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Peripheral Visual Information and Its Effect on Distance Judgments in Virtual and Augmented Environments

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ABSTRACT

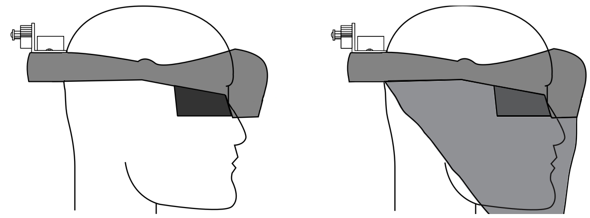
A frequently observed problem in medium-field virtual environments is the underestimation of egocentric depth. This problem has been described numerous times and with widely varying degrees of severity, and although there has been considerable progress made in modifying observer behavior to compensate for these misperceptions, the question of why these errors exist is still an open issue. This paper presents the findings of a series of experiments, comprising 111 participants, that attempts to identify and quantify the source of a pattern of adaptation and improved depth judgment accuracy over time scales of less than one hour. Taken together, these experiments suggest that peripheral visual information is an important source of information for the calibration of movement within medium-field virtual environments.

CR Categories: I.3.7 [Computer Graphics]: Three-Dimensional Graphics and Realism—Virtual Reality; I.4.8 [Scene Analysis]: Depth Cues; H.5.1 [Information Systems]: Multimedia Information Systems—Artificial, Augmented, and Virtual Realities H.1.2 [Information Systems]: User/Machine Systems—Human Factors

Keywords: depth perception, augmented reality, virtual reality, optical see-through display, peripheral vision

1 INTRODUCTION

The underestimation of depth in virtual environments at medium-field distances of 2 to 10 meters is a well studied phenomenon. However, the degree by which underestimation occurs varies widely from one study to the next, with some studies reporting as much as 68% underestimation in distance and others with as little as 6% (Knapp [1999]; Jones et al. [2008]). In particular, the study detailed in Jones et al. [2008] found a surprisingly small underestimation effect in virtual reality (VR) and no effect in augmented reality (AR). These are highly unusual results when compared to the large body of existing work in virtual and augmented distance judgments (e.g., Willemsen et al. [2009]; Richardson and Waller [2007]; Swan et al. [2007]; Swan et al. [2006]; Thompson et al. [2004]; Willemsen et al. [2004]; Willemsen and Gooch [2002]; Knapp [1999]; Witmer and Sadowski [1998]). The series of experiments described in this document attempted to determine the cause of these unusual results. Specifically, Experiment I aimed to determine if the experimental design was a factor and also to determine if participants were improving their performance throughout the course of the experiment. Experiment II analyzed two possible sources of implicit feedback in the experimental procedures and identified visual information available in the lower periphery as a key source of feedback. Experiment III analyzed distance estimation when all peripheral visual information was eliminated. Experiment IV then illustrated that optical flow in an observer's periphery is a key factor in facilitating improved depth judgments in both virtual and augmented environments.



(a) (b)

Figure 1: The HMD in (a) the standard configuration, and in (b) the fully occluded configuration.

2 EXPERIMENT I

One of the main criticisms of the experiment described in Jones et al. [2008] was that the within-subjects, repeated-measures experimental design could potentially lead to transfer effects across conditions, introducing the possibility that exposure to one condition could affect performance in another. This concern was the motivation behind Experiment I, which was a between-subjects replication of the experiment described in Jones et al. [2008]. Experiment I's aim was to determine whether or not the unusual lack of underestimation in Jones et al. [2008] was due to transfer effects introduced by the within-subjects experimental design.

2.1 METHOD

A group of 39 naive participants were recruited from the general university population and were monetarily compensated for their participation. Figure 2 shows the experimental environment, which was a hallway at the Mississippi State University Institute for Neurocognitive Science and Technology, measuring 1.82 meters in width and 23.45 meters in length. Participants were screened for visual dysfunction by self-report and tested for normal stereo vision prior to being allowed to participate in the experiment. Additionally, participants' eye-heights and interpupillary distances were measured prior to beginning the experiment. These measurements were used for individual calibration of the virtual and augmented environments. To present the virtual and augmented environments, a NVIS nVisor ST optical see-through head-mounted display (HMD) equipped with an Intersense IS-1200 motion tracking system was used for the presentation of all computer generated imagery. Opaque, foam rubber occluders were attached to the left and right sides of the HMD in order to prevent participants from seeing the surrounding environment.

