Peripheral Stimulation and its Effect on Perceived Spatial Scale in Virtual Environments

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ABSTRACT

The following series of experiments explore the effect of static peripheral stimulation on the perception of distance and spatial scale in a typical head-mounted virtual environment. It was found that applying constant white light in an observer's far periphery enabled the observer to more accurately judge distances using blind walking. An effect of similar magnitude was also found when observers estimated the size of a virtual space using a visual scale task. The presence of the effect across multiple psychophysical tasks provided confidence that a perceptual change was, in fact, being invoked by the addition of the peripheral stimulation. These results were also compared to observer performance in a very large field of view virtual environment and in the real world. The subsequent findings raise the possibility that distance judgments in virtual environments might be considerably more similar to those in the real world than previous work has suggested.

Index Terms: 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—Artifical, Augmented, and Virtual Realities; H.1.2 [Information Systems]: User/Machine Systems—Human Factors

1 INTRODUCTION

Users of virtual environments, when judging positions along the ground plane, have consistently indicated that the apparent distance of objects appear closer than their actual geometric position [5, 13–15, 19, 25, 30, 32, 33, 37, 38, 40, 44–47]. This effect is confusing as great lengths are often taken to ensure that the retinal projection of the virtual environment closely matches that of an equivalent real world environment [2, 28, 31, 42]. This is even more interesting when comparing these results to the significantly larger body of distance judgment literature that exists for real world environments. These studies quite uniformly demonstrate veridical performance across a large range of distances when full visual cues are available [19, 25, 29, 41, 43]. However, it is frequently the case that not all visual signals available in the real world can be reasonably reproduced in the virtual world. It is an open question as to which of these signals are necessary to enable accurate spatial perception in virtual environments. Jones et al. [14, 16] provide evidence indicating that visual stimulation in the far periphery may be an important source of information when performing spatial judgments. This was an intriguing result as many virtual environments seldom present visual stimulation outside of the near periphery, see Figure 1. However, their work was not conclusive as to the exact manner by which this stimulation provided benefit. This document details a series of five experiments intended to expand upon the work described by Jones et al. [14, 16] and to further inform the nature of the benefit provided by peripheral stimulation.

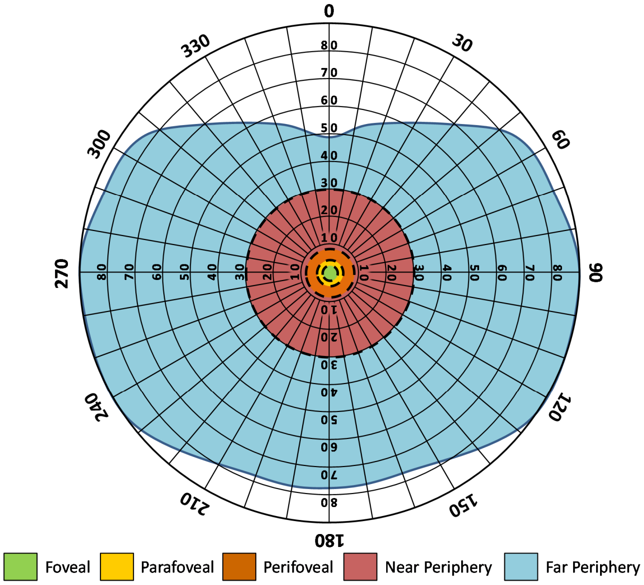

Figure 1: Regions within the human binocular field of view. Adapted from Taylor [39], Boring et al. [3], and Strasburger et al. [36].

2 RELATED WORK

It has long been established that vision is a strong guide to action, especially with regard to our movements within an environment [9–11, 41]. As such, visually guided movements, including walking, jumping, pointing, or reaching, are generally well calibrated with regard to our spatial understanding of the world around us [8, 10, 18, 29, 32, 41]. This connection between movement and vision has led to a considerable body of research devoted to how we judge distances under varying viewing restrictions. Cutting and Vishton [6, 7] offer an informative introduction to the basic visual cues indicative of distance and their effectiveness across three ranges of distances: personal, action, and vista space. An often used alternative nomenclature for these spaces is respectively near, medium, and far field. These labels are effectively equivalent, with near field distances being those within arm's length, medium field being distances extending to roughly 30m, and the far field representing all distances beyond 30m.

There is no lack of prior work in the field of distance judgments as visually guided movements are an important part of our everyday lives. In real world viewing conditions, people are quite accurate in judging positions across a large range of distances using a variety of methods [19, 24, 29, 32, 33, 37, 41]. Observers have been shown to be able to accurately judge distances within arm's length

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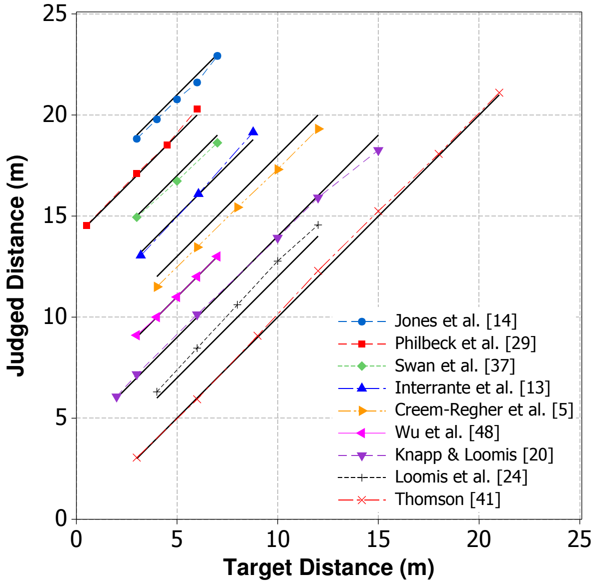

Figure 2: Mean distance judgments from several real world blind walking experiments. Individual series of judgments have been vertically offset for ease of viewing. Each is presented with a bold, black line indicative of ideal performance.

using blind reaching tasks. In such tasks, an observer is shown a target displaced in space and then asked to blindly reach to its location [8, 32, 33]. In the medium field, blind walking (otherwise referred to as visually directed walking) is commonly used as a means of reliably measuring distance judgments out to roughly 20 meters with remarkable accuracy [19, 20, 29, 41]. A modest sampling of real world blind walking results can be seen in Figure 2. In blind walking, observers are typically shown a target located along the ground plane at a given distance. They then either close their eyes or have their vision blocked and walk until they feel they are standing at the target distance. The walked distance is then used as an indication of the perceived distance of the target position. Variants of this technique, such as imagined walking and triangulated walking, have been shown to provide similar results [18, 44].

