The Vergence-Accommodation Conflict in Stereoscopic Environments: A Comparison of Theoretical and Gaze-Based Vergence Angle

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Abstract
The utilization of 3D displays has become significant in various fields such as vision research, medical imaging, surgical training, scientific visualization, virtual prototyping, and other related applications. In many of these applications, it is necessary for the graphic image to accurately depict the 3D structure of the portrayed object. Unfortunately, the perception of 3D structures in 3D displays is often distorted by the reality depicted in the displays. The effects of these conflicts may affect binocular fusion and may cause visual fatigue. The extensive study of the vergence-accommodation conflict has shed light on the distortion in 3D structure. In this study, the aim was to investigate this phenomenon by comparing the theoretical eye vergence angle with the gaze-based eye vergence angle using eye tracker gaze data. The findings showed that the gaze-based eye vergence angle was largest at the greatest parallax, indicating a correlation between parallax and vergence angle. Furthermore, the results revealed that the accuracy of the eye vergence angle was highest at the nearest parallax, suggesting that virtual objects placed closer to the screen and in the middle generally exhibited improved accuracy. These findings contribute to a better understanding of the vergence-accommodation conflict in stereoscopic environments, providing insights that can inform the design and development of virtual reality systems.

Keywords: Stereoscopic Environment, Parallax, Vergence Angle, Vergence-Accommodation Conflict

Introduction

Virtual Reality (VR) has emerged as a significant technological advancement, facilitating numerous applications across diverse industries including retail, healthcare, education, entertainment, architecture, tourism, real estate, and more. The proliferation of VR is evident in the growing number of users, with a current estimated global user base of 171 million, and a projected trajectory of rapid growth. Notably, the latest developments in VR technology have introduced stand-alone headsets, immersive experiences, realistic graphics, and interactivity, enhancing the overall quality of VR experiences. Despite advancements in stereoscopic 3D technology, consumer skepticism persists due to concerns about appearance, naturalness, and convenience. Generating high-quality stereoscopic 3D images from two images is challenging due to potential fixation errors in binocular fixation (Zilly et al., 2011). However, prolonged exposure to virtual environments (VEs) can have negative effects on users, resulting in symptoms of visual fatigue. These symptoms may include headaches, dizziness, nausea, eye strain, and diplopia (double vision) (Brunnström et al., 2017; Hua, 2017; Iskander et al., 2019; Kuze & Ukai, 2008). These adverse effects can impact the user experience and limit the practicality and comfort of extended VR sessions.

In 1989, Finke proposed that the mental imageability inherent in humans has the potential to improve their ability to concentrate on objects in their surroundings. However, when objects are displayed on a flat screen in the form of a series of shots, the eye can easily lose track of the object's intended focal point due to unforeseen alterations in location or camera angle. This is due to the fact that changes in the disparity of the object's visual presentation eliminate binocular vision, resulting in diplopia or double vision, which can be disorienting and confusing. The eye's response to changes in depth, which affects its vergence (eye alignment) and accommodation (lens focusing), typically work together to create a clear image. However, when immersed in a virtual environment, a conflict arises between vergence and accommodation, known as vergence-accommodation conflict (VAC) (Hoffman et al., 2008).This conflict occurs when a 3D object is displayed on a flat screen, as a 3D display provides depth cues like shading, size, occlusion, and binocular disparity, while a flat display is associated with focus and blurring cues. This discrepancy between what the eyes perceive and how the lens focuses poses a challenge in the development of stereoscopic 3D technology (Hoffman et al., 2008).

Evaluating the performance of the vergence system on a stereoscopic display is essential, as depth perception relies on the vergence response. Previous research has examined the conflict between vergence and accommodation in the visual system, particularly in the vergence eye movement system, by analyzing changes in vergence and accommodation using techniques such as ocular biomechanics and eye-tracking(Hoffman et al., 2008; Vienne et al., 2014). To compare vergence angles in matching (theoretical) and conflicting (actual) viewing conditions, this study utilized a combination of eye-tracking, 3D stereoscopic displays, and trigonometric computations. Simulating eye-head coordination requires a sophisticated model of eye-head-neck biomechanics, which can be embedded in a virtual reality device, such as the latest version of a head-mounted display (Iskander et al., 2019).

