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Improvements in Visually Directed Walking in Virtual Environments Cannot be Explained by Changes in Gait Alone

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ABSTRACT

A previous study indicated that peripheral visual information strongly affects the judgment of egocentric distances for users of immersive virtual environments. The experiment described in this document aimed to investigate if these effects could be explained in terms of changes in gait caused by visual information in the extreme periphery. Three conditions with varying degrees of peripheral occlusion were tested and participants' walking characteristics measured. The results indicate that the improvements in distance judgments, as peripheral information increases, can only partially be explained in terms of gait modification, but likely involve both changes in the characteristics of gait and other spatial or movement parameters.

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, mixed reality, virtual reality, peripheral vision, gait, walking, locomotion

1 INTRODUCTION

The study of distance underestimation has been a long standing topic of interest in the virtual environments community (e.g., Jones et al. [2011]; Singh et al. [2010]; Willemsen et al. [2009]; Jones et al. [2008]; Richardson and Waller [2007]; Swan et al. [2007]; Swan et al. [2006]; Interrante et al. [2006]; Creem-Regher et al. [2005]; Thompson et al. [2004]; Willemsen et al. [2004]; Loomis and Knapp [2003]; Willemsen and Gooch [2002]; Knapp [1999]; Witmer and Sadowski [1998]). However, surprisingly little progress has been made towards identifying the mechanisms that are involved in producing these widely observed errors. Jones et al. [2011] conducted a large series of experiments in virtual environments, augmented environments, and the real-world that studied the effect of varying levels of visual information available in the lower, extreme periphery and their effect on distance judgments. This work demonstrated that as peripheral information was increased, the accuracy of distance judgments increased as well. Participants in an immersive virtual environment rapidly approached real-world performance over the course of the experiment. However, the question remains open as to why small amounts of peripheral information caused such large increases in accuracy.

One possible explanation for the improvement seen in Jones et al. [2011] is that participants were using the peripheral visual information as a means of altering their gait. It is important to take this opportunity to clarify the term "gait" as it applies to this document. We define gait as described in Whittle's book "Gait Analysis: An Introduction" [2001], and we thus consider gait to be the "manner or style of walking" and not the general application of this style or manner. As such, references to gait in this document describe walking in terms of the characteristics of a single gait cycle consisting of a full step made by each the left and right legs.

2 EXPERIMENT

This experiment investigated the possibility that participants may be unintentionally walking more cautiously when in the virtual environment, for instance by taking smaller steps. If participants were unaware of such an error in gait, it would manifest itself as underestimations in walked distances. A natural method of regulating self-motion is by correlating gait with optical flow. Rieser et al. [1995] demonstrated that individuals, when presented with mismatched optical flow and walking speed, would adjust their movements. By manipulating the relationship between walking speed and optical flow, Rieser et al. [1995] were able to subsequently bias individuals' walking distances relative to the rearrangement they experienced. Their study clearly demonstrated the importance of visual information in accurately walking in the real-world. If observers of immersive virtual environments default to smaller, more reserved, steps yet lack sufficient visual information to register their errors, distance judgments expressed by walking would remain compressed throughout their experience in the environment. However, if the participants were provided with visual flow indicative of erroneous gait, they may be able to use this information to correct their movements. The current experiment aimed to replicate the findings presented in Jones et al. [2011] and also to determine if change in gait was, in fact, the mechanism by which participants were able to improve their distance judgments.

2.1 METHOD

A group of 21 naïve participants were recruited from the general student population at Mississippi State University. Each participant experienced one of three possible conditions (*High Cue*, *Low Cue*, and *No Cue* conditions) which were designed to test the effect of varying degrees of peripheral information displayed at the far edge of the lower periphery. These conditions are illustrated in Figure 1. In the *High Cue* condition, participants were presented with an immersive virtual environment with the extreme lower periphery open to the surrounding real-world environment. The floor in the real-world environment consisted of dark carpet with a linear weave pattern and a white measuring tape that extended down its length. It was suspected that this would provide strong cues to the participants' movements. In the *Low Cue* condition, participants were presented with the same virtual environment, but their periphery was obscured with a semi-opaque, black cloth through which only a faint glow from the real-world environment