In head-mounted virtual environments, however, a curious trend of underestimated distances has been documented [5, 13–15, 19, 25, 30, 32, 33, 37, 38, 40, 44–47]. Many of these studies employ one or more of the psychophysical measurement techniques described above. The magnitude of the underestimation varies appreciably from one set of results to the next. Many researchers have attempted to offer speculative explanations. Unfortunately, no consensus has been reached as to why these underestimations occur in virtual environments. Some have investigated the possibility that improper modeling of the display device's optical and geometric characteristics is to blame, but found only somewhat negligible effects on distance estimation errors [17, 22]. This is a reasonable concern as the proper modeling of the optical characteristics of the image producing system (the display device) and the image receiving system (the human eye) is necessary to produce an image of the virtual environment that would result in a retinal projection comparable to that of an equivalent real world environment. Considerable effort, however, has been invested in calibration techniques that ensure that these parameters are controlled [2, 28, 31, 42]. Other work has indicated that humans are capable of tolerating a certain amount of miscalibration in the modeling of their physical and display characteristics [4]. Another often speculated candidate is the variable depth of focus in the real world which triggers the ocular accommodative response [6]. Variable focus does not usually exist in virtual environments due to technical limitations of the fixed optical systems typically used in head-mounted displays. This results in a decoupling of the ocular accommodative response from other depth cues available in a virtual environment. To somewhat mitigate this factor, many head-mounted displays have fixed focal distances at or near optical infinity as the accommodative response of most humans is negligible beyond roughly 2 meters [6]. This, of course, reduces bias introduced by accommodative mismatch for distances at 2 meters and beyond, but not for closer distances. For most medium field virtual environments, this is an acceptable compromise and leads one to discount accommodation as a source of the oft cited underestimations. Others have speculated that the limited field of view of many head-mounted displays is a possible culprit. However, there exists conflicting results regarding field of view as the contributing factor. Work by Wu et al. [48] indicated that distance judgments in the real world suffered as the vertical, but not horizontal, field of view was restricted. However, Wu et al. [48] also found that this effect could be countered by allowing observers to pan their view vertically along the ground plane. However, both Knapp and Loomis [20] and Creem-Regher et al. [5] found no effect of field of view on distance judgments. Other work by Jones et al. [14] found evidence that indicated that a small field of view virtual environment could produce improved distance judgments when real world optical flow was added to the lower, far periphery. However, they were unable to explain why this was the case. A follow-up study by Jones et al. [16] attempted to determine if this far peripheral optical flow was causing observers to recalibrate their gait, enabling them to move more accurately in the virtual environment. They found that gait did seem to be a partial contributing factor but that it was insufficient to explain all the observed improvements. They speculated that the peripheral stimulation may have served as an additional reference to the location of the ground plane relative to the observers' eye position.

The findings described by Jones et al. [14, 16] are intriguing as the area within the visual field where the stimulation was provided is outside of that typically considered in most virtual environment experiments. The binocular field of view for most humans spans a range of 180°×120°. Figure 1 shows a polar representation of the angular expanse of the typical, forward looking, binocular field of view. This figure is adapted from that described by Taylor [39] which is itself based on that described by Boring et al. [3]. Most current head-mounted displays seldom provide fields of view larger than 60°. As can be seen in Figure 1, this is a substantially small portion of that which would be available under real world viewing conditions. The remainder of our field of view is not without purpose. A large body of research in the visual sciences has been dedicated to studying differences in the detection of visual stimuli in the periphery. For instance, motion detection thresholds in the periphery are much higher than for central vision [23, 27]. The ability to resolve minute variations in luminance in low light conditions is significantly better in the periphery [36]. Though detail resolution is quite low, peripheral vision provides finer temporal resolution than central vision [12]. Reports, dating back as far as the late 1800s, claim that our peripheral vision is used to aid in orientation and obstacle avoidance [1, 9]. Other studies have shown that when vision in the periphery is restricted, in either the real or virtual world, our ability to understand our surroundings and judge spatial relationships suffers greatly [1, 14, 16, 48]. These are fundamental features of how the periphery influences visually driven actions. However, the vast majority of the periphery is unavailable in most virtual environments.

Before continuing further, it is important to clarify the terminology to be used when discussing the periphery. For these purposes, we borrow and somewhat adapt the terminology described by Stras-

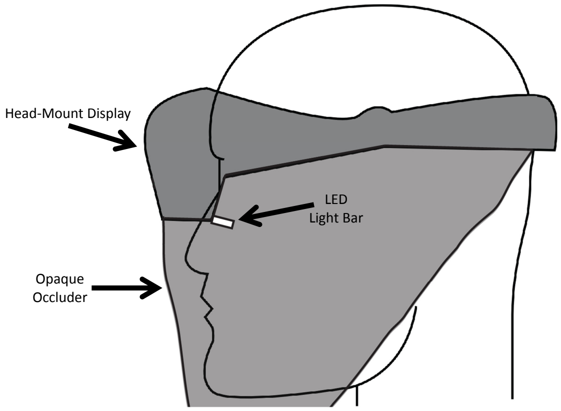

Figure 3: Head-mount display, occluder, and light bar used in Experiment I.

Figure 4: The virtual environment used in Experiments I through IV.

burger et al. [36]. We refer to foveal vision as the area within the radius of 2.5°, parafoveal extending from 2.5° to 4.5°, and perifoveal extending from 4.5° to 8.5°. We will collectively refer to these areas as central vision. The area beyond central vision extending to a radius of 30° we refer to as near periphery. All areas beyond a radius of 30° will be referred to as far periphery. A visual representation of these areas is shown in Figure 1.