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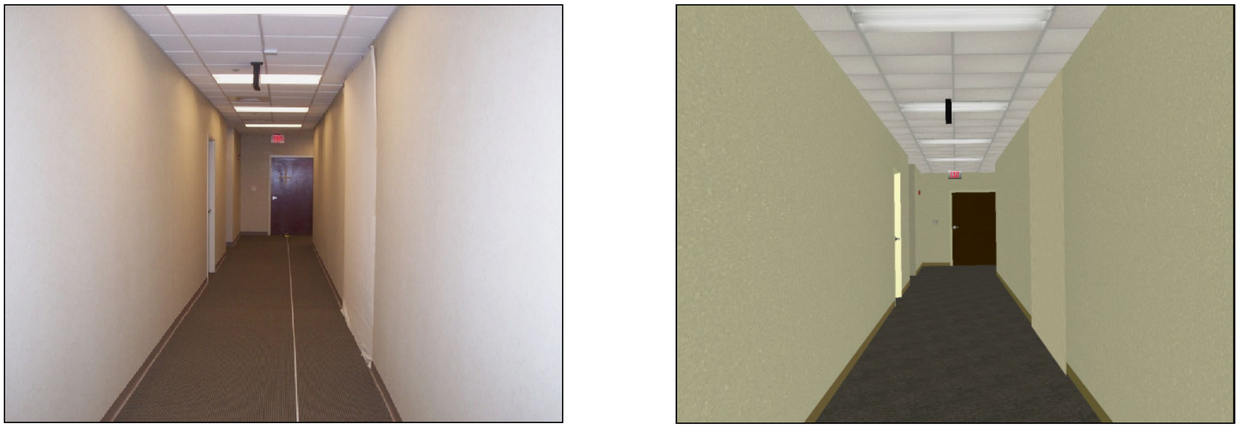

(a) (b)

Figure 2: (a) The real-world and (b) virtual experimental environments.

Figure 1a depicts the HMD and occluder configuration used in both Experiment I as well as in Jones et al. [2008]. Participants performed visually directed blind walking (e.g., Loomis and Knapp [2003]; Knapp [1999]; Rieser et al. [1995]) as a method of measuring their egocentric distance judgments, as illustrated in Figure 2. Participants were instructed to blindly walk until they felt as though the tips of their toes were at the target distance. The stimulus used to indicate the target distance was a white, wireframe pyramid measuring 23.5 cm in height with a 23.5 cm square base.

Prior to beginning the experiment, participants were briefed on the blind walking procedure and were given 5 practice trials of blind walking in an adjacent hallway of similar proportions to the experimental environment. This was done to build the participants' confidence in walking without vision. At this point, participants were escorted to the experimental environment. To prevent miscellaneous auditory cues from influencing the participants' behavior, they were equipped with earphones that played continuous white noise. The volume of the white noise was adjusted until the participants judged it to be subjectively comfortable. Additionally, the earphones were patched into a wireless microphone system through which the experimenters communicated instructions to the participants. The wireless microphone receiver and white noise generating device were stored in a backpack that the participants wore during all experimental conditions. Distance judgments from the blind walking task were measured with a white surveyor's tape (Figure 2a) that spanned the length of the hallway.

2.2 Design & Procedures

This experiment was intended to be a between-subjects replication of the experiment described in Jones et al. [2008]. For this reason, four experimental conditions were tested: Real World (*Real*), Real World seen through the HMD (*ReHMD*), Augmented Reality (*AR*), and Virtual Reality (*VR*). Jones et al. [2008] also tested two viewing conditions: *still* and *motion*. Respectively, participants either viewed stimuli while standing stationary (*still*) or while swaying from side-to-side to induce motion parallax (*motion*). However, since no consistent effect of the *motion* condition was observed, it was excluded from this experiment. Participants' movements were not restricted, but they were instructed to look directly at the stimulus during the experiment. Exact computer models of the experimental environment and stimulus were used in the *VR* condition, depicted in Figure 2b. An exact computer model of the stimulus was used in the *AR* condition. Stimuli were presented at one of five distances ranging from 3 to 7 meters in 1 meter increments. Each distance was repeated three times, providing 15 total trials per experimental session. The presentation order of the stimulus distances was determined using a restricted random shuffle, with the restriction that no target distance was repeated in consecutive trials.

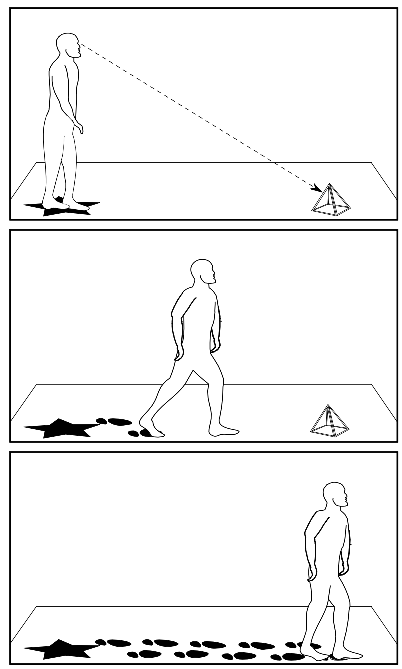

Figure 3: The visually directed blind walking procedure.