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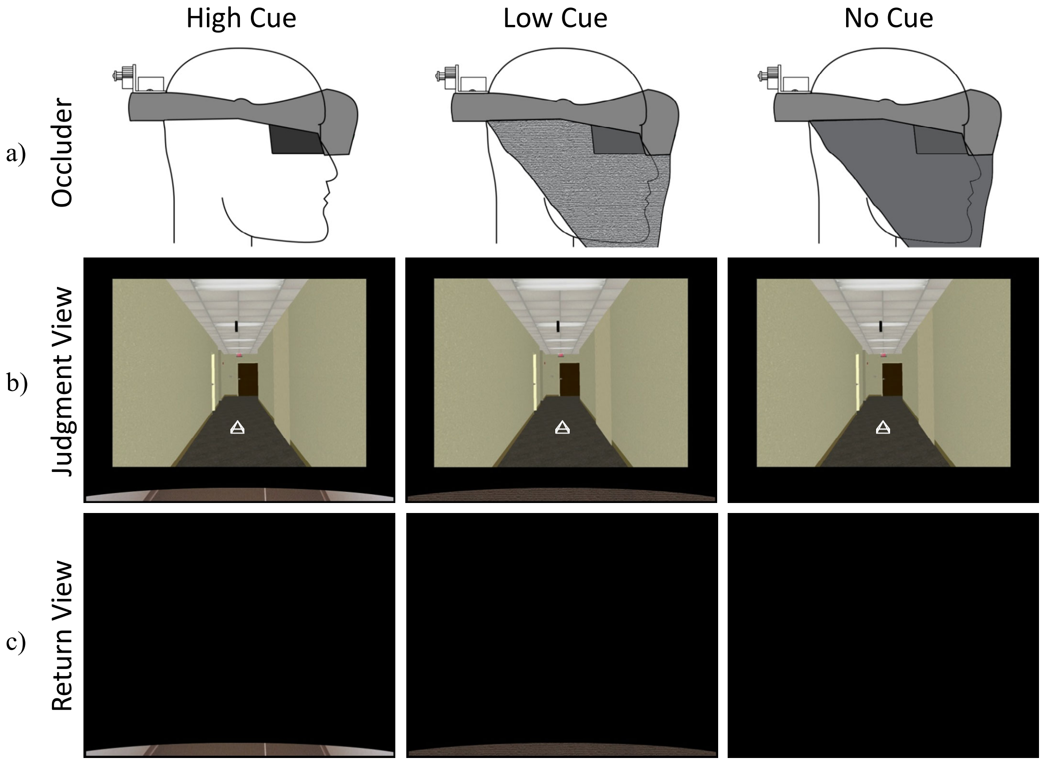

Figure 1: (a) Occluder configurations and simulated views through the HMD of the (b) judgment phase and (c) return walks of each condition.

was visible. Additionally, the white tape, the most prominent feature on the ground plane, was removed from the real-world environment. In the *No Cue* condition, participants' periphery was completely blocked with an opaque, black cloth. All conditions were viewed through an NVIS nVisor ST60. This head-mounted display has 60° diagonal, 48° horizontal, and 40° vertical fields-of-view. The ST60 is an optical see-through augmented reality display, but may also be used as a virtual reality display by closing the optical see-through window. The window was closed for all conditions, and participants judged distances using visually directed walking. Figure 1b shows simulated views of the environments as seen by the participants. On the return walk portion of the procedure, the virtual environment was replaced with a black screen and participants were instructed to keep their eyes open, leaving the lower periphery as the only source of visual information, illustrated in Figure 1c.

2.2 DESIGN & PROCEDURES

This experiment was intended to closely mimic the conditions presented in Jones et al. [2011]. Specifically, the *No Cue*, *Low Cue*, and *High Cue* conditions described in this document correspond to the *VR Fully Occluded*, *VR Partially Occluded*, and initial *VR* conditions discussed in Jones et al. [2011].

The stimulus used to indicate target distances was a white, wireframe pyramid with a square base of 23.5cm and a height of 23.5cm. The stimulus was 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.

At the beginning of each trial, participants were instructed to close their eyes. Next, the virtual environment, including the stimulus appeared in the display. 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. At this point, the virtual environment was replaced with a black screen. Once the participants 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 instructed to walk back to the starting position with their eyes open. The distances walked by the participants were recorded, along with the total number of steps taken and their elapsed walk time.

The view calibration and alignment procedures used in Jones et al. [2008, 2011] were used in this experiment as well. Participants performed a series of boresight alignments using the 3D-Compass method. This procedure was performed before each experimental session, on a per-subject basis, in order to ensure that the participants' real-world views matched those modeled in the virtual environment. Participants were screened both before and after participation for signs of motion sickness and impaired locomotion.