3 EXPERIMENT I: LIGHT BAR STIMULATION

The work described by Jones et al. [14] demonstrated substantial improvements in distance judgments as participants were exposed to varying levels of peripheral visual information near the lower edge of the observers' natural field of view. The speculative explanation offered for these results was that participants were using peripheral optical flow as a means of either correcting their movements or internalized scale of the environment. However, one of the conditions described in these experiments brings this explanation into question. Specifically, the *VR Partially Occluded with Attention* condition described by Jones et al. [14] provided remarkably little visual information, yet it yielded significant improvements in distance judgments. In the *VR Partially Occluded with Attention* condition, participants were provided with low fidelity optical flow in near darkness at the extreme lower edge of their periphery while viewing a small field of view virtual environment. Could it be possible that this improvement came from a source other than optical flow? Experiment I aimed to answer this question by providing visual stimulation but no optical flow in the observers' lower, far periphery.

3.1 Method

Eight participants (*4 males, 4 females, mean age: 25*) with normal or corrected to normal vision were recruited for this experiment. All participants were naive to the purposes of the experiment. Participants viewed a virtual environment through an NVIS nVisor ST60 head-mounted display. This display offers horizontal, vertical, and diagonal fields of view of 48°×40°×60°. The virtual environment, shown in Figure 4, consisted of a high fidelity model of a real world hallway which spanned 1.82m in width and 16.53m in length from the participants' viewing position. The virtual environment was realistically lit and textured to match its real world counterpart. Participants wore earphones that played continuous white noise in order to prevent auditory influences from affecting distance judgments. Instructions were communicated to the participants via a wireless microphone system. Participants performed blind walking as a means of judging distances to previously viewed objects placed along the ground plane. After each blind walking trial, the virtual environment was visually muted and participants were guided back to their starting position. Though no visual information was presented during the return walk, to maintain methodological consistency between this study and those described by Jones et al. [14,16], participants were instructed to keep their eyes open until they were returned to the starting position. The object used to indicate target distances was a white, wireframe pyramid with a square base of 23.5cm and an apex of 23.5cm. Target distances ranged from 3 to 7 meters in 1 meter increments. Each distance was presented three times resulting in a total of 15 trials. Presentation order of target distances was determined by a restricted random shuffle, with the restriction criterion that no target distance could be presented twice in immediate succession. In Jones et al. [14], participants were exposed to varying levels of real world peripheral stimulation through a small gap between the display and the participants' faces. For this experiment, two stationary white LED light bars were placed in this gap, one corresponding to each of the display's eyepieces, as shown in Figure 3. Each light bar was constructed from a length of white plastic conduit with a single white LED placed in one end. The LED was powered by direct current from a small battery. The light bars were powered on after each participant donned the head-mounted display, and they remained illuminated for the duration of the experiment. The remainder of the periphery was fully occluded using an opaque, black cloth. Figure 5 shows the arrangement of the virtual environment and light bar in terms of their position within the field of view. All areas within the field of view, excepting the display area and light bars, were completely darkened. This *Light Bar* condition was intended to provide light stimulation in the same area as described by Jones et al. [14] but without the influence of optical flow. This condition should be no more spatially informative than having no stimulation in the periphery. Jones et al. [14] demonstrated that when participants viewed a virtual environment with the far peripheral fully occluded, they judged distances to be only 63.8% of their actual length. Given the similarity of these two conditions, one would expect no substantial difference. It is important to note that for this experiment the virtual environment, physical location, head-mounted display, and procedures exactly matched those used in Jones et al. [14].

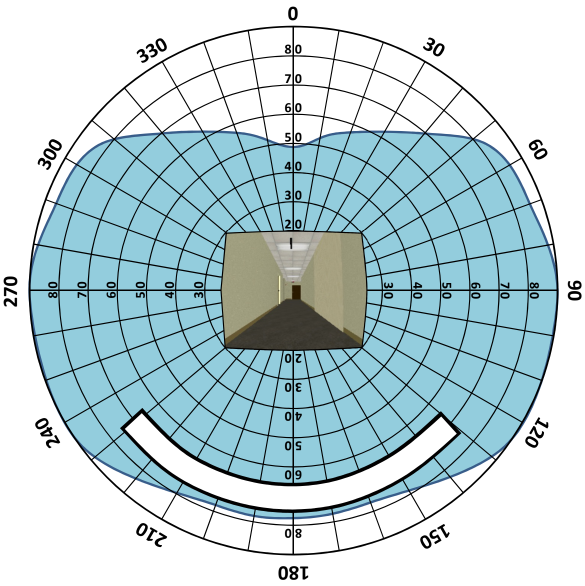

Figure 5: Placement of virtual environment and light bar within the field of view. The shaded region denotes the extent of the typical human's field of view.

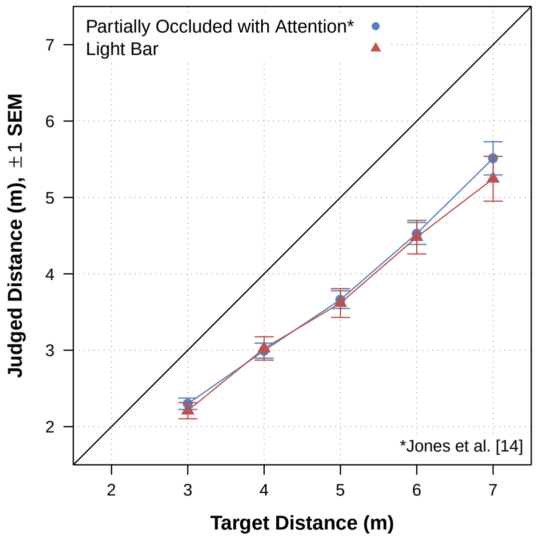

Figure 6: Mean distance judgments from Experiment I and the *VR Partially Occluded with Attention* condition from Jones et al. [14].

3.2 Results

The accuracy of distance judgments in this and the following experiments are analyzed in terms of percent distance defined as the distance walked during the blind walking procedure divided by the target distance. An accurate distance judgment, therefore, would result in a percent distance of 100% while underestimations will result in a value less than 100% and overestimations higher than 100%. All judgments were analyzed using a mixed model analysis of variance (ANOVA). Figure 6 shows the main findings from this experiment. Participants in the *Light Bar* condition averaged 74.24% accuracy. When comparing this to the performance of participants in the *VR Partially Occluded with Attention* condition (75.79%) from Jones et al. [14] who were supposedly benefitting from optical flow, we find that they do not significantly differ ($F(1,14)$=0.048, p=0.831). Also, the improvements seen in the *VR Partially Occluded with Attention* condition were found to significantly increase as a function of time. However, this trend did not significantly express itself in the *Light Bar* condition ($F(2,14)$=2.210, p=0.147). Instead, the improved performance was more generally distributed over the course of the experiment. These are confusing results as the *Light Bar* condition essentially added no information to the scene, yet participants judged distances as accurately as those who were supposedly benefitting from optical flow indicative of their movements.

