comparison of performance in the DK2 with real world viewing using restricted FOV). It is somewhat surprising that most object distances produced judgment ratios less than 1.0, in both the virtual and real environments. Loomis and Knapp (2004) reviewed several studies in which participants made blind-walking judgments to visually previewed targets and most studies showed average performance near 1.0 for all distances tested, although there are some exceptions in which performance was below 1.0 (e.g., Loomis et al. (1998)). It is possible that blind-walking ratios were below 1.0 because of lack of practice and/or feedback, which some studies have provided (practice without feedback: Li et al. (2014) and Thompson et al. (2004); practice with feedback: Interrante et al. (2006) and Steinicke et al. (2009)). Regardless, the underperception found in the real classroom should not mitigate the conclusion that blind-walking judgments were comparable when the VE was closely matched to the real environment.

Verbal distance judgments (Figure 5) were also evaluated in a 2 (environment: virtual versus real world) by 5 (distance: 1, 2, 3, 4, and 5m) ANOVA. The main effects of environment, $F(1,43) = 4.68$, $p = 0.036$, $\eta_p^2 = 0.10$, and distance, $F(4,172) = 8.12$, $p < 0.001$, $\eta_p^2 = 0.16$, were significant. The interaction was not significant ($p = 0.49$).

Verbal judgments in the real world ($M = 0.967$, $SE = 0.036$) were more accurate than those in the Vive ($M = 0.868$, $SE = 0.028$), and judgments were larger for far compared to near object distances.

Verbal judgments were significantly smaller in the Vive classroom VE compared to the real classroom. It is possible that additional contextual cues in the real classroom produced more accurate verbal judgments. For example, some objects in the real classroom were not present in the VE classroom, such as personal belongings that the experimenter and participant brought into the classroom.

Considering the blind-walking and verbal data together, it is interesting that only verbal judgments differed between the real and virtual classrooms. This distinct effect of environmental manipulations on the two dependent variables may be similar the findings of Kunz et al. (2009), who reported that verbal distance judgments were more accurate in a high- compared to low-quality VE, whereas blind-walking judgments did not differ. We believe that the additional contextual cues provided by the real classroom may have provided participants with a more accurate scale for the relevant units (e.g., feet) of measurement in the verbal task, but that the blind-walking task was largely controlled by other cues that did not vary across environments, such as angle of declination (Messing and Durgin 2005; Ooi et al. 2001). Further consideration in the context of theories of space perception can be found in the General Discussion.

4.3 Comparison between Grass and Classroom VEs

Blind-walking distance judgments were expected to be equivalent in the classroom and grass VEs, but verbal and size judgments were expected to be more accurate in the classroom than the grass VE. To test this, each dependent measure was evaluated using a 2 (VE: grass versus classroom) by 5 (distance: 1, 2, 3, 4, and 5m) ANOVA.

For blind-walking judgments (Figure 3), only the main effect of distance was significant, $F(4, 208) = 45.94$, $p = 0.036$, $\eta_p^2 = 0.47$, reflecting a trend toward smaller judgments at farther distances. Neither the main effect of VE (classroom: $M = 0.849$, $SE = 0.029$; grass: $M = 0.838$, $SE = 0.030$) nor the interaction were significant (ps > 0.79). For verbal judgments (Figure 5), there were no significant effects, although verbal judgments were numerically higher in the classroom VE ($M = 0.868$, $SE = 0.042$) compared to the grass VE ($M = 0.789$, $SE = 0.045$; $p = 0.21$). For size judgments (Figure 4), there were significant main effects of VE, $F(1,52) = 4.86$, $p = 0.032$, $\eta_p^2 = 0.09$, and distance, $F(4,208) = 13.28$, $p < 0.001$, $\eta_p^2 = 0.20$. Size judgments were more accurate in the classroom ($M = 0.861$, $SE = 0.024$) compared to grass VE ($M = 0.784$, $SE = 0.025$), and there was a trend toward larger size judgments at farther distances. The interaction was not significant ($p = 0.48$).