Participants were instructed to close their eyes between each trial, at which point the stimulus was placed. Participants were then instructed to open their eyes and observe the stimulus until they felt confident enough to blindly walk to its position. Upon indicating their readiness, the participants were instructed to close their eyes and walk to the object. Once the participant reached their judgment distance, they stopped walking and kept their eyes closed until instructed to turn back in the direction of their starting position. Participants were then allowed to walk back to the starting position with their eyes open. In the *Real*, *ReHMD*, and *AR* conditions the experimental environment was fully visible during the return walk. However, the virtual environment was not displayed and the optical see-through window was closed during the return walk in the *VR* condition.

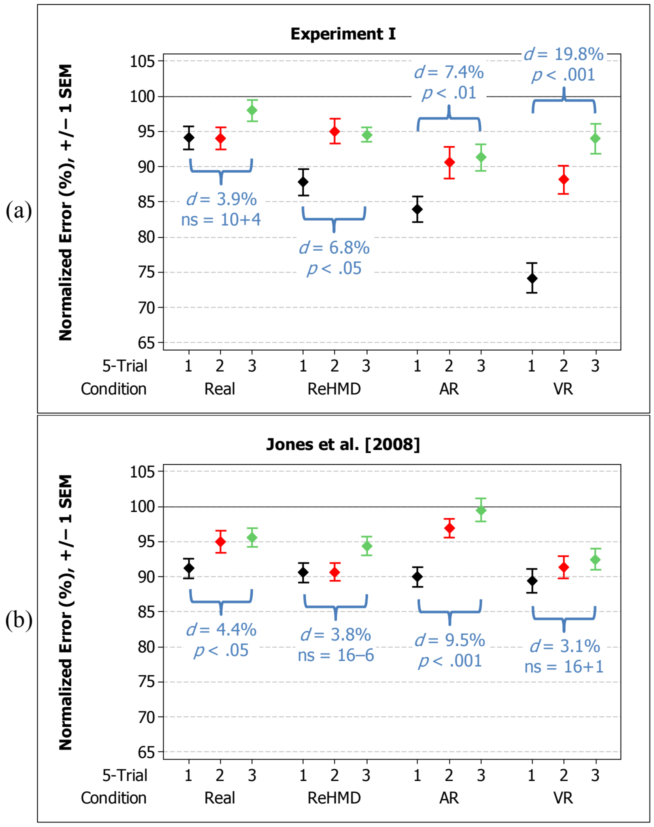

Figure 4: Distance judgments for the experimental conditions in (a) Experiment I, and (b) the first 15 trials of Jones et al. [2008].

The same calibration and alignment procedures discussed in Jones et al. [2008] were used prior to beginning each experimental session. These procedures helped ensure that the participants' real-world eye and head positions and orientations matched those modeled in the virtual and augmented environments. Before and after each experimental session, participants were screened for signs of simulator sickness and impaired locomotion.

2.3 Analysis

All analyses were conducted with *normalized error* = *judged distance* / *actual distance*. Each experimental *Condition* is subdivided according to *5-Trial*, the mean of 5 consecutive trials, so $5\text{-}Trial_1 = mean(\ trial_1 : trial_5\ )$, $5\text{-}Trial_2 = mean(\ trial_6 : trial_{10}\ )$, and $5\text{-}Trial_3 = mean(\ trial_{11} : trial_{15}\ )$; in other words *5-Trial* breaks the normalized error into the first, second, and final thirds of the experimental sessions. In addition, this paper reports non-significant hypothesis tests in the form "ns = $N + A$", where "ns" denotes a non-significant result, N is the number of participants that were run, and A is the number of additional participants that an a priori power analysis indicates would need to be run in order to achieve *power* = .80, assuming the effect size f and the correlation among repeated measurements r remain constant as additional participants are run, and assuming $\alpha = .05$. Thus the magnitude of A relative to N quantifies evidence for the truth of the null hypothesis. Some results are reported "ns = $N - A$"; these indicate that with N participants *power* > .80, and A is the number of participants that would need to be removed for *power* = .80, given the same assumptions for f, r, and α. Power calculations used G*Power software and the techniques discussed by Faul et al. [2007].