2.3 ANALYSIS

Analyses of distance judgments were conducted with *percent error = (walked distance / target distance) – 100%.* Analyses of gait were conducted on *step length = walked distance / number of steps taken*; *steps per stimulus meter = number of steps taken / target distance*; and *walking speed = walked distance / duration of judgment walk*. Each experimental *Condition* is subdivided according to *5-Trials*, the mean of 5 consecutive trials, so $5\text{-}Trials_1 = mean(\ trial_1 : trial_5\ )$, $5\text{-}Trials_2 = mean(\ trial_6 : trial_{10}\ )$, and $5\text{-}Trials_3 = mean(\ trial_{11} : trial_{15}\ )$. The *5-Trials* break the experiment into the first, second, and final thirds. All time based analyses were conducting using *5-Trials* as the time scale. Additionally, the effect size for analyses are reported as the total

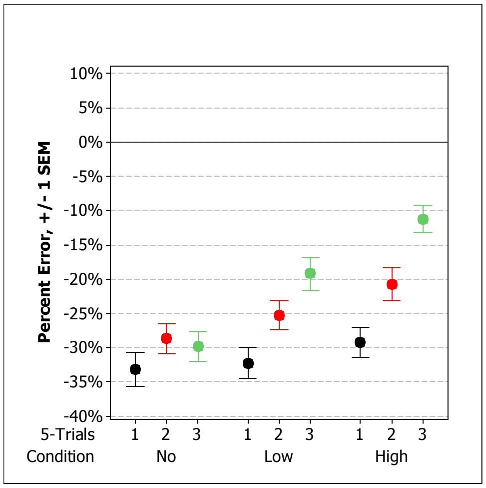

Figure 2: Distance judgment errors for the *No*, *Low*, and *High Cue* conditions.

change in a given term between the first and final *5-Trials* such that $d = \textit{5-Trials}_3 - \textit{5-Trials}_1$.

2.4 RESULTS

An analysis of variance was conducted on *percent error* with respect to time in terms of *5-Trials*. Figure 2 shows these results. The *No Cue* condition served as the control and was used to gauge the relative improvement seen in the *Low Cue* and *High Cue* conditions. Seven participants experienced each condition. However, one participant was removed from analysis in the *No Cue* condition due to a failure to follow the experimental procedure. The *No Cue* condition exhibited no significant change in distance judgments over the course of the experimental session with a mean percent error of -30.6% ($F(2, 10) = 1.43$, $p = 0.284$, $d = 3.43\%$). The *Low Cue* condition exhibited significant improvement over the course of the experiment with percent error reaching -19.2% ($F(2, 12) = 14.43$, $p = 0.001$, $d = 13.1\%$). The *High Cue* condition exhibited the most improvement with mean error in judgments shrinking to -11.2% ($F(2, 12) = 13.72$, $p = 0.001$, $d = 18.0\%$). These results generally replicate those found in Jones et al. [2011] with no significant improvement when no peripheral information is available, moderate improvement when the periphery is partially obscured, and large improvement when peripheral information is unimpeded.

Step length was also analyzed to determine if it could explain the improvements in distance judgments. Figure 3 shows step length as a function of time. As hypothesized, step length in the *High Cue* condition did significantly increase over the course of the experiment ($F(2, 12) = 5.12$, $p = 0.025$, $d = 0.12$m). However, step length did not change in either the *Low* or *No Cue* conditions (*No*: $F(2, 10) = 0.31$, $p = 0.739$, $d = 0.03$m; *Low*: $F(2, 12) = 1.24$, $p = 0.324$, $d = 0.03$m). Additionally, step length in the *Low* and *No Cue* conditions did not significantly differ from each other ($F(2, 22) = 0.03$, $p = 0.968$). This result was contrary to expectations and indicates that the improvement seen in the *Low Cue* condition is not due to changes in step length. Interestingly, participants in the *Low* and *No Cue* conditions also took much longer steps than their *High Cue* counterparts, ranging from 0.10m to 0.31m longer. One might assume that if participants were walking more hesitantly in the *Low* and *No Cue* conditions, then they would take smaller steps relative to the *High Cue* condition, where visual information is most plentiful. However, this was not the case in this study.