4 EXPERIMENT II: PERIPHERAL FRAME STIMULATION

The results from Experiment I show that participants gained at least some benefit from the presence of a stationary light source in the lower, far periphery. However, is this benefit limited to the lower periphery? Would participants glean even more benefit from also receiving stimulation across the top and sides of their periphery? Experiment II aimed to answer these questions by introducing a *Frame* condition where white light stimulation was provided more broadly across the participants' far periphery.

4.1 Method

For this experiment, a Fakespace Wide5 head-mounted display was used. This display has horizontal, vertical, and diagonal fields of view of 150°×88°×150°. This enabled stimulation to be graphically rendered in the far periphery. To keep the view of the virtual environment consistent with Experiment I and those described by Jones et al. [14], the field of view of the NVIS nVisor ST60 was simulated by only using the central 48°×40°×60° portion of the screen area to display the virtual environment. A white frame was also displayed in the periphery at 80°×73°×84° and extended inward 5°. The vertical edges and corners of the frame fell outside the area of stereo overlap within the HMD's field of view, thereby preventing convergence cues indicative of the frame's depth. The real world that would otherwise be visible in the far periphery was fully occluded using an opaque, black cloth that covered the sides and bottom of the display. The placement of the virtual environment and frame is illustrated with the full extent of the head-mounted display's field of view denoted by a dashed line in Figure 7. Otherwise, the methods used in this experiment exactly matched those described in Experiment I. Since the display device used in this experiment differed from that of Experiment I and Jones et al. [14], an additional condition was performed without the peripheral frame. This *No Frame* condition, illustrated in Figure 8, was intended to serve as a control condition and establish baseline performance for this head-mounted display. Aside from the change in display device, this condition exactly matched the *VR Fully Occluded* condition described by Jones et al. [14]. A group of 15 participants with normal or corrected to normal vision were recruited for this experiment. All participants were naive to the purposes of the experiment. Eight participants experienced the *Frame* condition (*5 males, 3 females, mean age: 27*) while seven experienced the *No Frame* condition (*7 males, mean age: 27*).

4.2 Results

Figure 9 depicts the main findings from this experiment. Participants in the *No Frame* condition judged distances with an accuracy of 58.37% and did not significantly differ from those in the *VR Fully Occluded* condition, which averaged 63.8% ($F(1,13)$=0.823, p=0.381). This indicates that simulating the smaller field of view of the nVisor ST60 inside the Wide5's larger display area provided mutually comparable distance judgments. Participants that experienced the *Frame* condition judged distances with an accuracy of

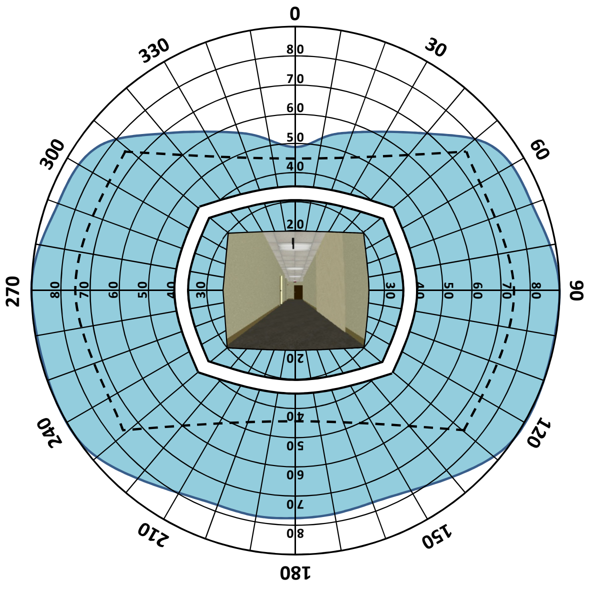

Figure 7: Placement of the virtual environment and peripheral stimulation within the field of view for the *Frame* condition.

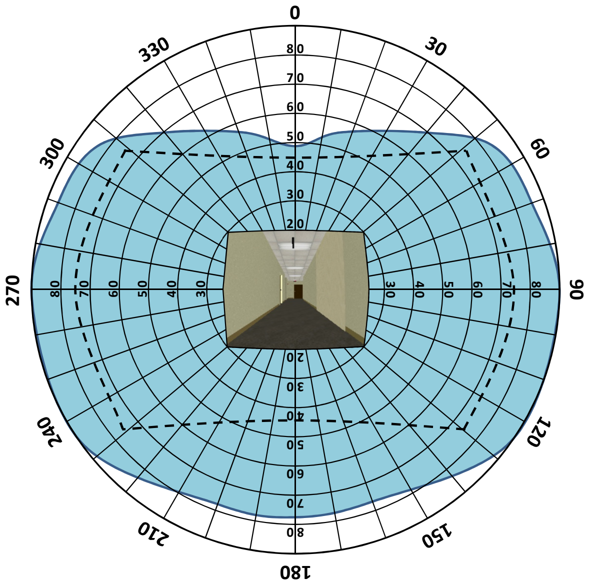

Figure 8: Placement of the virtual environment within the field of view for the *No Frame* condition.

71.90%, which was significantly more accurate than their *No Frame* counterparts, ($F(1,13)$=6.123, p=0.028). Additionally, the *Frame* condition did not significantly differ from the *Light Bar* condition from Experiment I ($F(1,14)$=0.119, p=0.736). These results seem to indicate that adding visual stimulation to the periphery is sufficient to provide a substantial improvement in distance judgments as expressed by blind walking.