The use of eye trackers enables the collection of eye gaze data, which can be used to calculate eye vergence angle. However, in situations where the eye tracker output does not provide the required information, additional computations may be necessary. Difficulties in perceiving depth or maintaining focus on objects can adversely affect eye-gaze interaction performance, leading to increased visual fatigue and frustration among users. Therefore, our study specifically investigated the influence of virtual object parallax and position on the vergence response. The findings of this study can serve as a foundation for future research on the vergence-accommodation conflict in virtual environments. By understanding how virtual object parallax and position affect the vergence response, researchers and practitioners can further improve the design and implementation of virtual reality experiences to minimize visual discomfort and optimize user performance.

Method

The study sought to deepen the comprehension of vergence accommodation conflict in stereoscopic environments. The research compared theoretical vergence angles with gaze-based vergence angles to gain insight into this phenomenon. Twelve graduate students (four males and eight females) aged 22 to 31 years old (M ± SD = 24.5 ± 3.0) from Taiwan Tech participated. All participants had normal or corrected visual acuity and underwent a stereo vision test to confirm their eligibility based on maximum stereo vision. The participants did not receive any form of compensation, such as payment or academic credit, for their participation in this study. Prior to the commencement of the experiment, the participants gave informed consent for their participation in the study, as well as for the publication of their identifiable information or images.

Experiment procedure

In preparation for the experiment, all participants underwent a Tumbling E visual acuity test. Those whose visual acuity was greater than 20/20 were considered to have optimal vision. We also determined the parallax threshold for each participant to assess their maximum stereo vision. After confirming eligibility for adequate 3D vision, participants had their inter-pupillary distance (IPD) measured and provided written consent. They were thoroughly briefed on the study's objectives and procedures before volunteering for the virtual reality environment. To ensure precise eye gaze data, the Tobii eye tracker was calibrated prior to parallax adjustment. The default calibration setting of Tobii studio, utilizing nine points and medium speed, was employed to capture binocular eye movements of participants (Fig. 1).

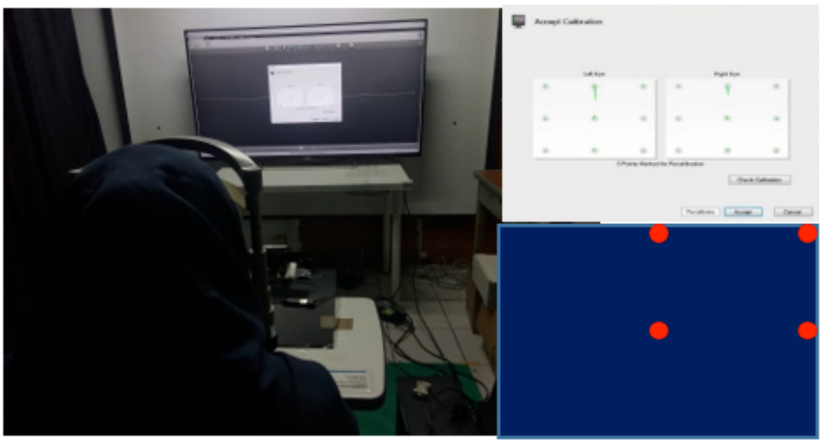

Figure 1. An illustration depicting a participant during the experiment.

Experimental design

During the experiment, participants were presented with stereoscopic targets that were projected in front of a 3D TV. These targets were positioned at various egocentric distances and positions on a frontal plane. The targets, depicted as spherical objects, were randomly displayed in red (Fig. 1).

Independent variables

This study independently manipulated two variables, namely three parallax levels (zero, 30 cm, and 60 cm) and four object positions (middle, middle right, top right, and top). The experimental design was a 3 (parallax) × 4 (position) within-subject design, which meant that there were 12 possible combinations for each participant. The statistical analysis used was a repeated-measures analysis of variance.

