Estimating Perceptual Depth Changes with Eye Vergence and Interpupillary Distance using an Eye Tracker in Virtual Reality

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ABSTRACT

Virtual Reality (VR) technology has advanced to include eye-tracking, allowing novel research, such as investigating how our visual system coordinates eye movements with changes in perceptual depth. The purpose of this study was to examine whether eye tracking could track perceptual depth changes during a visual discrimination task. We derived two depth-dependent variables from eye tracker data: eye vergence angle (EVA) and interpupillary distance (IPD). As hypothesized, our results revealed that shifting gaze from near-to-far depth significantly decreased EVA and increased IPD, while the opposite pattern was observed while shifting from far-to-near. Importantly, the amount of change in these variables tracked closely with relative changes in perceptual depth, and supported the hypothesis that eye tracker data may be used to infer real-time changes in perceptual depth in VR. Our method could be used as a new tool to adaptively render information based on depth and improve the VR user experience.

CCS CONCEPTS

• **Human-centered computing** → **Virtual Reality**; • **Eye Tracking** → *Perceptual Depth Changes*; • **Human Visual System** → Vergence and Interpupillary Distance.

KEYWORDS

Perceptual Depth, Eye Vergence, IPD, Virtual Reality

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1 INTRODUCTION

Virtual reality (VR) technology has been increasingly used in a variety of applications, such as immersive training, as well as in several basic research fields, including visual perception, psychology, and cognitive science [Callahan-Flintoft et al. 2021; Clay et al. 2019]. In addition, VR provides an opportunity to further understand the human visual system, by investigating behavior in controlled yet naturalistic contexts. Recent commercial technology developments have allowed the combination of VR and eye tracking, enabling novel investigations. For example, researchers have used eye tracking to measure eye movements and pupil size fluctuations to elucidate perceptual and cognitive processes [Cohen Hoffing et al. 2020; Feil et al. 2017; Hooge et al. 2019; Solé Puig et al. 2021]. However, an open research question, which is well-suited for VR experimentation, is how our visual system behaves in response to depth changes. Because VR devices incorporated with eye trackers have only recently been developed, there have only been a handful of investigations using these devices to understand visual responses in VR [Imaoka et al. 2020; Iskander et al. 2019; Kim et al. 2021; Lynn et al. 2020]. The primary purpose of this work is to investigate whether perceptual depth can be estimated using eye tracker data from participants performing a task in VR [Callahan-Flintoft et al. 2021].

Eye Vergence Angle (EVA). Depth perception requires rapid and precise eye movements (e.g., saccadic, fixation, vergence, etc.), because perceived depth is influenced by monocular and binocular depth cues (e.g., binocular disparity, size, accommodation, vergence, etc.) [Leigh and Zee 2015; Singh et al. 2018]. During accommodation, the ciliary muscles of the eye adjust the lens to bring objects at different depths into sharp focus. In addition to accommodation, viewing objects at different distances requires the eyes to rotate simultaneously, known as *vergence*, which allows the eyes to maintain combined binocular vision. The link between vergence and accommodation is known as the *vergence-accommodation reflex* [Hoffman et al. 2008]. When changing the depth of binocular viewing, there are two types of *vergence* eye movements: *convergence* and *divergence* [Gross et al. 2015]. When shifting gaze from far to near objects, the eyes rotate inward horizontally, known as *convergence* (see Fig. 1a), and when shifting gaze from near to far, the eyes need to rotate outward horizontally, known as *divergence* (see Fig. 1a). Therefore, when focusing on an object binocularly, the *eye vergence angle* (EVA) is the angle between the visual axes of both eyes [Iskander et al. 2019]. In general, the value of EVA is

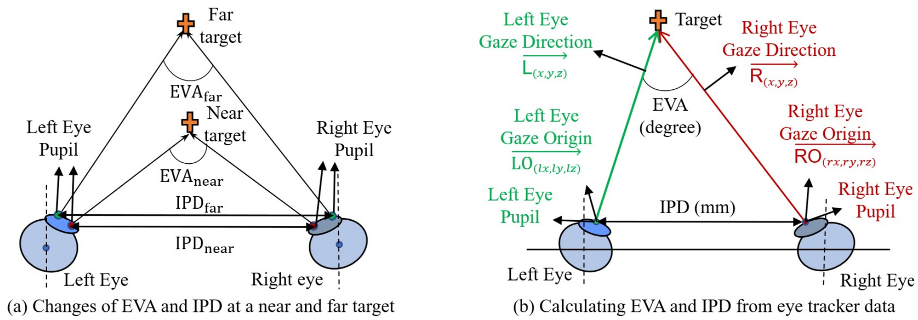

Figure 1: (a) The *eye vergence angle* (EVA) and *inter-pupillary distance* (IPD) defined according to binocular human vision, when the eyes are verged on a near or far target. (b) Calculating EVA and IPD from eye tracker data, using the vectors of 3D gaze direction and 3D gaze origin.