5 EXPERIMENT III: EFFECT OF PERIPHERY ON SCALE

Blind walking is typically considered to be a reliable method for gauging an observer's perceived egocentric distance to a given point in the surrounding environment. However, it is important to understand that blind walking consists of essentially two components: visuospatial and locomotive. Participants use their vision to encode the spatial location of a target and then express this encoded location by walking to the target's position. Blind walking, as a distance measure, relies on the assumption that an observer's vision and motor responses are well calibrated spatially. When a factor, such as peripheral stimulation, alters blind walking behavior, it can be unclear as to whether observers have changed their spatial understanding or simply altered their walking behavior. Jones et al. [16] attempted to disambiguate this relationship but found mixed results indicating that high fidelity optical flow in the far periphery did seem to have an impact on participants' gait while lower fidelity optical flow had none. They report, however, that both high and low fidelity optical flow significantly improved blind walking performance in virtual environments. This leaves open the possibility that peripheral stimulation may be modifying the participants' spatial representation of the environment. However, this could not be clearly determined with the experimental design utilized by Jones et al. [16]. In order to resolve this point of uncertainty, the current experiment aimed to determine whether or not participants were experiencing a change in the perceived scale of the environment as a result of the added peripheral stimulation.

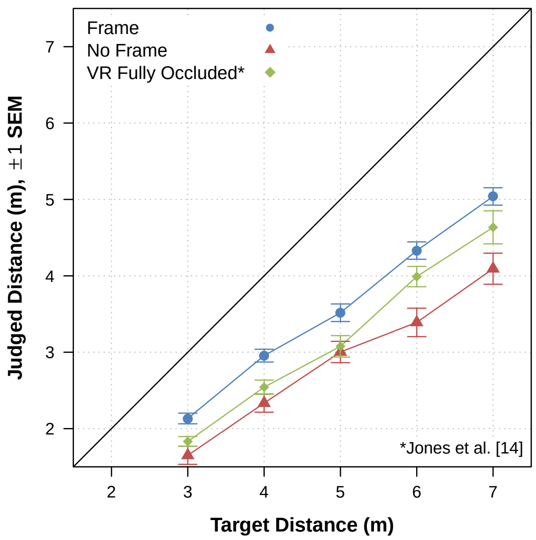

Figure 9: Mean distance judgments from Experiment II and the *VR Fully Occluded* condition from Jones et al. [14].

5.1 Method

Ten participants (*8 males, 2 females, mean age: 27*) with normal or corrected to normal vision were recruited for this experiment. All participants were naive to the purposes of the experiment. Participants were shown the same head-mounted virtual environment through the simulated 48°×40°×60° field of view used in Experiment II. The participants were asked to freely look about the environment until they felt they had a good sense of the size of the virtual space. When participants indicated their readiness, they were removed from the head-mounted display and walked a short distance to a screen depicting a projected, static image of the virtual environment as seen from their prior observation position. The projected image spanned an area of 0.67m × 0.56m on the projection screen and was positioned at the participants' approximate eye height. Participants stood 4 meters from the projection screen and were instructed to walk towards the projected image until they felt as though the size of the environment in the projected image

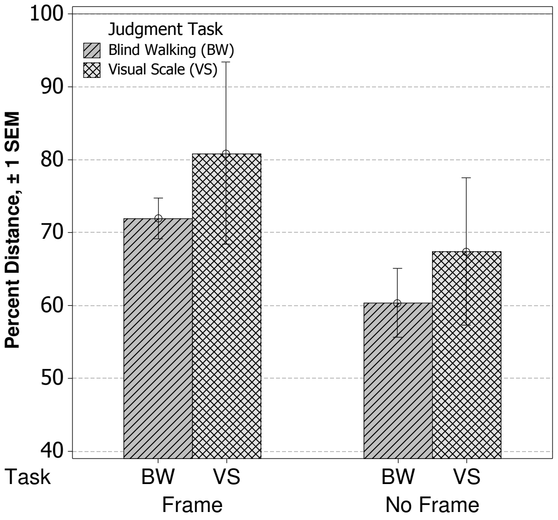

Figure 10: Comparison of blind walking and visual scale tasks.

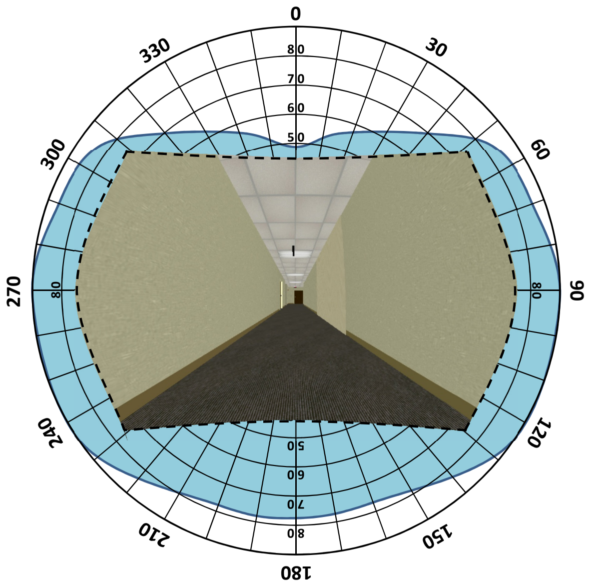

Figure 11: Placement of the virtual environment within the field of view for the *Full Field of View* condition.

matched that seen in the head-mounted display. Once the participants indicated they were standing at the distance where the projected image matched the scale of the head-mounted environment, their distance from the projection screen was recorded. This procedure was repeated six times, three with the presence of the peripheral frame (*Frame*) and three without (*No Frame*). Presentation order was alternated between subjects with half of the participants first experiencing the presence of the peripheral frame and the remainder without.

Gogel's Theory of Phenomenal Geometry [10] theorizes that any point within visually perceived space can be described in terms of three fundamental variables: 1) perceived direction relative to the observer, 2) perceived egocentric distance from the observer, and 3) perceived position of the observer. One can easily see these variables expressed in many commonly used spatial judgment tasks. For instance, perceived direction is a factor in triangulation based tasks, such as pointing. Other tasks, such as blind walking, provide an estimation of direct egocentric distance. We suggest that the visual scale task described here is driven by the third variable, perceived position of the observer. This judgment task operates by having observers reproduce their approximate viewing position within the virtual environment, as driven by the visual angle subtended by the projected image. This method is somewhat similar to natural perspective estimation procedures, but retains an explicit coupling between observation position and visual scale [34, 35].