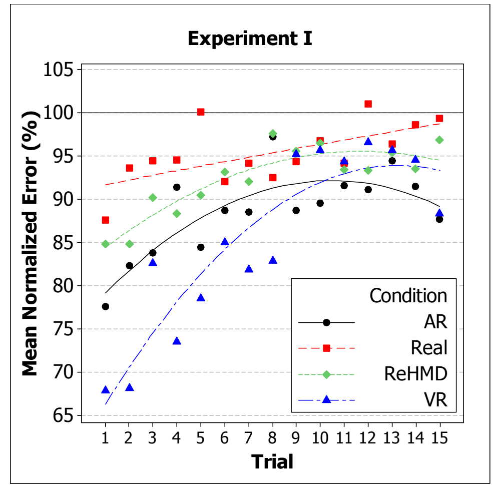

Figure 5: Distance judgments by trial fit with quadratic regressions.

2.4 Results

Figure 4a shows the results of Experiment I; here The *Real* condition served as the control for comparison with the *ReHMD, AR,* and *VR* conditions. Distance judgments in neither the *ReHMD* (92.4%) nor *AR* (88.6%) conditions significantly differed from those in the *Real* (95.3%) condition (*ReHMD*: $F(1,18) = 0.928$, $p = 0.348$, ns = 20+152; *AR*: $F(1,18) = 3.084$, $p = 0.096$, ns = 20+34). The *VR* (85.4%) condition exhibited significant underestimation of distance as compared to the *Real* condition ($F(1,17) = 7.324$, $p = 0.015$).

As previously discussed, Experiment I was intended to be a between-subjects replication of Jones et al. [2008], in order to determine if the unusual results seen in Jones et al. were an effect of that experiment's within-subjects design. Figure 4b shows the mean distance judgments found in Jones et al. [2008][*]: *Real* (93.9%), *ReHMD* (91.8%), *AR* (95.5%), and *VR* (91.0%). These are very similar to those found in Experiment I, differing by 1.4%, 0.6%, 6.9%, and 5.7% respectively. The low amount of underestimation is especially noteworthy in the *VR* condition, where underestimation has typically been reported ranging from 50% to 80% of veridical (e.g., Knapp [1999]; Richardson and Waller [2007]; Thompson et al. [2004]; Willemsen and Gooch [2002]; Willemson et al. [2004]; Witmer and Sadowski [1998]). Disregarding previous exposures and treating each condition from Jones et al. [2008] as a unique exposure, an analysis of variance was conducted comparing distance judgments between the two experiments. This analysis reveals that there was no significant difference between the conditions described in Jones et al. [2008] and their counterparts in Experiment I (*Real*: $F(1,24) = 0.170$, $p = 0.684$, ns = 26+1184; *ReHMD*: $F(1,24) = 0.040$, $p = 0.843$, ns = 26+4220; *AR*: $F(1,24) = 2.930$, $p = 0.100$, ns = 26+46; *VR*: $F(1,23) = 1.959$, $p = 0.175$, ns = 25+79).

These results seem to counterindicate experimental design as the main factor behind the unusual lack of underestimation seen in both Jones et al. [2008] and Experiment I. However, they prompted a thorough reexamination of Experiment I which revealed a strong trend of improved distance judgments throughout the course of the experiment. Figure 5 shows a plot of *normalized error* means for the conditions by trial and fit with quadratic re-

[*] In Jones et al. [2008] 16 trials were collected per condition, but in order to allow the two experiments to be directly compared, for this analysis the final trial is dropped.

gressions (*Real*: R^2 = 41.0%; *ReHMD*: R^2 = 81.4%; *AR*: R^2 = 67.1%; *VR*: R^2 = 83.3%). As Figure 4a shows, the effect of improved distance judgments over time becomes even more obvious when examining the data subdivided by *5-Trial*.

An analysis of variance was conducted to examine the effect of time in terms of *5-Trial* on distance judgments. Additionally, an effect size $d = \textit{5-Trial}_3 - \textit{5-Trial}_1$ was calculated between the last and first *5-Trial* to illustrate the size and direction of the adaptation over time. This revealed that all conditions, excepting *Real*, exhibited significantly improved normalized error between the first and third *5-Trial* (*Real*: $F(2,18) = 1.029$, $p = 0.378$, ns = 10+4, $d = 3.9\%$; *ReHMD*: $F(2,18) = 3.732$, $p = 0.044$, $d = 6.8\%$; *AR*: $F(2,18) = 7.176$, $p = 0.005$, $d = 7.4\%$; *VR*: $F(2,16) = 27.071$, $p = 0.000$, $d = 19.8\%$). As illustrated in Figure 4a, toward the end of the experimental session, for each condition participants are judging distance within 90%, on average, of the actual target distance. This finding prompted another look at the data from Jones et al. [2008] to see if a similar trend existed there as well.