larger when verged on a closer object, and smaller when verged on a farther object. As the object distance becomes large relative to the interpupillary distance, EVA tends towards zero. At a value of zero, the visual axes of both eyes become parallel [Leigh and Zee 2015].

During various studies of the human visual system in natural and virtual environments, researchers have been measuring vergence eye movements with eye trackers, typically using the angle between the two eyes' lines of sight as the vergence component [Feil et al. 2017; Hooge et al. 2019; Solé Puig et al. 2021; Sulutvedt et al. 2018]. While there have been a few studies relating gaze depth and EVA [Duchowski et al. 2014, 2011], based on our knowledge only Iskander et al. [2019] studied how to measure EVA using a consumer-grade VR headset with integrated eye trackers (HTC VIVE Pro). This study calculated vergence through inverse kinematics with a biomechanical head and eye model. Results revealed that the real-time vergence angle from the eye tracker in VR had higher variability, and suggested that the vergence-accommodation conflict present in the VR headset might cause higher variability of vergence values in VR, contributing to the misperception of depth.

Interpupillary Distance (IPD). Another essential component of binocular human visual system that changes with object depth is *interpupillary distance* (IPD)—the distance between the centers of the left and right eye pupils [Dodgson 2004]. Changing the depth of a verged object can measurably affect IPD. According to Jones et al. [2016], IPD changes also bring changes in eye gaze distances, and changes in vergence strongly affect IPD. Therefore, if the eyes focus at a near distance, the IPD value will be smaller, and if the eyes focus at a far distance, the IPD values will be larger (see Fig. 1a). There is evidence that infrared eye tracking technology is reliable enough for measuring small changes in IPD [Kim et al. 2021; Murray et al. 2017]. Most prior investigations of eye vergence have been conducted in a controlled experimental environment with custom-built displays and eye-tracking technology. Most researchers restricted the participants from moving their heads; only eye movements were allowed. In addition, a few papers have measured vergence movements in response to depth changes in VR environments, but these did not consider other depth-related eye movement metrics, such as IPD [Duchowski et al. 2014, 2011; Iskander et al. 2019].

The main contribution of this paper is demonstrating a method of estimating EVA and IPD in VR, using a consumer-grade VR display (HTC VIVE Pro) with an integrated Tobii eye tracker. The behavior of EVA with perceptual depth changes was validated by considering the behavior of IPD. Since EVA and IPD were measured independently from the same eye tracker data, similar responses to depth changes increases the confidence that estimated EVA and IPD can track perceptual depth changes in VR.

2 HYPOTHESIS

We hypothesize that data collected from an eye tracker concurrently while participants perform a perceptual task in VR will be able to track relative changes in the perceived depth plane associated with fixated objects. More specifically, we hypothesize that EVA will increase and IPD will decrease when participants shift their gaze from a far object to a near object (see Fig. 2b and c). Likewise, we hypothesize that EVA will reduce and IPD will increase when participants shift their gaze from a near object to a far object (see Fig. 2e and f). Last, we hypothesize that the degree of change in these two variables will reflect the amount of change in perceptual depth such that greater changes in depth will be associated with greater changes in EVA and IPD.

3 METHOD

This study was approved by the IRB at the US Air Force Academy (USAFA) and the US Army Research Laboratory under Project Number ARL 19-122. All procedures were in accordance with the Declaration of Helsinki. In this study, we analyzed data from a virtual reality environment where subjects (USAFA Cadets, n=24, female=9, mean=19.3 years) performed a two-alternative forced choice task. All subjects had normal or corrected vision and provided written informed consent. We briefly describe the methods here, but more information can be found in Callahan-Flintoft et al. [2021]. Subjects foveated on a centering cross placed 11m away in Unity coordinate space, and were instructed to saccade to a cued disk among an array of disks, which contained a target. Subjects were asked to report whether the target was facing right or left. The disks were organized in two circular arrays around the centering cross in either the parafovea or periphery, respectively 6 or 20 degrees of visual angle away from the cross. Additionally,