5.2 Results

A repeated measures analysis of variance was conducted to determine if the alternating presentation order of the peripheral frame had an effect on responses. No significant effect of presentation order was detected ($F(1,8)$=2.495, p=0.153). Participants stood significantly further from the projection screen (1.293m) when having previously viewed the virtual environment with the peripheral frame than when having viewed the same environment without the frame (1.078m) ($F(1,8)$=7.556, p=0.025). Using the visual angle occupied by the back face of the hallway for each of these viewing distances, the change in visual scale of the virtual environment can be calculated. The width of the virtual hallway was 1.82m and extended 16.53m from the participants' viewing position. The width of the hallway's end occupied 3.86° of visual angle in the *Frame* condition and 4.61° in the *No Frame* condition. Using the hall width as a scaling factor, we can now calculate the distance from the observer to the end of the hallway. It was found that the hallway appeared to be 13.49m long in the *Frame* condition and 11.28m long in the *No Frame* condition. These correspond to 80.8% and 67.4% of the hallway's actual length, respectively. Recall that the blind walking results indicated that participants in the *Frame* condition judged distance as 71.9% of their actual distance while participants in the *No Frame* condition judged distances as 58.4% of their actual distance. As can be seen in Figure 10, the results of the scaling task very closely mimic the trends seen in the previously discussed blind walking judgments. Interestingly, the percentage difference between the *Frame* and *No Frame* conditions in both distance judgments (13.5%) and scale judgments (13.4%) are quite identical. When comparing the percent distance judged in the blind walking task with the calculated percent distance from the scaling task, no significant difference could be found (*Frame*: $F(1,16)$=0.400, p=0.536; *No Frame*: $F(1,16)$=0.339, p=0.568). These results are consistent with the hypothesis that the addition of visual stimulation in the far periphery is not simply causing participants to walk farther but is introducing a change in the perceived scale of the virtual environment.

6 EXPERIMENT IV: LARGE FIELD OF VIEW ENVIRONMENT

Experiments I and II demonstrated appreciable improvements in the performance of distance judgments when participants viewing a virtual environment through a relatively narrow field of view were provided with a small amount of static peripheral stimulation outside of the display area. Previous work has indicated that larger fields of view allow individuals to perform distance judgments more accurately [48]. How does the improvement in performance seen with added peripheral stimulation compare to the performance of participants viewing a virtual environment through a very large field of view? Experiment IV sought to answer this question by introducing a *Full Field of View* condition that presented the same virtual environment seen in Experiments I and II but in a very large field of view.

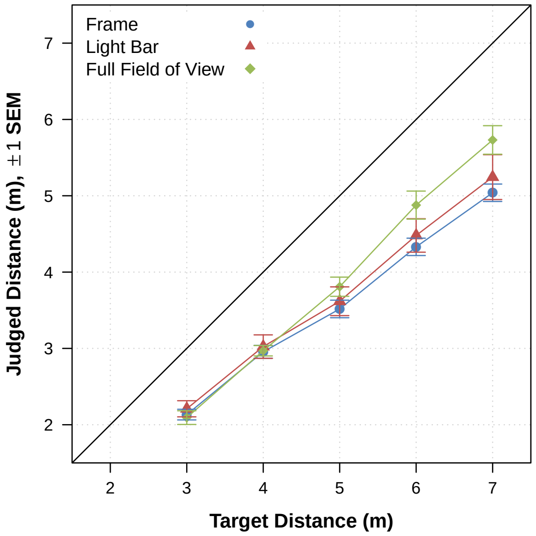

Figure 12: Mean distance judgments from Experiment IV.

6.1 Method

Eight participants (*5 females, 3 males, mean age: 33*) with normal or corrected to normal vision were recruited for this experiment. These participants viewed the virtual environment using the same Fakespace Wide5 display used in Experiment II. However, for this experiment, the display's full 150°×88°×150° field of view, illustrated in Figure 11, was used to display the virtual environment. Otherwise, the apparatus and procedures for this experiment exactly matched those described in Experiments I and II.

6.2 Results

Participants in the *Full Field of View* condition judged distances (75.96%) significantly more accurately than participants who utilized the smaller field of view in the *No Frame* condition (58.37%) ($F(1,13)$=8.852, p=0.011). As can be seen in Figure 12, these participants did not significantly differ in average performance from their *Light Bar* (74.24%) and *Frame* (71.90%) counterparts (*Light Bar*: $F(1,14)$=0.059, p=0.811; *Frame*: $F(1,14)$=0.848, p=0.373). However, if we look at the *Full Field of View* distance judgments as a function of target distance, we see a pattern of significantly improved judgments as target distances increase ($F(4,28)$=5.971, p=0.001). This pattern does not manifest itself in either the *Light Bar* or *Frame* conditions (*Light Bar*: $F(4,28)$=0.645, p=0.635; *Frame*: $F(4,28)$=0.623, p=0.650). A possible explanation is that the larger field of view provides substantially more texture information along the ground plane than is available in the smaller field of view, giving more information with increasing distance.

7 EXPERIMENT V: REAL WORLD OCCLUSION

Most normally sighted individuals have a binocular field of view that spans roughly 180°×120°. The field of view of the environment seen by participants in Experiment IV, 150°×88°, is approaching that of the real world. It has been well documented that individuals judge distances with near 100% accuracy when performing blind walking in the real world [19, 20, 24, 29, 41]. This includes the *Real World* condition described by Jones et al. [14], where participants averaged 93.5% accuracy. Many blind walking experiments in virtual environments compare performance against a real world control condition. In this paradigm, participants experiencing the virtual environment are usually disallowed from seeing anything outside the display's narrow field of view and are typically presented with no visual stimulus between trials. However, participants in the real world condition may experience insufficient occlusion or occlusion that is not directly comparable to the experimental condition. Since minute, nonspecific visual stimulation between trials, particularly with regard to the periphery, has until recently not been considered as a possible influence on the outcome of blind walking tasks, such asymmetries between the experimental and control conditions may have gone unnoticed and undocumented. However, the results from Jones et al. [14] and Jones et al. [16] show that the presence of visual stimulation, even in near total darkness, during the return portion of the blind walking procedure quite strongly influences distance judgments. This brings up an interesting question regarding comparability between experimental and control conditions where occlusion procedures are incongruent or insufficient. Experiment V aimed to determine if rigorously disallowing visual stimulation during the return walk using occlusion procedures that very closely mimicked those used in Experiments I through IV would alter performance in an otherwise unencumbered real world condition. To test this possibility, we introduce a *Real World Occluded* condition.