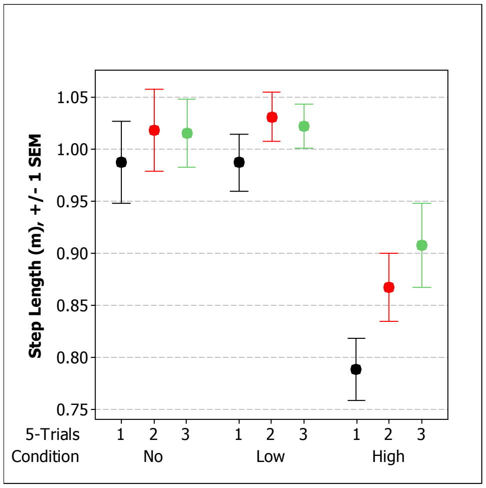

Figure 3: Step length per condition, separated by time.

Walking speed was analyzed to determine if participants may be expressing hesitation in their movements by walking more slowly. These results, depicted in Figure 4, indicate that walking speeds did not significantly differ between conditions ($F(2, 17) = 2.02$, $p = 0.164$). However, there was an insignificant trend indicative that participants in the *Low* and *No Cue* conditions may actually be walking faster than participants in the *High Cue* condition. In all conditions, participants did significantly increase their walking speed over time (*No*: $F(2, 10) = 11.34$, $p = 0.003$, $d = 0.08$m/s; *Low*: $F(2, 12) = 4.46$, $p = 0.036$, $d = 0.04$m/s; *High*: $F(2, 12) = 7.23$, $p = 0.009$, $d = 0.07$m/s).

These results are somewhat surprising as the *Low* and *No Cue* conditions seem to not differ in their general gait characteristics even though participants in the *Low Cue* condition do significantly outperform participants in the *No Cue* condition when performing distance judgments. By the nature of walking, at least one of two factors must change in order for the participants to be walking further. When walking a further distance, one must take more steps or one must take longer steps. Since participants in the *Low Cue* condition are not taking longer steps, they must be taking more steps. To confirm this, the mean number of steps per stimulus meter was analyzed. This parameter is defined as the number of steps taken divided by the target distance for a given trial. Figure 5 shows these results. As expected, participants in the *Low Cue* condition significantly increased their number of steps through the course of the experiment ($F(2, 12) = 4.65$, $p = 0.032$, $d = 0.10$ steps). Participants in the *No* and *High Cue* conditions did not significantly increase their number of steps (*No*: $F(2, 10) = 0.22$, $p = 0.803$, $d = 0.01$ steps; *High*: $F(2, 12) = 1.15$, $p = 0.348$, $d = 0.11$ steps). However, it is worth noting that even though participants in the *High Cue* condition did not significantly change their number of steps over time, they did take significantly more steps, on average, than participants in the either the *Low* or *No Cue* conditions (*High vs Low*: $F(1, 12) = 5.05$, $p = 0.044$; *High vs No*: $F(1, 11) = 6.16$, $p = 0.030$).

This indicates that a combination of increased number of steps and increased step length is responsible for the improved accuracy in the *High Cue* condition. On the other hand, improvements in the *Low Cue* condition seem to be predominately due to an increase in the number of steps walked. When accurately walking, these parameters have an inverse relationship. This relationship is visualized in Figure 6 by plotting step length and steps per meter of stimulus distance in the virtual environment on a per-trial basis along logarithmically increasing axes. Points that fall along the

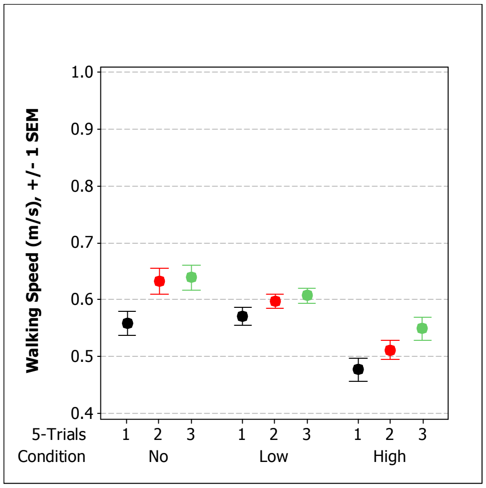

Figure 4: Walking speed as a function of cue condition and time.