To summarize, blind-walking judgments did not significantly differ across the grass and classroom VEs, but size judgments were more accurate in the classroom VE than the grass VE and verbal judgments showed a similar but non-significant trend. In related work, Kunz et al. (2009) found that manipulation of graphics quality affected verbal judgments of distance but not blind-walking judgments of distance. Furthermore, Murgia and Sharkey (2009) found that environmental context affected judged size. Based on those studies, it was expected that blind-walking judgments would be unaffected by the VE manipulation, but that verbal and size judgments would be affected. Blind-walking and size judgments confirmed the hypothesis, and verbal judgments showed the anticipated trend but did not reach significance.

4.4 Effect of Walking Interaction

All three measures of perceived space in the Vive were expected to be more accurate after walking interaction, but only if underperception occurred prior to interaction. This prediction was based on the idea that feedback during walking interaction generates an error signal between the predicted (i.e., perceived) distance to the object and the distance required to walk to the object. If distance perception were accurate prior to interaction, then no error signal would result from walking interaction and no influence of walking interaction would occur. Since pre-interaction judgment ratios were less than 1.0 for all dependent measures at all distances, it was expected that walking interaction would lead to more accurate judgments across all measures.

Each dependent measure was analyzed in a separate 2 (pre- versus post-interaction) by 2 (VE: grass and classroom VE) by 5 (object distance) mixed ANOVA. Since the effects of VE and object distance have already been reported in this section, the focus is on the effects of walking interaction (main effects and interactions are reported). Blind-walking judgments (Figure 3) revealed a main effect of walking interaction, $F(1,52) = 31.72$, $p < 0.001$, $\eta_p^2 = 0.38$, which did not interact with any other variables. Blind-walking judgments were overall more accurate after walking interaction ($M = 0.924$, $SE = 0.021$) compared to before walking interaction ($M = 0.844$, $SE = 0.021$). For verbal judgments (Figure 5), the main effect of walking interaction was not significant, nor were any interactions with other variables. For size judgments (Figure 4), the main effect of walking interaction was significant, $F(1,52) = 23.33$, $p < 0.001$, $\eta_p^2 = 0.31$, as was the interaction between walking interaction and object distance, $F(4,208) = 2.58$, $p = 0.038$, $\eta_p^2 = 0.05$. Size judgments were overall more accurate after walking interaction ($M = 0.857$, $SE = 0.021$) compared to before walking interaction ($M = 0.822$, $SE = 0.018$), and the improvement caused by walking interaction appeared more pronounced for intermediate object distances (2–4m) than for the nearest and farthest object distance.

The finding that walking interaction in a VE caused subsequent blind-walking judgments to increase has been demonstrated several times (Richardson and Waller 2005, 2007; Waller and Richardson 2008). Similarly, the finding that walking interaction in a VE caused subsequent size judgments to increase has also been demonstrated multiple times (Kelly et al. 2013; Siegel and Kelly 2017; Siegel et al. 2017). This finding has led to the speculation that walking interaction causes rescaling of perceived space, whereby walking interaction not only causes recalibration of the walking response but that it also changes perceived scale of the VE. However, if this were the case then walking interaction should have affected all judgments of perceived distance, but verbal judgments were unaffected by walking interaction. This finding is contrary to that reported by Mohler et al. (2006), who reported a study in which walking interaction caused an increase in subsequent verbal judgments of distance. Its unclear why their result did not replicate in this study, but the lack of change in verbal judgments in the current study calls into question the rescaling interpretation proposed elsewhere. Kunz et al. (2015) previously questioned whether improvement in blind walking judgments generalized to size judgments, and Mohler et al. (2006) suggested the reported change in verbal judgments may be due to cognitive correction. It is worth noting that response variance was higher for verbal judgments of distance than it was for blind walking or size judgments. For example, between-participant standard deviations of pre-interaction judgments made in the classroom VE averaged 0.14 for blind-walking judgments, 0.13 for size judgments, and 0.22 for verbal judgments. Additional training on verbal report or additional verbal trials should reduce response variance, but its not clear that this issue was primarily responsible for the null effect of walking interaction as no trend was apparent in the data.