Dependent variables

The primary focus of this research was on the measurement of eye vergence angle as a dependent variable. The participants' eye gaze was recorded using an eye-tracking device, which allowed for the measurement of the vergence angle. The eye tracker software records the gaze position based on the projection of the gaze line onto the observed surface, rather than the eye rotation angle. Consequently, the eye vergence angle was not automatically measured by the eye tracker and computation was required to determine it from the raw eye-tracking data. The equation for calculating the vergence angle can be derived from the same trigonometric functions (Fig. 2).

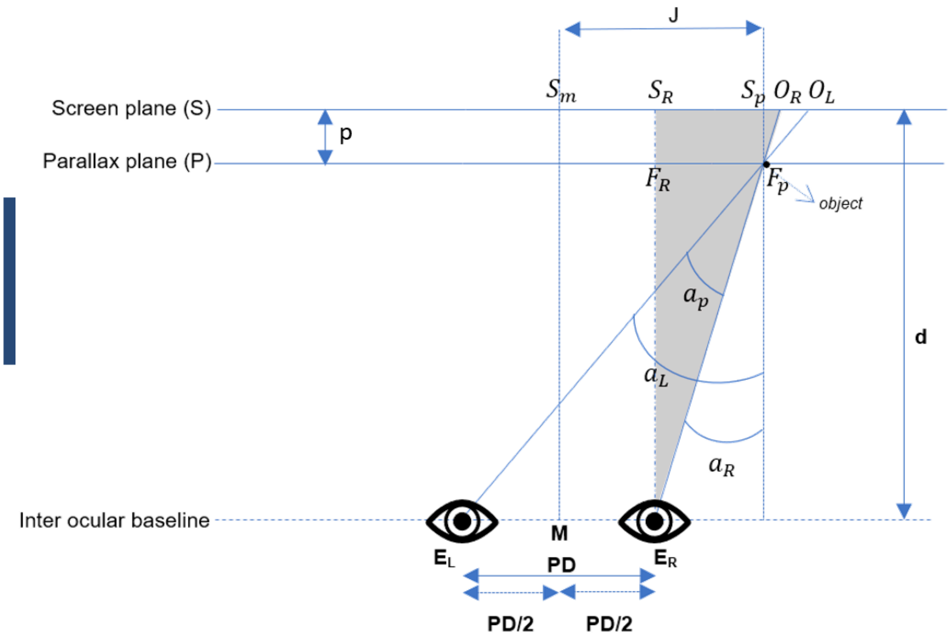

Figure 2. The virtual object in the 30 and 60 parallax and the right.

Where:

E_R : The right eye rotation center
E_L : The left eye rotation center
PD : Distance between the eye rotation centers E_R and E_L
d : The distance between screen plane and the inter ocular baseline
M : The midpoint between E_R and E_L
S_m : The orthogonal projection of M on screen plane and corresponds to the center of the horizontal meridian of the screen.

J : The distance between S_p and S_m
O_R : The center of the object on screen plane for right eye
O_L : The center of the object on screen plane for left eye
y : The distance between O_R and O_L
S_p : The orthogonal projection of F_p (the fixation point) on the screen plane
F_p : The fixation point
S_R : The projection on-screen plane of the right eye line of gaze in the primary position
F_R : The projection on-parallax plane of the right eye line of gaze in the primary position
a_p : Vergence angle
a_R : Right eye angle
a_L : Left eye angle

Based on Fig. 2, we know that:

$$a_p = a_L - a_R \tag{1}$$

$$a_p = ArcTan\left[\frac{\mathrm{PD} + \frac{\left(O_R - \left(S_m + \frac{\mathrm{PD}}{2}\right)\right)\left(\mathrm{d} - \frac{\mathrm{dy}}{\mathrm{PD}+\mathrm{y}}\right)}{\mathrm{d}}}{\mathrm{d} - \frac{\mathrm{dy}}{\mathrm{PD}+\mathrm{y}}}\right] - ArcTan\left[\frac{\left(O_R - \left(S_m + \frac{\mathrm{PD}}{2}\right)\right)}{\mathrm{d}}\right] \tag{2}$$