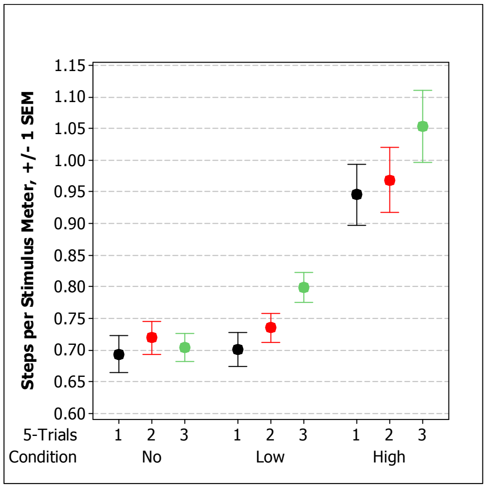

Figure 5: Steps taken per stimulus meter (steps per target position in the virtual environment).

diagonal represent *step length*/*steps per meter* pairs that would result in accurately walking a given distance. Points below the diagonal, by necessity, would result in compressed walking distances while points above the diagonal would indicate overly lengthened distances. This figure shows individual values, separated by *5-Trials*, and their corresponding group means. It can be seen that little change happens over time in the *No Cue* condition. It can also be seen that the majority of the changes in the *Low Cue* condition occur along the *steps per meter* axis, bringing the grouping closer to the diagonal. However, in the *High Cue* condition, it can be seen that both more steps and longer step lengths heavily influence the participants' performance.

3 DISCUSSION

The importance of understanding which parameters are being altered by the varying levels of peripheral information is that it can help us determine if these changes are adjustments of the participants' movements or if the participants' spatial understanding is being further informed. This experiment attempted to separate these two possibilities by examining changes in gait to determine if participants were altering the way they walked or simply walking longer distances. These, of course, are not mutually exclusive changes, but each suggests something different about why an individual walks a given distance. If the participants' step length is changing, this may imply that they are altering characteristics of their gait based on the visual information available in their periphery. On the other hand, if participants' step length does not change but instead they take more steps, this could imply a change in some other representation potentially related to the perceived scale of distances. However, further experimentation is needed to clarify these possibilities.

When analyzing changes in step length, it became obvious that participants in the *High Cue* condition were significantly increasing their step length throughout the course of the experiment while participants in the *Low* and *No Cue* conditions were not. Alteration of step length could, in fact, be a cause for improved performance in the *High Cue* condition, but recall that improvements also occurred in the *Low Cue* condition. This indicates that changes in step length cannot be the sole factor contributing to improved walking distances. As depicted in Figure 3, participants in the *High Cue* condition still took smaller steps than their *Low* and *No Cue* counterparts. The step lengths found in the *Low* and *No Cue* conditions are quite similar to those reported by Mohler et al. [2007] and Phillips et al. [2010], where participants walked in typical HMD-based virtual environments. Additionally, there were no significant differences in walking speed between any of the conditions. Shorter steps and slower speeds are generally associated with cautious or disordered gaits (Hausdorff [2007]; Rubino [2002]). This indicates that participants the *Low* and *No Cue* conditions are no more cautious while walking than participants in the *High Cue* condition. These observations seem to somewhat contradict anecdotal observations of highly reserved movement in virtual environments, implying that participants may be walking less cautiously than has been previously assumed. However, no real-world walking condition was recorded for this experiment, and some previous work has indicated that users tend to walk with somewhat slower and shorter steps in virtual environments as compared to the real-world (Mohler et al. [2007]; Souman et al. [2011]).

Though gait changes do not appear to be a common contributing factor for the improvements seen in the *High* and *Low Cue* conditions, number of steps taken per stimulus meter is significantly higher in these two conditions as compared to the *No Cue* condition. A large amount of the improved performance seen in these conditions seems to be associated with this parameter. This is consistent with the real-world changes in walking distances demonstrated by Rieser et al. [1995]. In that study, after participants experienced mismatched optical flow and walking speeds, no significant change was detected in step length, but participants did significantly alter the number of steps taken to walk a given distance. Changes in the number of steps taken imply that the additional visual information may be modifying the participants' sense of the scale of their movements or of the distance to be traversed. Using the methods described in this document, it is not possible to determine which of these representations is changing.

It is also important to note that work by Philbeck et al. [2008] has indicated that lengthened judgment walks in real-world environments can occur in the absence of any explicitly provided visual information, resulting in a positive bias in distance judgments over time. However, the changes observed in this experiment and Jones et al. [2011] do not seem to be caused by a general tendency to walk further over time. These experiments have consistently demonstrated that no significant changes in walking distance occur when participants' periphery is sufficiently impoverished.