5 DISCUSSION

There are several key findings from this study. First, perceived space when using the HTC Vive was more accurate than when using two older HMDs based on blind-walking distance judgments and size judgments. Second, perceived space when using the HTC Vive was comparable to real-world viewing, but only for blind-walking judgments of distance. Verbal judgments of distance showed underperception in the Vive compared to real-world viewing. Third, perceived space was more accurate in a high-quality classroom VE than a lower-quality grass VE but only for judgments of size; blind-walking distance judgments did not differ between the two VEs. Fourth, judgments of perceived space in both VEs improved after a period of walking interaction, but only for blind-walking distance judgments and size judgments and not for verbal distance judgments.

These data are the first to evaluate space perception in the Vive and also to compare with a very similar real-world environment under unrestricted viewing (but see Li et al. (2015) for comparison with real world under restricted viewing). To that end, the nearly equivalent blind-walking results are encouraging. Although the verbal judgments were smaller in the Vive than in the real classroom, this difference was relatively small compared to past comparisons of real and virtual environments (e.g., Thompson et al. (2004)). In the current study, verbal judgments in the real classroom averaged 96.7% of actual distance, whereas verbal judgments in the virtual classroom (pre-interaction) averaged 86.8%. Therefore, these data show that the problem of distance underperception in VR may not be completely resolved, but at least is less severe than it once was.

Adding further data to the claim that the problem of underperception in VR is improving, two measures of space perception (blind-walking distance judgments and size judgments) were more accurate when the same VE was viewed through the Vive compared to two older HMDs, the nVisor ST50 and SX111. These results corroborate findings reported by Creem-Regehr et al. (2015b), who found more accurate blind-walking judgments in a development edition of the Oculus Rift as compared to an older display. The exact cause of the improvement is unclear, but it is likely related to one or more of the several technical differences between the Vive and older displays. Below, we consider the potential influence of three such factors that are widely reported: display field-of-view (FOV), display weight, and display resolution. There are many more technical differences that might be important, such as lens characteristics and display brightness and contrast, but details on those factors are not widely reported. The FOV of the Vive is approximately 100° horizontal × 110° vertical, whereas FOV of the ST50 is 40° horizontal × 32° vertical and the SX111 is 102° horizontal × 64° vertical. However, reduction of real-world FOV has no measurable effect on blind-walking distance judgments when head rotations are unrestricted (Creem-Regehr et al. 2005; Knapp and Loomis 2004), suggesting that this might not be an important factor. The weight of the Vive is 1.22 lbs, whereas the ST50 and SX111 weigh 2.31 and 2.87lbs, respectively. When combined with reduced FOV, display weight and inertia appear to cause some underperception in a real environment (Willemsen et al. 2009). The resolution of the Vive is 1080 horizontal × 1200 vertical per eye, and the ST50 and SX111 both have 1280 × 1024 resolution per eye. When considered in the context of FOV differences across displays, the ST50 and SX111 both have higher resolution than the Vive in that they have more pixels per degree of visual angle. Although the three HMDs considered vary considerably in weight, FOV, and resolution, it is not obvious that differences in perceived space are caused by differences in these technical factors.

Two results from the current study seem related to environmental context. First, blind-walking distance judgments in the real and virtual classrooms did not differ, but verbal judgments were smaller in the virtual compared to real classroom. Second, blind-walking distance judgments were similar in the classroom and grass VE, but size-judgments in the grass VE were smaller than those in the classroom VE. We believe that these differences were affected by the distance cues that are relevant to each judgment type. Specifically, blind-walking judgments are strongly affected by declination angle (Messing and Durgin 2005; Ooi et al. 2001), which was available in the real classroom as well as the grass and classroom VEs. Size judgments have been shown to be affected by environmental context (Murgia and Sharkey 2009). This is consistent with informal debriefing in an unpublished study from our lab, in which the experimenter asked participants for strategy information after performing several dependent measures testing perceived space. One consistent strategy reported when making size judgments was that participants referenced other known objects, such as nearby cabinets and doors. We also believe that familiar objects helped participants to scale the units of measurement required for making verbal reports of distance. This notion is supported by the finding of Kunz et al. (2009), who reported that verbal judgments of distance showed greater underestimation in a VE with low-quality textures compared to high-quality textures. Importantly, only the high-quality textures contained familiar size cues, such as whiteboards and doors.