In the present study, eye vergence angle accuracy was another dependent variable considered. The accuracy of the eye vergence angle, which reflects the proximity to the theoretical eye vergence angle, was calculated using a formula previously employed in studies conducted by Dey et al., (2010) and Chiuhsiang JoeLin et al., (2019):

$$\text{Accuracy} = \left(1 - \left|\frac{a_p\ gaze\ based - a_p\ theoretical}{a_p\ theoretical}\right|\right) \tag{3}$$

Results

The main objective of this study was to compare and contrast the theoretical vergence angle (response vergence) with the gaze-based vergence angle (stimulus-response) as proposed by (Jaschinski, 2001). Additionally, the study aimed to investigate the potential impact of parallax and virtual object position on eye vergence angle. To achieve this, the study manipulated three different parallax levels (on the screen, 30 cm in front of the screen, and 60 cm in front of the screen) and four object positions (middle, middle right, top right, and top). Eye-tracking data was collected and analyzed, and an equation based on trigonometric computation was developed to accurately measure the vergence angle.

The eye movements of the participants were recorded using a Tobii eye-tracker with a framerate of 60 Hz. Each participant generated approximately 4778 gaze data points for 12 different experiment combinations. These data were classified into three types: fixation, saccade, and unclassified. In this study, only the fixation point coordinates were used to calculate the eye vergence angle. The results of the one-way repeated measures ANOVA for three levels of parallax on each dependent variable, namely eye vergence angle and accuracy, are presented in this section. In cases where significant effects were observed, Tukey's HSD post hoc tests were conducted at a significance level of p = 0.05.

Source	*F-value*	*p-value*
Parallax	$28.501_{(2,22)}$	.000
Position	$.961_{(3,33)}$	.423
Parallax*Position	$.695_{(6,66)}$	.654

Table 1. A summary of the results from the repeated measures ANOVA for the gaze-based vergence angle is presented, with non-significant interactions omitted from the ANOVA table.

A detailed summary of the results obtained from the repeated measures ANOVA (Table 1) reveals that there is a significant impact of parallax on the gaze-based vergence angle ($F(_{2,22})$ = 28.501, p <.000). The average gaze-based vergence angles, based on the eye tracker's gaze point, were 1.800 degrees (SD = 0.109), 3.270 degrees (SD = 1.017), and 4.478 degrees (SD = 2.104) for 0 cm, 30 cm, and 60 cm parallax levels, respectively. In comparison, the theoretical vergence angles were 1.751 degrees (SD = 0.086), 3.173 degrees (SD = 1.275), and 4.005 (SD = 1.646) for 0 cm, 30 cm, and 60 cm parallax levels, respectively. Notably, the gaze-based vergence angle exceeded the theoretical vergence angle for each parallax level, as shown in Fig. 3. All pair-wise differences were statistically significant, as determined by the grouping information obtained from the Tukey method.