An analysis of variance was conducted on the data from Jones et al. [2008] to examine the effect of time in terms of *5-Trial* on distance judgments. The effect size, as previously described, was also calculated to illustrate the size and direction of the adaptation across over time. Figure 4b shows the results of this analysis, which are very similar to those found in Experiment I. The *Real* and *AR* conditions exhibited significantly improved normalized error over time while the *ReHMD* and *VR* conditions did not (*Real*: $F(2,30) = 3.538$, $p = 0.042$, $d = 4.4\%$; *ReHMD*: $F(2,30) = 2.376$, $p = 0.110$, ns = 16–6, $d = 3.8\%$; *AR*: $F(2,30) = 17.874$, $p = 0.000$, $d = 9.5\%$; *VR*: $F(2,30) = 0.995$, $p = 0.382$, ns = 16+1, $d = 3.1\%$). Though the ReHMD and VR conditions did not exhibit statistically significant effects, they could, in fact, be masked by the within-subjects design after all. This seems plausible as the effects observed in Experiment I are subtle and time dependant.

3 Experiment II

Though previous work has demonstrated that participants can significantly improve their performance in the absence of explicit feedback (e.g., Gibson and Gibson [1955], Philbeck et al. [2008]), the strong trend of improved distance judgments seen in Experiment I raised the possibility that participants may have been receiving feedback regarding their performance from some uncontrolled aspect of the experiment. This prompted a thorough reexamination of the experimental procedures used in both Jones et al. [2008] and Experiment I. After carefully scrutinizing the experimental procedures, we could find no sources of *explicit feedback* that could give participants knowledge of their performance. However, two possible sources of *indirect feedback* were identified: (1) proprioceptive feedback from the blind walking task itself and (2) peripheral visual information available via a gap below and between the HMD and the participants' face. The vertical field-of-view of the gap varied depending on the declination of each participant's head but ranged from roughly 35° to no more than 50°. Experiment II attempts to identify which of these potential sources of feedback could be influencing participants' perception of the virtual environment.

This experiment compared two conditions: extended walking (*Extended*) and fully occluded periphery (*Fully Occluded*). The *Extended* condition was intended to remove any proprioceptive feedback by forcing observers to perform their return walk from a randomly selected distance further than their judgment distance. The *Fully Occluded* condition involved wrapping an opaque, black cloth around the bottom and sides of the HMD in order to prevent exposure to any peripheral visual information, as depicted in Figure 1b. These conditions were tested only in the virtual reality condition, as *VR* exhibited the strongest adaptation effect in Experiment I.

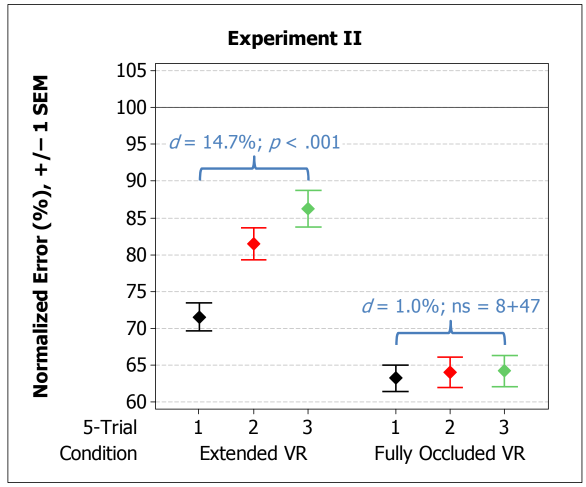

Figure 6: Distance judgments in the *Extended* and *Fully Occluded* conditions.

3.1 Method

For this experiment, 16 naive participants were recruited from the general university population and either received course credit or monetary compensation for their participation. Eight participants experienced each condition in a between-subjects design. The procedures for this experiment closely followed the procedures used in Experiment I: the same screening and training protocols were used, but the experimental protocol differed slightly as required by the new experimental conditions. For the *Extended* condition, participants performed the same blind walking task as in Experiment I, except that the return walk differed. Once the participants completed their judgment walk and their walked distance was measured, they were asked to blindly walk forward until instructed to stop. The extended distance varied randomly from 1 to 4 meters. The participants then performed a normal return walk from the new position. This condition was intended to ambiguate any proprioceptive feedback from walking the judged distance twice: once on the judgment walk and again on the return walk. For the *Fully Occluded* condition, as depicted in Figure 1b, participants were required to wear an opaque cloth that wrapped around the bottom and sides of the HMD. This cloth was intended to prevent the participants from viewing any peripheral information that may provide feedback during their return walk. Otherwise, this condition did not differ from the blind walking protocol used in Experiment I.