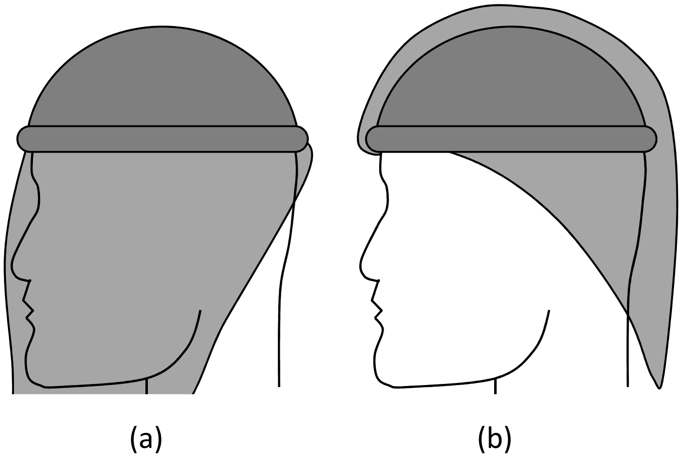

Figure 13: Occluder used for Experiment V shown in (a) occluding and (b) viewing configurations.

7.1 Method

Eight participants (*5 males, 3 females, mean age: 22*) with normal or corrected to normal vision were recruited for this experiment. As depicted in Figure 13, participants wore a veil constructed of opaque, black cloth attached to a hard plastic cap. This veil, when pulled over the top of the head, allowed participants to have a full, unimpeded view of the real world environment. Participants performed the blind walking task with the veil in this position. When participants completed their judgment walk, the veil was lowered before they returned to their starting position. The experiment took place in the real world location that was modeled for the previous virtual environments. Otherwise, the experimental procedures matched those used in the previous experiments.

7.2 Results

Interestingly, the *Real World Occluded* participants judged distances with only 81.74% accuracy. This is considerably lower than has been reported by many studies examining real world blind walking [13–15, 19, 20, 24, 29, 41]. Work by Kuhl et al. [21] has

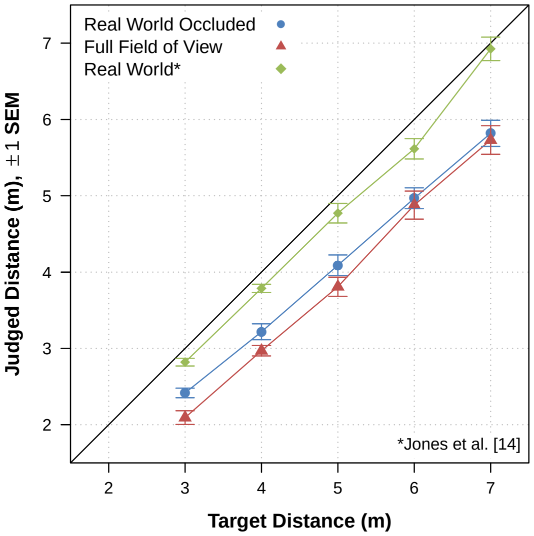

Figure 14: Mean distance judgments from Experiments IV, V, and the *Real World* condition from Jones et al. [14].

shown that significant individual variations exist between participants in blind walking tasks, with roughly one third of participants being predisposed to underestimating real world distances relative to a population mean of 96% accuracy. This value is consistent with the 93.5% accuracy seen in the *Real World* control condition reported by Jones et al. [14]. In the current experiment, 95% confidence intervals were calculated per participant revealing that 7 of the 8 participants significantly underestimated distances relative to the mean performance reported by Kuhl et al. [21] and 6 of the 8 participants relative to the mean reported by Jones et al. [14]. Though it is possible that these results could be the product of randomly recruiting an above average number of participants predisposed to underestimation, this seems unlikely given the substantial number of participants exhibiting underestimation. This suggests that depriving participants of visual information during the return walk appreciably hinders the participant's ability to judge distances with blind walking. As can be seen in Figure 14, participants in the *Real World Occluded* significantly underestimated distances relative to those in Jones et al. [14]'s *Real World* condition ($F(1,16)$=10.905 p=0.004). Perhaps more interesting is the lack of a significant difference between the performance of the *Real World Occluded* participants and their *Full Field of View* counterparts ($F(1,14)$=1.254, p=0.282). This suggests that participants in a large field of view virtual environment may, in fact, judge distances as accurately as participants in an equivalently occluded real world viewing condition. A comparison of performance in the *Real World Occluded* and the *Light Bar* and *Frame* conditions reveals that participants also did not significantly differ in their distance judgments (*Light Bar*: $F(1,14)$=1.063, p=0.321; *Frame*: $F(1,14)$=4.364, p=0.055). The improvement in distance judgments with increasing target distance observed in Experiment IV did not manifest itself in this experiment ($F(4,28)$=1.106, p=0.373).

8 DISCUSSION

Somewhat surprisingly, the results from Experiment I indicate that at least some of the performance improvements seen by Jones et al. [14] may not have been a result of optical flow, but from the presence of light in the far periphery. This is a curious result as the simple presence of a light source does not, in itself, convey any information about the surrounding environment or the observer's position within the environment. However, Experiments II and III continue to support the hypothesis that adding peripheral stimulation to a virtual environment improves one's ability to judge distance and scale. It is especially interesting that the effect of the peripheral stimulation expresses itself equally in terms of both egocentric distance and visual scale judgments. As with any psychophysical phenomenon, observers' responses are colored both by their internalized perceptual representations and the physical manifestation of those representations [26, 43]. For instance, changes in blind walking responses could be caused not only by changes in perceived target distance, but also by changes in the way one walks. Using a single technique, such as blind walking, cannot reveal which influence has caused a change in an observer's response. We suggest that by observing changes in the blind walking and visual scale tasks, both of which are driven by one's spatial understanding, that the peripheral stimulation provided in these experiments is influencing behavior on a perceptual level.