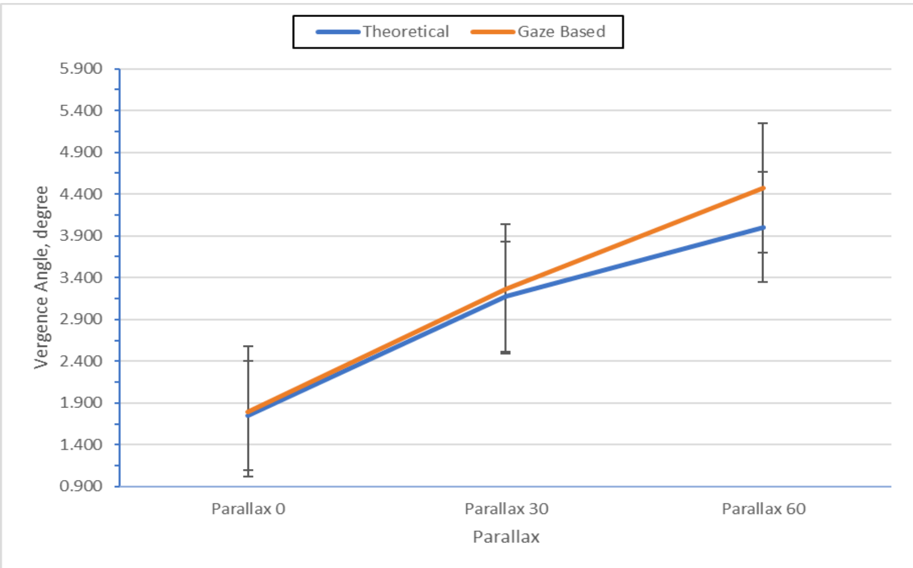

Figure 3. Eye vergence angle compared using gaze point and theoretical data for parallax.

The outcomes of the repeated measures ANOVA (Table 2) revealed significant effects of parallax ($F(2,22) = 36.908$, $p < .000$) on the accuracy of the vergence angle (Fig. 4a). The overall accuracy of the vergence angles varied for different parallax levels, with average accuracies of 0.966 (SD = 0.013), 0.774 (SD = 0.145), and 0.755 (SD = 0.165) for zero, 30 cm, and 60 cm parallax, respectively. Post hoc analysis using Tukey's method identified two groups of independent variables with statistically significant differences in the accuracy of the vergence angle at 30 - 0 (p = .000) and 60 - 0 (p = .000) parallaxes. Among the four object positions (middle, top middle, middle right, top right), the middle position resulted in the highest accuracy (0.863 ± 0.168) followed by top middle (0.833 ± 0.160), middle right (0.819 ± 0.156), and top right (0.812 ± 0.151) (Fig. 4b).

Source	*F-value*	*p-value*
Parallax	$36.908_{(2,22)}$	.000
Position	$.993_{(3,33)}$	.408
Parallax*Position	$.319_{(6,66)}$	.925

Table 2. Summary of repeated measures ANOVA outcomes for accuracy of vergence angle, excluding non-significant interactions from the ANOVA table.

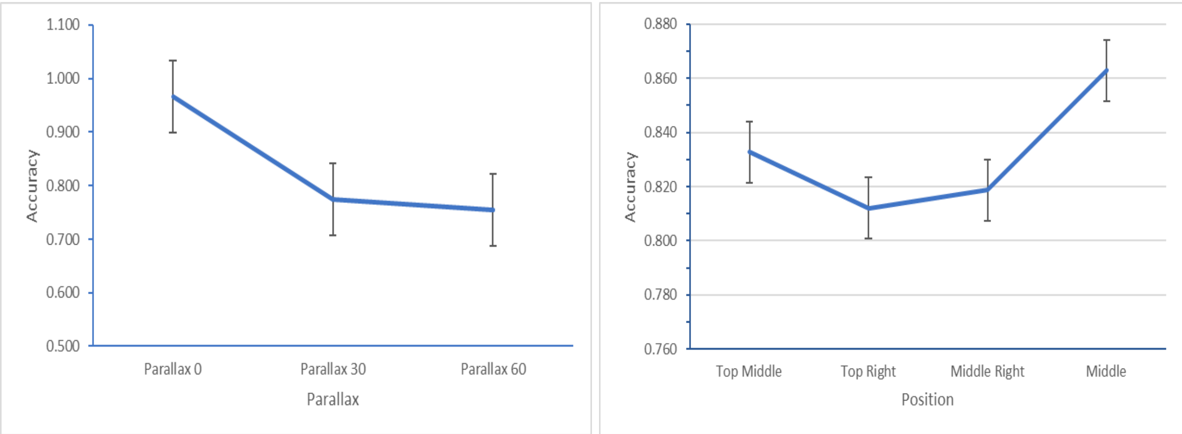

Figure 4. (a) Accuracy concerning parallax, (b) Accuracy with respect to position. The error bar shows the standard error of the mean.