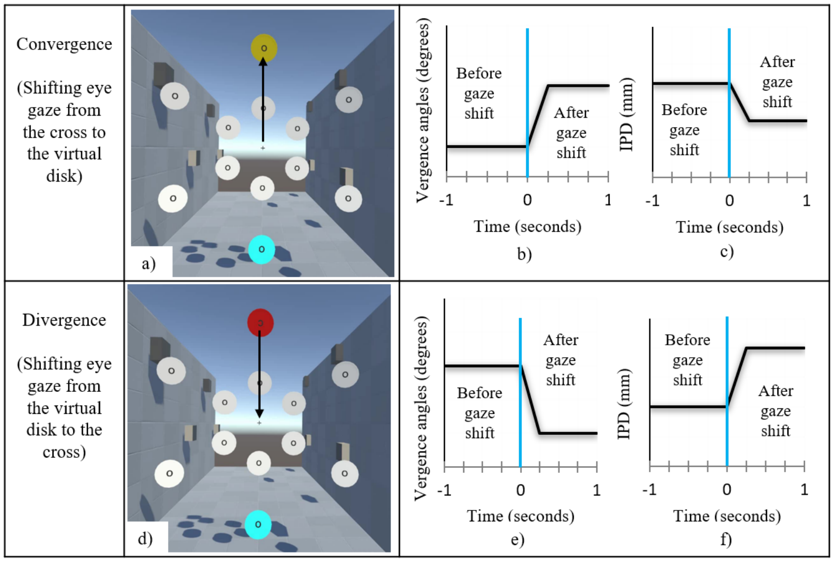

Figure 2: Two-alternative forced choice task in VR with experimental prediction. (a) During convergence, participants shifted the eye gaze from the virtual cross (perceptually far) to the virtual disk (perceptually near). In this scenario, if we consider a time window of −1s to +1s and lock the event on the first saccade onset after the cue is presented (blue vertical line), our hypothesis is that after shifting the gaze, EVA will be increased and IPD will be decreased (b, c). (d) During divergence, participants shifted the eye gaze from the virtual disk (perceptually near) back to the virtual cross (perceptually far), and our hypothesis is that after shifting the gaze, the opposite pattern of results will be seen: EVA will be decreased and IPD will be increased (e, f). Note that graphs b, c, e, and f are made using theoretical data.

subjects completed *static* and *dynamic* conditions. In the static trials disks appeared either at 13m (near) or 32m (far) away in Unity coordinate space. In the dynamic trials participants moved through the environment and disks appeared to pass behind the subject. In this manuscript we only analyze data from the static condition, to isolate discrete times when vergence and IPD should change.

This task was designed to investigate characteristics of saccadic eye movements for targets presented at different locations and depth planes in the naturalistic yet controlled environment that is afforded by VR. Eye movements were classified by applying a dynamic threshold to gaze and eye speed that is scaled by the current head speed. Missing data were excluded from the classification. Eye movement classification was validated using ray-casts of each gaze sample. For a detailed discussion of eye movement classification see Fig. 2 in Callahan-Flintoft et al. [2021] and Agtzidis et al. [2019]. We found the design of this study to be suitable for preliminary analysis to determine (i) whether EVA and IPD can be reliably estimated from the output of the eye tracker device, and (ii) whether relative changes in EVA and IPD accurately track and temporally coincide with experimentally-induced changes in perceptual depth.

4 DATA PROCESSING

4.1 Filtering

Our study aims to compute and analyze EVA and IPD from the eye tracker data while shifting gaze from far to near (*convergence*) and near to far (*divergence*). During the *convergence* phase, participants shifted their eye gaze from the centering cross (perceptually far) to the disks (perceptually near) (see Fig. 2a). Therefore, we time-locked to the first saccade onset after the cue (yellow virtual disk) was displayed. After time-locking, we considered the valid trails considering the eye movements before the time locked. To be a valid trial, the eye gaze should be labeled as on the recentering cross in the time window ranging from 0–3 seconds between after the first saccade offset and second fixation onset before the saccade onset. If the time period was more than 3 seconds, we considered only the first fixation onset instead of the second fixation onset before the first saccade offset. In addition, for a valid trial at least 25% of eye-gaze should be on the recentering cross during the time period. Based on these criteria, an average of 191 trials (66% of the trials) were considered as valid trials for our convergence phase analysis.