3.2 Results

The current experiment aimed to determine if the improved performance seen in Experiment I was the results of a source of uncontrolled feedback, such as proprioceptive information gained by walking the judged distance twice or peripheral visual information. By systematically removing the possible sources of feedback, one would expect no adaptation to occur in the suspect condition. Otherwise, one could assume that participants were modifying their blind walking behavior without feedback, as reported in Philbeck et al. [2008]. Figure 6 shows the results. An analysis of variance and effect size calculation reveals that participants in the *Extended* condition continued to significantly adapt through the course of the experiment, while participants in the *Fully Occluded* condition did not (*Extended*: $F(2,14) = 14.496$, $p = 0.000$, $d = 14.7\%$; *Fully Occluded*: $F(2,14) = 0.111$, $p = 0.896$, ns =

8+47, d = 1.0%). Figure 6 clearly shows that observers in the *Extended* condition exhibited significant adaptation, indicating that proprioception is an unlikely source of feedback. This seems to indicate a relationship between the observed adaptation and the presence of peripheral visual information. It is also worth noting that the mean normalized error in the *Fully Occluded* condition is 63.8%. This puts the underestimation observed in this condition firmly in the range that has been widely observed in numerous other VR studies (e.g., Willemsen et al. [2009]; Richardson and Waller [2007]; Thompson et al. [2004]; Willemsen et al. [2004]; Willemsen and Gooch [2002]; Knapp [1999]; Witmer and Sadowski [1998]).

4 Experiment III

Experiment II established that the source of the implicit feedback that influenced the results of Experiment I and likely influenced Jones et al. [2008] was peripheral visual information seen through a small gap below the HMD, between the HMD and the participants' face. However, Experiment II only established that this effect occurs in purely VR environments. One of the motivations of Jones et al. [2008] was to determine if the underestimation effects typically seen in virtual environments also occur in augmented environments. The relationship between distance judgment errors in augmented environments is not as well studied as virtual environments and is somewhat conflicting (Jones et al. [2008]; Swan et al. [2007]; Swan et al. [2006]). Depth cue theory seems to indicate that the more cue rich an environment is, the more accurately distances should be judged (e.g., Cutting [1997]). Given that the augmented environment used in these experiments consisted of a virtual stimulus presented in a real-world environment, one would expect that the available cues would allow for more accurate depth judgments than in a purely virtual environment. This is somewhat indicated, but not significantly so, in the results of Experiment I. However, given the findings of Experiment II, one must ask if these results were also influenced by the presence of the uncontrolled peripheral visual information. The current experiment aims to answer this question by studying a *Fully Occluded AR* and *ReHMD* condition.

4.1 Method

For this experiment, 16 naive participants were recruited from the general university population and either received course credit or monetary compensation for their participation. Eight participants experienced each condition in a between-subjects design. Participants wore the same opaque cloth depicted in Figure 1b, and the procedures very closely mimicked those in the *Fully Occluded* condition discussed in Experiment II. In the *AR* condition, participants observed a virtual stimulus presented in a real-world environment (Figure 2a). In the *ReHMD* condition, participants saw no computer generated imagery, but instead viewed a real-world stimulus placed in the same real-world environment, as seen through the optical see-through window of the HMD. For both conditions, the optical see-through window was closed before the participants performed the return walk.

4.2 Results

Figure 7 shows the results. An analysis of variance and calculated effect size indicated that the improved performance observed in Experiment I is not expressed in either the *ReHMD* or *AR* conditions when the periphery is restricted (*ReHMD*: $F(2,14) = 0.119$, $p = 0.889$, ns = 8+54, $d = 0.5\%$; *AR*: $F(2,14) = 0.317$, $p = 0.733$, ns = 8+15, $d = 1.4\%$). A somewhat remarkable finding is that the *ReHMD* and *AR* conditions did not significantly differ from each other ($F(1,14) = 0.110$, $p = 0.745$, ns = 16+1100). These findings are clearly visible in Figure 7, which for comparison purposes

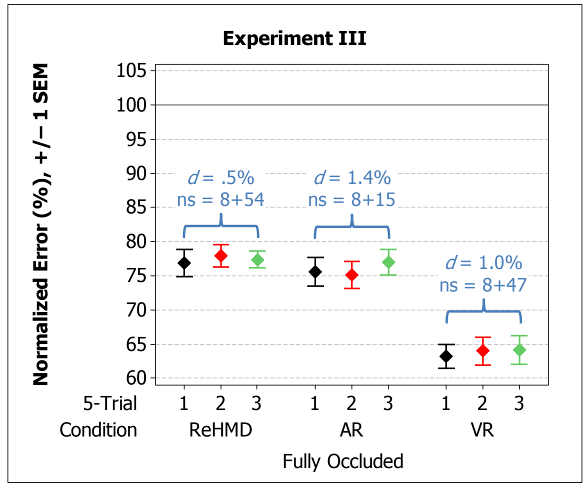

Figure 7: Distance judgments in the *Fully Occluded ReHMD, AR,* and *VR* conditions. For comparison purposes, this figure replicates the *Fully Occluded VR* condition from Figure 6.