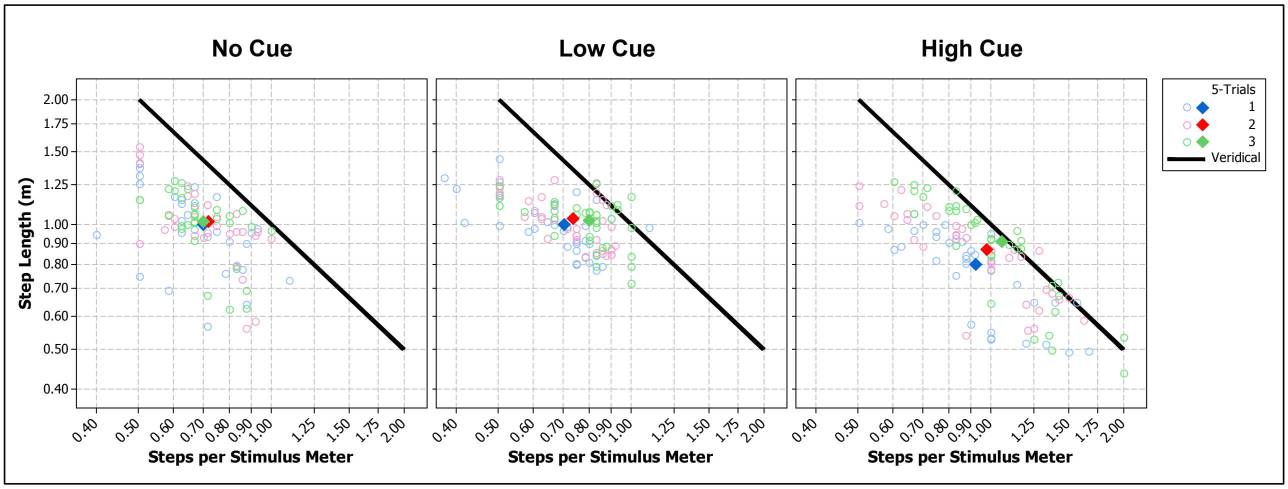

Figure 6: Scatter plot visualizing the relationship between *step length* and *steps per stimulus meter*. Circles represent individual values while diamonds represent the mean for a given group. The veridical line is representative of *step length* and *steps per stimulus meter* combinations that would results in accurately walking a given distance.

Wu et al. [2004] experimented with expanding an observer's field-of-view, effectively increasing the amount of periphery that would be available. They demonstrated that as vertical field-of-view increased so did walking distance judgments. Though the relative amount of visual area available in the current experiment does not change between the *High* and *Low Cue* conditions, the fidelity of that information does change. In terms of availability of information in the vertical periphery, the results of this experiment are consistent with those described in Wu et al. [2004].

4 CONCLUSIONS

Though the exact mechanisms involved in the improved performance observed in this study and Jones et al. [2011] may not be clear, the influence of the periphery beyond the standard screen area is quite obviously important. However, we can see from these results that compressed distance judgments in virtual environments cannot be solely explained in terms of errors in gait. This is not to say that gait errors do not contribute to underestimation in virtual environments, but that it is likely a combination of this and other factors.

To better understand the effects measured in this experiment, a more robust study must be performed. A rigorous evaluation of the relative normalcy of the participants' gait could not be performed as no real-world baseline was recorded. A comparison of gait in the real-world before and after immersion into the virtual environment would likely yield a clearer understanding of the observations reported in this document. It may also determine whether or not participants are recalibrating their gait in response to the presence or absence of peripheral visual information.

Additionally, the experiment described here was designed to detect gait modification, but did not include sufficient conditions to explain the causes of increased number of steps. As previously mentioned, the increased number of steps taken during the experimental sessions can have multiple explanations. Future work should aim to determine which parameters are being altered by the presence of additional peripheral information.

Regardless of the limited scope of this experiment, these findings and those of Jones et al. [2011] have important implications for the design of virtual environments and head-mounted displays. The vast majority of virtual environments research has been directed toward narrow, forward-looking fields-of-view, leaving the extreme periphery largely ignored. The choice to focus on narrow, forward views is not without cause. This is where humans typically look while navigating and performing tasks. However, as indicated by these experiments, visual stimulation in the extreme periphery is exceedingly important for correctly judging walkable distances in virtual environments. This experiment, however, only examined the effect of information presented in the lower periphery. The question is still open as to whether or not similar benefits can be gleaned from other peripheral areas as well.

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