During the *divergence* phase, the opposite pattern of eye gaze shifting occurred when subjects shifted their gaze from the target back to the centering cross (see Fig. 2d)). We time-locked to the first saccade onset after the target (red virtual disk) was deactivated. To be a valid trial, the eye gaze should be labeled as on the recentering cross in the time window ranging from 0–3 seconds between after the first saccade onset and second fixation offset after the saccade onset. If time period is more than 3 seconds, we considered only the first fixation onset instead of the second fixation onset before the first saccade offset. In addition, for a valid trial, at least 25% of eye-gaze should be on the recentering cross during the time period. Considering these criteria, an average of 195 trials (67.5% of the trials) were considered valid trials for our divergence analysis.

EVA and IPD data were first preprocessed by identifying blinks using the pupil signal. Data during periods of blinking were replaced with with "not a number" (NaN) in Matlab so that these data would not be incorporated in the mean data. Additionally, estimating EVA and IPD from the commercial eye tracker can occasionally introduce noise and artifacts that appear as large changes in EVA and IPD from one sample to another that are not physiologically realistic. Therefore, EVA and IPD data artifacts were identified from the first derivative (velocity) of the measurements and also replaced with NaN values. To get rid of the largest artifacts first, we thresholded data to remove any EVA measurements greater than 2400 deg/sec, and IPD measurements greater than 600 mm/sec respectively. This yielded a robust measure of standard deviation (SD). Next, we replaced data points over +2.5 SDs from the mean with NaN values. Finally, due to both blinking and artifacts, 18.6% data for the EVA and 18.2% data for IPD were replaced with NaNs and therefore omitted from analysis.

4.2 Eye Vergence Angle (EVA) Calculation

In our study, experimental stimuli were located in three different regions: foveal (virtual cross), parafoveal (virtual disk), and periphery (virtual disk). There was no restriction on head movements during the study. Further, there was a lack of documentation regarding the focal distance of the lenses of our experimental device (HTC Vive Pro) [Iskander et al. 2019]. Therefore, we considered *3D eye gaze direction vector*, and vector dot product formula to calculate the vergence angle. Previously, Sulutvedt et al. [2018] used a similar approach to calculate vergence from the eye tracker-provided vector data in their vergence analysis with depth and image size. In this approach, we considered the angle created by the lines of sight of each eye (the angle formed by the left and right eye gaze direction vectors) as our EVA. For example, let us consider that we had the left eye gaze direction vector ($\overrightarrow{L_{x,y,z}}$) and the right eye gaze direction vector ($\overrightarrow{R_{x,y,z}}$) from the eye tracker, and that both eyes were focusing a target in the parafoveal region (See Figure 1b). Therefore, according to the vector dot product formula we can get the EVA (θ) in degrees:

$$\overrightarrow{L_{x,y,z}} \cdot \overrightarrow{R_{x,y,z}} = \left|L_{x,y,z}\right| \left|R_{x,y,z}\right| \cos\theta \tag{1}$$

4.3 Interpupillary Distance (IPD) Calculation

As mentioned previously, IPD is the distance between the center of the two pupils, and it varies with depth changes. According to the Tobii Pro SDK, the *gaze origin vector* indicates the center of the pupil position for both eyes. Therefore, we considered the *3D eye gaze origin vector* to calculate the IPD in our analysis. For example, let us consider that we had the left eye gaze origin vector ($\overrightarrow{LO_{lx,ly,lz}}$) and the right eye gaze origin vector ($\overrightarrow{RO_{rx,ry,rz}}$) from the eye tracker, and the both eyes were focusing a target in the parafoveal region (See Figure 1b). According to the Euclidean distance formula we can get the IPD in millimeters (mm),

$$IPD = \sqrt{(lx - rx)^2 + (ly - ry)^2 + (lz - rz)^2} \tag{2}$$

5 ANALYSIS

Our analysis focused on tracking the perceptual depth changes with EVA and IPD using eye-tracker data. For this, we considered a time interval from −1s to +1s. For the convergence phase, 0s is when the first saccade onset made after cue (yellow virtual disk) was displayed. Furthermore, for the divergence phase, 0s is the moment when the first saccade onset was made after the target (red virtual disk) was deactivated (divergence phase). The time from −1s to 0s was considered before the gaze shift time frame (*pre-event*), and 0s to 1s was considered after the gaze shift time frame (*post-event*). We averaged the EVA and IPD of all participants to track the perceptual depth changes. Δ quantifies the amount of mean EVA and mean IPD change between the post-event and pre-event periods. Therefore, Δ captures the degree of change induced to each variable by changes in perceptual depth. To test our hypothesis, we performed a repeated-measures ANOVA analysis on three experimental variables: *vergence (convergence, divergence)*, *perceptual depth (near, far)*, and *target position (parafovea, periphery)*.