Kunz et al. (2009) detailed three theories that could account for the differential effect of VE quality on measures of perceived distance. We believe these theories also nicely characterize the differences between VEs reported in the current study. The first theory is the two-systems theory, which proposes that different visual representations underlie perception and action (e.g., Milner and Goodale (1995)). The second theory is the task-specific representations theory, which proposes that different representations may be formed to accommodate different responses. This theory emphasizes the possibility that different perceptual tasks cause participants to direct their attention toward different cues, resulting in different representations of the space. The third theory is the unitary representation but different judgments theory, which proposes that the visual system creates a single representation, and that differences in perceptual judgments reflect differences in the judgment process. For example, a verbal judgment may be more subject to cognitive strategies than an action-based task, or recalibration of one type of judgment might not influence another type of judgment. The current data do not strongly favor one theory over another. One possibility for future work is to show participants the virtual object before telling them which of several judgments (e.g., verbal, size, blind-walking, or blind-throwing) to perform on that trial. According to the two-systems and the task-specific representations theory, no differences should be observed between environments (e.g., grass versus classroom VE) for any of the judgment types, because the representation was formed without consideration of a specific response. According to the unitary representation but different judgments theory, the results should replicate those of the current study, because the effect of VE manipulation is caused by processes in the judgment itself, not in the formation of the representation.

Size judgments and blind-walking judgments of distance improved after a brief period of walking through the VE with visual feedback, replicating past work (Kelly et al. 2013, 2014; Richardson and Waller 2005, 2007; Siegel and Kelly 2017; Siegel et al. 2017; Waller and Richardson 2008). However, verbal judgments did not improve after walking interaction, which contrasts with previous work (Mohler et al. 2006). If walking interaction causes rescaling of perceived space whereby the VE is perceived as larger after interaction (e.g., Siegel et al. (2017)), then it should affect all judgments within the rescaled environment. Therefore, the verbal data from the current study casts some doubt on the rescaling hypothesis. Kunz et al. (2015) also questioned the rescaling hypothesis, reporting evidence that walking interaction did not affect judged size. From a practical standpoint, walking interaction may not be necessary when using the Vive. Pre-interaction blind-walking judgments in the classroom VE were quite similar to those in the real classroom. If real-world performance is the gold standard, then interaction may not be needed, even if pre-interaction judgments are less than veridical. Although pre-interaction verbal judgments in the classroom VE were somewhat smaller than those in the real classroom, walking interaction had no effect on verbal judgments. Taken together, it appears that walking interaction may not be particularly useful in conjunction with the Vive, although it may still be useful when paired with other displays for which judgments of perceived space are considerably worse than in the real world.

The anchoring effect found in size judgments, whereby judgments were biased toward the initial ball size on a given trial, have been reported in two other studies from our lab (Siegel and Kelly 2017; Siegel et al. 2017). It is possible that the underperception of perceived size reported in the current experiment is exaggerated because of the way in which initial ball size was determined. On each trial, initial ball size was randomly selected from an even distribution between 30% and 300% of actual ball size in increments of 10%. This means that the average initial ball size was 165%, which is larger than actual and might have caused responses to be biased larger. In light of the anchoring effect reported here, future studies using this method should ensure that average initial ball size is 100% of actual ball size to avoid biasing the results.

In summary, space perception in the Vive was comparable to real-world space perception when measured by blind-walking but slightly underperformed real-world perception when measured by verbal report. Furthermore, space perception in the Vive was more accurate when compared to older HMDs. These results are encouraging for the use of VR in applied settings, especially those for which accurate space perception is important, because they indicate that the 20-year-old problem of distance underperception in VR may be coming to an end as technology improves. As perception of VEs becomes more accurate, alternative methods for improving judgments of perceived space, such as walking interaction, will become less important.

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