also shows the *Fully Occluded VR* condition from Experiment II. When comparing distance judgments in the *Fully Occluded AR* condition (75.9%) to those recorded in Experiment I for the *Real* condition (95.3%), we find that they are significantly different ($F(1,16) = 24.139$, $p = 0.000$). This seems to establish that the underestimation effect exists in augmented environments, but to a lesser degree than seen in virtual environments. Perhaps an even more interesting finding is that the *Fully Occluded ReHMD* condition (77.4%) also differs significantly from the *Real* condition (95.3%) in Experiment I ($F(1,16) = 28.129$, $p = 0.000$). These results are consistent with those reported in Creem-Regehr et al. [2005] where participants viewed a real-world environment through field-of-view restricting goggles with a horizontal field-of-view of 42°. This field-of-view exactly matches the horizontal field-of-view of the HMD used in the experiments described in this document. Creem-Regehr et al. [2005] found that participants significantly underestimated distances (78.9%[*]) when restricted field-of-view was coupled with restricted head movements. Though, in the current experiment, participants' head movements were not restricted, they were instructed to look directly at the stimulus during the viewing phase of the blind walking task. These findings are also quite similar to those reported in Willemsen et al. [2009], where participants significantly underestimated distances (85.4%[*]) when viewing a real-world scene through a mock-HMD.

5 Experiment IV

Experiments II and III established that the addition and subtraction of peripheral visual information seen through the gap below the HMD has a strong effect on distance judgments. However, it is unclear if this facilitation was due to participants being able to localize their position through this gap or if visual information, such as optical flow, is correcting their spatial or motor perception. Experiment IV aims to answer this question by introducing a *Partially Occluded* condition. In this condition, the opaque occluder is replaced with a semi-opaque cloth through which luminance changes can be detected but shapes cannot be resolved.

[*] These normalized error values were derived from the figures presented in Creem-Regehr et al. [2005] and Willemsen et al. [2009].

5.1 Method

Sixteen naive participants were recruited from the general university population and either received course credit or monetary compensation for their participation. Both *AR* and *VR* viewing conditions were studied in Experiment IV. Eight participants experienced each condition in a between-subjects design. Other than the use of a semi-opaque cloth, the experimental procedures used in Experiment IV exactly mimic those used in Experiment III.

5.2 Results

Figure 8 shows the results. An analysis of variance and calculated effect size indicated that participants in the *AR* condition significantly improved their distance judgments over time, but their *VR* counterparts did not (*AR*: $F(2,14) = 7.399$, $p = 0.006$, $d = 8.3\%$; *VR*: $F(2,14) = 0.287$, $p = 0.755$, ns = 8+24, $d = 1.3\%$). These results are depicted in Figure 8a. The result that no adaptation was seen in the *VR* condition while it was apparent in the *AR* condition was somewhat confusing. At the end of all experimental sessions, participants undergo an informal debriefing where they discuss their experiences in the experiment with the experimenters. The experimenters noted that participants in the *VR* condition typically remarked that they noticed the glow of the backlight of the HMD's display elements on the return walk while none of the participants in the *AR* condition made this remark. It is worth noting that all of the return walk conditions are identical for both the *AR* and *VR* conditions; no graphics are displayed and the optical see-through window is closed. This seems to informally indicate that participants in the *VR* condition may be more narrowly directing their attention to the screen area, possibly due to the novelty of the virtual environment. This hypothesis prompted an extension to Experiment IV where participants in the *VR* condition were explicitly instructed to attend to their periphery during the return walk. Eight more participants were recruited for this new condition. As seen in Figure 8b, these participants exhibited significantly improved distance judgments with time when directed to attend to their periphery ($F(2,14) = 4.106$, $p = 0.040$, $d = 6.3\%$).

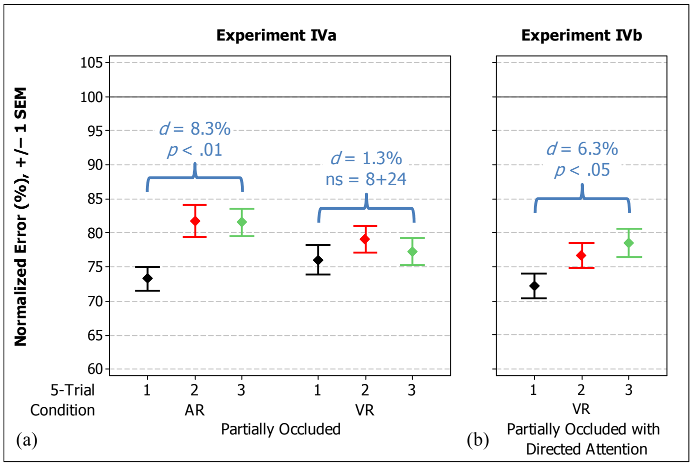

Figure 8: (a) Distance judgments in the *Partially Occluded AR* and *VR* conditions; (b) Distance judgments when *VR* attention is explicitly directed to the periphery.