6 RESULTS

Fig. 3 shows the results of our perceptual depth estimation with the mean EVA and IPD of all participants. Figs. 3a and b illustrate the result of the convergence phase. The results represent that shifting eye gaze from the virtual cross (far perceptual depth) to the virtual disk (near perceptual depth) increased EVA and decreased IPD. In other words, the transition from the pre-event to the post-event during the convergence phase increased EVA and decreased IPD, as hypothesized. Figs. 3c and d represent the result of the divergence phase. As expected, opposite patterns were observed during the divergence phase.

Fig. 4 shows the amount of EVA changes (Fig. 4a) and IPD changes (Fig. 4b) organized by perceptual depth and target positions. For EVA analysis, when *vergence*, *perceptual depth*, and *target position* conditions are compared, there is only a significant main effect of *vergence* ($F_{1,23} = 6.15$, $p < .05$), indicating that the magnitude of EVA during the convergence phase was significantly different from the divergence phase, considering all conditions. In addition, we observed a significant interaction effect between *vergence* and *target position* ($F_{1,23} = 7.05$, $p < .01$), indicating that the values of EVA during the convergence and divergence phases significantly differ between the parafovea and periphery positions of virtual objects. No other significant effects were detected for EVA.

For the IPD analysis, when *vergence*, *perceptual depth*, and *target position* conditions are compared, there is a significant main effect of *vergence* ($F_{1,23} = 62.10, p < .001$), *perceptual depth* ($F_{1,23} = 14.64$, $p < .001$), and *target position* ($F_{1,23} = 36.70, p < .001$), revealing that IPD significantly differed between the convergence and divergence phases, near and far depths, and parafovea and periphery target positions. In addition, we found a 2-way significant interaction effect between *vergence* and *perceptual depth* ($F_{1,23} = 19.36$, $p < .001$), and between *vergence* and *target position* ($F_{1,23} = 50.45$, $p < .001$). These effects are caused by a significant 3-way interaction effect among *vergence*, *perceptual depth* and *target position* ($F_{1,23} = 11.16$, $p < .001$). Altogether, these results indicate that IPD values significantly differed across all the conditions. No other significant