Prior work by Jones et al. [16] speculated that peripheral stimulation may affect the internal representation of an environment's spatial scale but lacked sufficient evidence to substantiate this hypothesis. The present work, however, indicates that peripheral stimulation can cause an observer to perceive a change in scale when, in fact, there was none. A counterargument could be made that perhaps participants were using the peripheral stimulation as a reference to the screen edge and thereby consciously judging the virtual environment as only being a small portion of a much larger screen area. However, the comments of the participants after the experiment seem to counter indicate this hypothesis. All participants in the *Light Bar* condition were aware that the bar was present in the periphery, but this is expected as the device was manually powered on at the beginning of the experiment in a manner that was difficult to ignore. However, most of the participants in this condition commented that they stopped noticing the bar's presence. Some of the participants claimed the light bar disappeared as the experiment progressed, assuming that it had been remotely disabled by the experimenters. This was not the case, and the light bar was confirmed to be illuminated at the end of each experimental session. Perhaps even more interesting are the comments of the participants in the blind walking *Frame* condition. Since the peripheral frame was graphically rendered, there were no obvious physical cues to explicitly direct participants' attention to the periphery. Only two out of the eight participants remarked that the frame was present when queried. The remaining participants reacted skeptically when informed that the frame was, in fact, present in their periphery. This implies that the majority of participants in the *Frame* condition were not consciously aware of the frame's presence, making cognitive efforts an unlikely explanation for the observed improvement in distance judgments.

A rather large amount of research has focused on distance judgments in virtual environment with results varying substantially from one experiment to the next. One possible explanation for the variation seen across the literature is uncontrolled peripheral stimulation. A remarkably small amount of stimulation seems to be necessary to trigger an effect [14, 16]. From the perspective of a researcher wanting to perform tightly controlled visual experiments in virtual environments, this is a troublesome thought as minor variations in peripheral stimulation may inadvertently contaminate experiments. Achieving sufficient occlusion can be a nontrivial task. In the process of investigating methods of occlusion, several common techniques were implemented [13, 17, 29, 35, 37, 45]. These included opaque goggles, foam rubber baffles, blindfolds, night-masks, cloth shrouds, and darkening the physical environment by extinguishing light sources. It was found that most reasonable implementations of these methods still allowed at least a small amount of light to be detected by observers. However, if instead we look through the eyes of a practitioner wanting to enhance the performance of a virtual environment, these findings are quite encouraging. If we consider the *Light Bar* condition from Experiment I, simply adding two large, low resolution pixels to the lower periphery of a small field of view display enabled its users to perform as if they were utilizing a much larger field of view. Additionally, if the surrounding real world environment is sufficiently similar to the virtual world, Jones et al. [14]'s findings indicate that mixing a virtual environment with real world periphery may even allow performance comparable to that observed in the real world. This is quite exciting when considering that large field of view displays can be difficult to engineer and are often prohibitively expensive.

An intriguing proposition raised by Experiment V is that some virtual environment blind walking studies may be using an inappropriate control condition. A typical scenario for a blind walking study using a head-mounted virtual environment involves observers viewing a target located at some distance. The observers then close their eyes and have the virtual environment visually muted. During this period without vision, the observers then walk to the apparent location of the target. The observers then return to the starting position, still without vision, and the procedure repeats. In the real world, however, it is substantially more difficult to visually mute the scene. Even when observers close their eyes, they quite often have a visual awareness of their position in the world from light passing their closed eye lids. This is made obvious by simply closing your eyes while walking through a well-lit environment. It quickly becomes apparent that you can resolve subtle shifts in light and shadow even with eyes shut. Even very small luminance changes viewed through the black cloth occluder used by Jones et al. [14] was sufficient to alter blind walking behavior. As demonstrated by Jones et al. [14, 16] and reiterated here, near darkness is not equivalent to darkness. A very small amount of light seepage is capable of altering distance judgments. Finding an occluding configuration that both prevents light seepage from the surrounding environment and is not overly cumbersome for the observer is, in fact, quite challenging. For our purposes, we found the most effective occlusion to be achieved by using a tightly woven, black cloth veil that drapes over the shoulders and lays flat against the chest.

The results of Experiment V seem to indicate that, when the return portion of the blind walking task is made comparable, accuracy of blind walking in the real world and the large field of view virtual environment cease to differ. However, it is worth noting that despite the lack of comparability under these specific circumstances, the typical real world blind walking procedure is likely a more valid comparison for other real world based judgments. Though real world performance drops when visual stimulation is removed between trials, it has yet to be definitively seen if performance will improve when comparable stimulation is added in the virtual environment. The results shown by Jones et al. [14, 16] imply that this may be the case. However, the stimulation they provided during the return walk was strictly peripheral, leaving this possibility only partially addressed.

9 CONCLUSION & FUTURE WORK

The results of the preceding experiments can be summarized in terms of three main findings:

- Adding static, white light stimulation to the far periphery invokes a positive change in perceived scale of a small field of view virtual environment as expressed by blind walking and visual scale estimation,
- The effect of peripheral stimulation on blind walking performance was not significantly different than that observed in a very large field of view virtual environment,
- Rigorous occlusion during the return portion of the blind walking procedure impairs blind walking performance in an otherwise unencumbered real world environment.

Substantial future work is required in order to fully understand the mechanisms that underlie the perceived change in scale caused by stimulating the far periphery. Since the peripheral stimulation provided no additional information about the virtual environment or the observer's position within the environment, we speculate that perhaps providing visual signal, even if nonspecific, more broadly across the field of view may serve sufficient to activate perceptual mechanisms associated with spatial understanding. This, however, is a strictly speculative explanation that requires further investigation. Additionally, it is as yet unclear whether there are draw backs associated with the peripheral stimulation as presented here. For instance, does having a light source in the far periphery impact an observer's sense of presence or immersion in a virtual environment? Based on the previously discussed feedback from participants in Experiment II, we speculate that impact on presence or immersion would be minimal. However, this is beyond the scope of the current work and necessitates further investigation.

In the authors' prior work, which served as the basis for this series of experiments, typical implementations of the real world blind walking procedure resulted in performance very much comparable to those reported in many other studies, ranging from 94% to 97% accuracy [14, 15, 37]. The real world occlusion procedures used in Experiment V were the first in this series of studies to both rigorously occlude and closely mimic the occlusion procedures used in the experimental conditions. The surprising amount of underestimation seen in this condition emphasizes the importance of comparability between experimental and control conditions. However, it has yet to be determined how little light is necessary to facilitate a change in distance judgments in the real world. It is our suspicion that very minor light seepage around the edges or through occluding apparatuses is quite possibly responsible for at least some of the variation in distance judgments reported through the contemporary literature. However, further investigation is needed to determine if this is, in fact, the case.

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