Discussion

The study revealed that the gaze-based vergence angle consistently showed an overestimation compared to the theoretical vergence angle, suggesting an overestimation of convergence. This finding supports the idea of a conflict between vergence and accommodation in virtual 3D environments, where constant accommodation without clear depth cues can create conflicts with the vergence movement induced by simulated depth changes (Hoffman et al., 2008; Vienne et al., 2014). The results of this study are consistent with prior research (Chiuhsiang J.Lin &Woldegiorgis, 2017; Woldegiorgis &Lin, 2017), which found that virtual environments exhibit space compression in all three dimensions, affecting object positions and making virtual objects appear smaller and closer. The study also revealed that participants tended to overestimate the vergence angle, with greater overestimation observed as the parallax increased from 0 to 60 cm. It is noteworthy that the majority of studies on virtual vergence angles have reported overestimation, indicating that this phenomenon is commonly observed in virtual environments (Iskander et al., 2019; Luca et al., 2009).

The results of this study demonstrated a significant association between simulated parallax and eye gaze points, influencing the accuracy of vergence angle measurements. As simulated parallax increased, participants experienced difficulty maintaining gaze fixation on the virtual object, resulting in decreased accuracy and increased visual fatigue. These findings align with previous research that has shown a decrease in vergence angle accuracy as virtual objects approach the eye (Chiuhsiang J.Lin &Woldegiorgis, 2017; Chiuhsiang JoeLin et al., 2019). The observed conflict between vergence and accommodation further reduces accuracy in virtual environments, particularly for objects displayed closer to the participant. This study contributes to the existing body of knowledge in this area and highlights the importance of carefully considering parallax and other factors when designing virtual environments for research and practical applications.

The study observed that the accuracy of vergence angle was highest when the virtual object was positioned near the center of the display. It is hypothesized that systemic effects, such as dextroelevation, which can impact pupil size and eye tracking accuracy, may influence the direction of gaze in virtual environments. Previous research has also shown that judging the vertical position of virtual objects displayed at the bottom of the screen is challenging. In contrast, our findings suggest that virtual objects displayed on the right side of the screen are more affected in the horizontal position compared to objects in the center. This indicates that participants' performance in judging virtual object positions is not uniform and can vary based on the object's location on the screen, which should be considered when designing virtual environments for accurate spatial perception. Additionally, the use of a 3D glasses emitter may interfere with the infrared light of the Tobii eye tracker, which highlights a potential limitation of simultaneous instrument use. Further research is needed to investigate the effects of these factors on eye-tracking accuracy in virtual environments.

The conflict between vergence and accommodation, which can lead to eye strain, was identified as a primary factor in the present study. The findings indicate that excessive eye movements during convergence may not decelerate or stabilize when focusing on a specific parallax, impacting the ocular system. Additionally, when immersion occurs, the median value of the vergence angle increases, suggesting a difference in perception of depth. This inaccurate depth perception makes it challenging to maintain focus on objects at different depths.

Future research should prioritize conducting additional studies to better understand the influence of virtual object height on the resulting vergence angle. Adjusting the trigonometric calculation by incorporating a height variable, representing the height difference between the eyes and objects, could provide more detailed insights into the factors contributing to the vergence-accommodation conflict. Exploring the effects of virtual object height on the ocular system in immersive environments could yield valuable information, with the goal of developing strategies to mitigate or manage visual fatigue.

Conclusion

This study examined how parallax and virtual object position impact the eye vergence angle in a virtual environment. The study used trigonometric computations to measure vergence angles from gaze positions and emphasized the importance of accurately computing vergence angles. The study found that increasing parallax decreased the ability to properly fixate on virtual object surfaces, significantly affecting gaze-based viewing angles. The largest gaze-based vergence angle was found with a 60 parallax. The study found that parallax significantly impacted the accuracy of vergence angle, with reduced accuracy when virtual objects were closer to the eyes. This information could be used by VR developers to optimize parallax and target locations to minimize vergence-accommodation conflict. Further research could investigate the influence of virtual object height on vergence angle, providing additional insights for managing the conflict between vergence and accommodation.

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