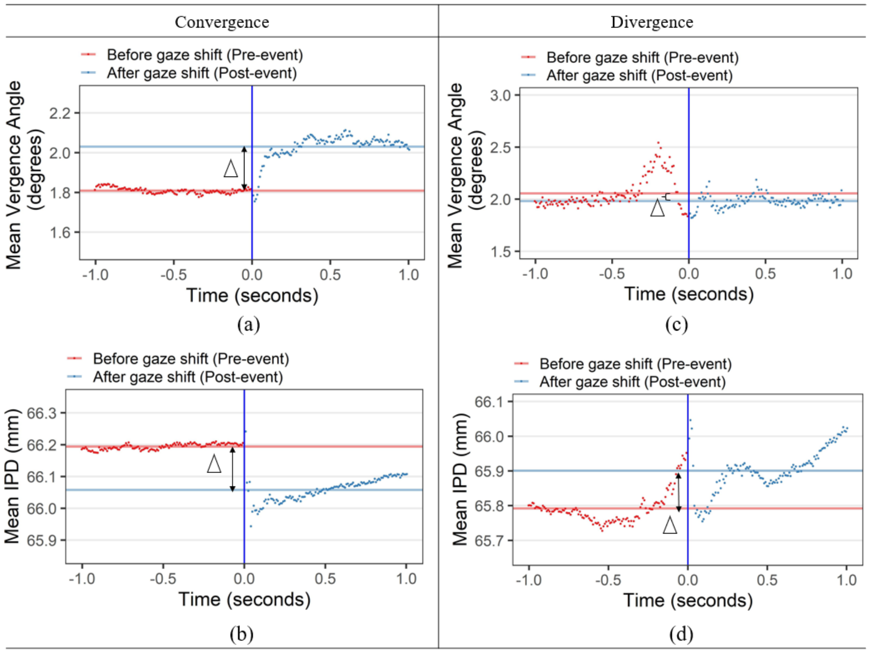

Figure 3: Tracking perceptual depth changes with EVA and IPD during convergence (left column) and divergence (right column). Red and points show the mean of EVA or IPD of all participants before (−1 to 0s, pre-event) and after gaze shift (0 to 1s, post-event), respectively. The blue vertical line represents the first saccade onset after the cue is presented (convergence phase), and the first saccade onset after the cue is deactivated (divergence phase). The red and blue horizontal line illustrates the mean EVA or IPD value from the pre-event and post-event, respectively. Δ indicates how much EVA and IPD changed between the post-event and pre-event. Supporting our hypothesises, during convergence EVA increased and IPD decreased. During divergence, EVA decreased and IPD increased.

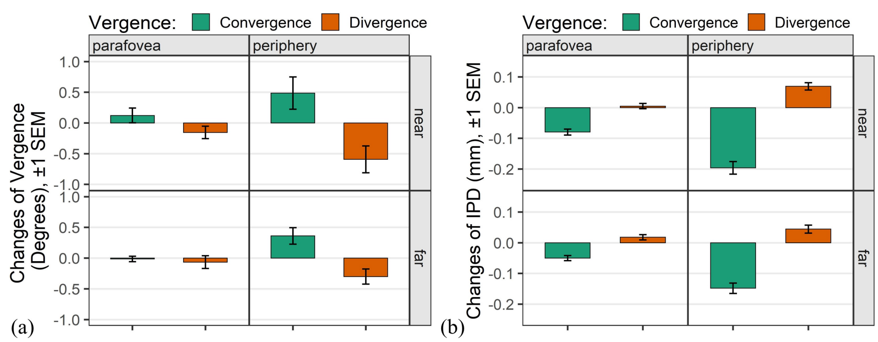

Figure 4: Results of the analysis for the change in of EVA (a) and IPD (b) with depth and target object position. In the near periphery condition, the largest perceptual depth changes occurred, as EVA and IPD change values were largest in convergence and divergence. In the far parafoveal condition, where perceptual depth discrepancies were expected to be smallest, changes in EVA and IPD were smallest in convergence and divergence. Therefore, the relationship between the magnitude of depth change and the magnitude of EVA and IPA change was consistent.

effects were detected for the IPD. In terms of the precision, IPD had higher precision and less variability (~0.01 mm SEM) than EVA (~0.15 degree SEM) in each of the conditions of depth and target position.

7 DISCUSSION

In this study, we examined whether measurements of EVA and IPD, derived from a commercial VR display with a built-in eye tracker, could reveal when subjects changed their perceptual depth plane to fixate on objects located in the fovea, parafovea, and periphery, within a VR environment. We time-locked our analysis of EVA and

IPD variables to moments in which we knew that participants successfully shifted their gaze from far to near (convergence) and from near to far (divergence). Further, because there was a background with walls and a horizon inducing an environment with linear perspective (e.g., looking down a hallway), targets located in the periphery, which were closer to the walls closest to the participant, appeared perceptually much closer than targets in the parafovea. We expected that changes in EVA and IPD would be greater for peripheral targets compared to parafoveal targets due to the greater change in perceptual depth from the distant centering cross.

Our results confirmed that both EVA and IPD changed measurably right at the moment that subjects landed their gaze on a new object at a different depth (see Fig. 3), and they changed in the hypothesized manner. EVA increased significantly after shifting from far to near and decreased significantly after shifting from near to far. Likewise, IPD decreased significantly after shifting from far to near and increased significantly after shifting from near to far. The time-locked degree of change measured in these variables, as represented in Fig. 4, also supported the final hypothesis that the degree of change in EVA and IPD would reflect the degree of change in perceptual depth. We observed that in the near periphery condition (Fig. 4 upper right quadrant), where the largest perceptual depth changes occurred, convergence and divergence EVA and IPD change values were largest. The relationship of magnitude of depth change and magnitude of EVA and IPD was also consistent in the far parafoveal condition where perceptual depth discrepancies were expected to be smallest, and EVA and IPD measures were smallest (Fig. 4 bottom left quadrant). In terms of the precision and variability, EVA has higher variability and less precision than IPD. One possible explanation behind this findings is the *vergence-accommodation conflict*, as previous results (Iskander et al. [2019]) found higher variability in vergence values in the commercial VR displays, and stated the same reason.