6 Discussion

Experiment I aimed to determine whether or not the unusual reduced underestimation seen in Jones et al. [2008] was a result of transfer effects due to the within-subjects experimental design. In Experiment I the general trend of reduced underestimation persisted despite the between-subjects design. However, a striking pattern of increased accuracy emerged as Experiment I progressed. Since this pattern seems to be time dependant, a within-subjects design would hamper its detection as a result of presenting multiple environments in succession. Even so, this pattern was still visible, though to a much lesser degree, in Jones et al. [2008]. Experiment I seemed to indicate that between- and within-subjects experimental designs for exploring cross-environmental distance judgments may likely yield mutually comparable results, but within-subjects designs may make time- or repetition-dependant effects difficult to detect.

The pattern of increase accuracy as a function of time, seen in Experiment I, was an interesting and somewhat troublesome result, as it could indicate that participants were augmenting their distance judgments with uncontrolled feedback. Experiment II examined two possible sources of implicit feedback: the blind walking task itself and a gap below the HMD. However, neither source seemed a likely candidate. If the walking task was influencing the participants' judgments, one would expect their performance to decrease in variability while remaining centered around the originally underestimated position. However, participants' judgments rapidly approached veridical throughout the course of the experimental session, which typically lasted approximately 20 minutes. If the participants were acquiring visual information from the gap below the HMD, there is very little that is visible to use as feedback. Typically, participants would only be able to see the carpet of the experimental environment. Regardless, the ability to see any part of the surrounding environment leaves open the possibility that participants are able to localize their position within the environment during the return walk portion of the blind walking task. Another possibility is that optical flow cues seen in the lower periphery were affecting either the participants' perception of the environment or their movement within the environment. Rieser et al. [1995] performed an elegant series of real-world walking tasks where participants were exposed to varying rates of optical flow while walking at different speeds, and this study demonstrated that the calibration of participants' movements can be greatly affected by changing the relationship between optical flow and walking speed.

The results of Experiment II revealed that participants failed to improve their performance when the gap below the HMD was completely occluded. This seems to indicate the gap was the source of the uncontrolled feedback. This raised the possibility that observers were simply visually localizing their position during the experiment. Given the amount of the environment which was visible through the gap, this seemed an unlikely possibility. However, there was also the possibility that participants could be calibrating their movements based on peripheral optical flow. Experiment IV seemed to strongly indicate the latter. In this experiment, participants' views were partially occluded, enabling them to detect luminance changes through the occluder but not resolve their location. In this experiment, participants in the *AR* condition still exhibited improved performance, but participants in the *VR* condition only improved when they were specifically instructed to attend to their periphery. This was both an unexpected and exciting finding as it implies that the attention of participants in the *VR* condition was more narrowly focused than their *AR* counterparts. All participants were naive and had never experienced HMD-based virtual reality prior to this experiment. Given that this is a very unfamiliar experience, it seems plausible that the novelty of the virtual environment may be narrowing their attention to the screen area, thereby preventing *VR* participants from utilizing peripheral information as effectively as the *AR* participants.

Experiment III sought to answer a question originally posed by Jones et al. [2008]: does the underestimation effects seen in virtual environments also exist in augmented environments? To test this, the gap below the HMD was occluded and participants performed blind walks to a virtual object seen in the real world. Participants did significantly underestimate distances, judging stimuli distance to roughly 76% of their actual distance. This is intriguing, but even more so when compared to distance judgments to real stimuli seen through the HMD. Experiment III demonstrated that distance judgments in an augmented environment was not significantly different from those in a real-world environment when viewed through the HMD. This seems to indicate that the majority of the distance information acquired while viewing an object comes from the surrounding environment and not the object itself. This also implies that augmented environments may not suffer as greatly from the underestimation effects typically seen in virtual environments. The bulk of the underestimation in the *ReHMD* and *AR* conditions seems to be caused by viewing the environment through the HMD. This is quite possibly due to the restricted field of view and inability to see visual information in the periphery, which these and several other experiments (Willemsen et al. [2009]; Creem-Regehr et al. [2005]; Wu et al. [2004]) have indicated to be an important factor in improving distance judgments.

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