8 CONCLUSIONS, LIMITATIONS, AND FUTURE WORK

One potential use of eye-tracking-enabled VR technology is to track which depth participants are looking at and present stimuli according to the perceptual depth to reduce switching between visual depth planes. Therefore, in this research, we presented an investigation of whether VR systems incorporated with eye-tracking technologies can be used to infer changes in perceptual depth in VR. Our findings indicate that it is possible, in principle, to predict perceptual depth changes with an eye tracker enabled VR display. Both EVA and IPD behaved according to our hypothesis, as well consistent with the theory of how the human visual system responds to depth changes. With validation our findings could lead to development of a closed eye-tracking enabled AR/VR system that leverages EVA and/or IPD to estimate individualized depth estimates. This capability could then be used to disambiguate fixated objects using depth (i.e. AR car dashboard and nearby road) as well as the displaying of objects at the perceptual depth plane. This ability could help improve interactive display experience and combat fatigue due to focal distance switching.

The main limitation of our investigation was in the design of the VR environment, where the linear perspective created by walls and horizon likely created depth cues and biased depth perception. Specifically, the cues likely caused the peripheral and near condition disks to be perceived as a larger depth change (because they were closer to the walls and thus the subject) from the fixation cross than the parafoveal and far condition disks (because the fixation cross, parafoveal and far disks were closer to the horizon and far away from the player). Thus, the linear perspective bias can explain the pattern of EVA and IPD values in each condition despite 'objective' unity coordinates placing peripheral and parafoveal disks at the same distance from the subject as well as far condition disks 'objectively' farther away from the fixation cross than near condition disks. While our results indicate that EVA and IPD values vary with the magnitude of perceptual depth changes, our experiment lacks a ground truth to assess accuracy in the extent to which EVA and IPD can measure depth changes. Future experimentation should include a ground truth such as subjective depth perception questions, or replication in an AR environment where real world depth changes can be utilized and measured.

REFERENCES

Ioannis Agtzidis, Mikhail Startsev, and Michael Dorr. 2019. 360-Degree Video Gaze Behaviour: A Ground-Truth Data Set and a Classification Algorithm for Eye Movements. In *Proceedings of the 27th ACM International Conference on Multimedia* (Nice, France) *(MM '19)*. Association for Computing Machinery, New York, NY, USA, 1007–1015. https://doi.org/10.1145/3343031.3350947

Chloe Callahan-Flintoft, Christian Barentine, Jonathan Touryan, and Anthony J. Ries. 2021. A Case for Studying Naturalistic Eye and Head Movements in Virtual Environments. *Frontiers in Psychology* 12 (2021). https://doi.org/10.3389/fpsyg.2021.650693

Viviane Clay, Peter König, and Sabine Koenig. 2019. Eye Tracking in Virtual Reality. *Journal of Eye Movement Research* 12 (04 2019). https://doi.org/10.16910/jemr.12.1.3

Russell A. Cohen Hoffing, Nina Lauharatanahirun, Daniel E. Forster, Javier O. Garcia, Jean M. Vettel, and Steven M. Thurman. 2020. Dissociable mappings of tonic and phasic pupillary features onto cognitive processes involved in mental arithmetic. *PLOS ONE* 15, 3 (03 2020), 1–14. https://doi.org/10.1371/journal.pone.0230517

Neil A. Dodgson. 2004. Variation and extrema of human interpupillary distance. In *Stereoscopic Displays and Virtual Reality Systems XI*, Mark T. Bolas, Andrew J. Woods, John O. Merritt, and Stephen A. Benton (Eds.), Vol. 5291. International Society for Optics and Photonics, SPIE, 36 – 46. https://doi.org/10.1117/12.529999

Andrew T. Duchowski, Donald H. House, Jordan Gestring, Robert Congdon, Lech undefinedwirski, Neil A. Dodgson, Krzysztof Krejtz, and Izabela Krejtz. 2014. Comparing Estimated Gaze Depth in Virtual and Physical Environments. In *Proceedings of the Symposium on Eye Tracking Research and Applications* (Safety Harbor, Florida) *(ETRA '14)*. Association for Computing Machinery, New York, NY, USA, 103–110. https://doi.org/10.1145/2578153.2578168

Andrew T. Duchowski, Brandon Pelfrey, Donald H. House, and Rui Wang. 2011. Measuring Gaze Depth with an Eye Tracker during Stereoscopic Display. In *Proceedings of the ACM SIGGRAPH Symposium on Applied Perception in Graphics and Visualization* (Toulouse, France) *(APGV '11)*. Association for Computing Machinery, New York, NY, USA, 15–22. https://doi.org/10.1145/2077451.2077454

Moritz Feil, Barbara Moser, and Mathias Abegg. 2017. The interaction of pupil response with the vergence system. *Graefe's Archive for Clinical and Experimental Ophthalmology* 255 (11 2017), 2247—-2253. https://doi.org/10.1007/s00417-017-3770-2

Herbert Gross, Fritz Blechinger, and Bertram Achtner. 2015. *Human Eye.* John Wiley & Sons, Ltd. 1–87 pages. https://doi.org/10.1002/9783527699247.ch1 arXiv:https://onlinelibrary.wiley.com/doi/pdf/10.1002/9783527699247.ch1

David M. Hoffman, Ahna R. Girshick, Kurt Akeley, and Martin S. Banks. 2008. Vergence-accommodation conflicts hinder visual performance and cause visual fatigue. *Journal of Vision* 8, 3 (Jan. 2008), 1–30. https://doi.org/10.1167/8.3.33

Ignace T.C. Hooge, Roy S. Hessels, and Marcus Nyström. 2019. Do pupil-based binocular video eye trackers reliably measure vergence? *Vision Research* 156 (2019), 1–9. https://doi.org/10.1016/j.visres.2019.01.004

Yu Imaoka, Andri Flury, and Eling D. de Bruin. 2020. Assessing Saccadic Eye Movements With Head-Mounted Display Virtual Reality Technology. *Frontiers in Psychiatry* 11 (2020). https://doi.org/10.3389/fpsyt.2020.572938

Julie Iskander, Mohammed Hossny, and Saeid Nahavandi. 2019. Using biomechanics to investigate the effect of VR on eye vergence system. *Applied Ergonomics* 81 (2019), 102883. https://doi.org/10.1016/j.apergo.2019.102883

J. Jones, Darlene Edewaard, Richard Tyrrell, and Larry Hodges. 2016. A schematic eye for virtual environments. 221–230. https://doi.org/10.1109/3DUI.2016.7460055

Jeong-Sik Kim, Byeong Hun An, Won-Been Jeong, and Seung-Woo Lee. 2021. Estimation of Interpupillary Distance Based on Eye Movements in Virtual Reality Devices. *IEEE Access* 9 (2021), 155576–155583. https://doi.org/10.1109/ACCESS.2021.3128991

R. John Leigh and David S. Zee. 2015. *The Neurology of Eye Movements*. Oxford University Press, Oxford, UK. https://doi.org/10.1093/med/9780199969289.001.0001

Marissa Lynn, Kevin Houston, Shrinivas Pundlik, Matteo Tomasi, and Gang Luo. 2020. Measuring Virtual Reality Headset Resolution and Field of View: Implications for Vision Care Applications. *Optometry and Vision Science* 97 (2020), 573–582. Issue 8. https://doi.org/10.1097/OPX.0000000000001541

Nicholas P. Murray, Melissa Hunfalvay, and Takumi Bolte. 2017. The Reliability, Validity, and Normative Data of Interpupillary Distance and Pupil Diameter Using Eye-Tracking Technology. *Translational Vision Science & Technology* 6, 4 (07 2017), 2–2. https://doi.org/10.1167/tvst.6.4.2

Gurjot Singh, Stephen R. Ellis, and J. Edward Swan II. 2018. The effect of focal distance, age, and brightness on near-field augmented reality depth matching. *IEEE Transactions on Visualization and Computer Graphics* (2018), 1–14. https://doi.org/10.1109/TVCG.2018.2869729

Maria Solé Puig, August Romeo, and Hans Supèr. 2021. Vergence eye movements during figure-ground perception. *Consciousness and Cognition* 92 (2021), 103138. https://doi.org/10.1016/j.concog.2021.103138

Unni Sulutvedt, Thea K. Mannix, and Bruno Laeng. 2018. Gaze and the Eye Pupil Adjust to Imagined Size and Distance. *Cognitive Science* 42, 8 (2018), 3159–3176. https://doi.org/10.1111/cogs.12684 arXiv:https://onlinelibrary.wiley.com/doi/pdf/10.1111/cogs.12684