Article

Exocentric Distance Judgment and Accuracy of Head-Mounted and Stereoscopic Widescreen Displays in Frontal Planes

Chiuhsiang Joe Lin 1, Betsha Tizazu Abreham 1, Dino Caesaron 2,* and Bereket Haile Woldegiorgis 1

1 Department of Industrial Management, National Taiwan University of Science and Technology, No.43, Sec. 4, Keelung Rd., Da’an Dist., Taipei City 10607, Taiwan; cjoelin@mail.ntust.edu.tw or chiuhsiangjoelin@gmail.com (C.J.L.); mistresaba@gmail.com (B.T.A.); berekethi12@gmail.com (B.H.W.)

2 Department of Industrial Engineering—School of Industrial and System Engineering Telkom University, Jl. Telekomunikasi Terusan Buah Batu, Sukapura, Dayeuhkolot, Bandung 40257, Jawa Barat, Indonesia

* Correspondence: dino.caesaron@telkomuniversity.ac.id or dino.caesaron@gmail.com; Tel.: +62-813-3428-3678

Received: 24 January 2020; Accepted: 16 February 2020; Published: 20 February 2020

Abstract: An experiment was done to explore the effects of two virtual display systems on the accuracy of exocentric distance judgment and position. Sixteen participants viewed animated virtual targets using either a head-mounted display (HMD) or a stereoscopic widescreen display (SWD). The virtual targets have been shown, one at a time, at three depth levels and with two corresponding exocentric distances and three target sizes at each target distance and, afterward, via pointing by holding a stick to estimate the exocentric distance and position of each target. The position data were collected using an OptiTrack motion capture system. The results showed that the accuracy of exocentric distance judgment was higher with the head-mounted displays than with the stereoscopic widescreen displays. In addition, higher position accuracy in the X-direction was obtained from the stereoscopic widescreen displays, whereas no significant difference was observed in position accuracy in the Y-direction. However, it is possible that the HMD could give better accuracy in both exocentric distance and position judgments in the frontal plane, if the HMD had been perfectly mounted and flawlessly fit the participant’s eyes. The result also revealed that exocentric distance judgment was significantly higher at the farthest target distances than at the nearest distance. Similarly, the position accuracy significantly increased as exocentric distance decreased. Moreover, engineers may allude to the findings as the evidence from the study suggests that the intermediate target distances might be fitting or ideal distances to design and structure 3D applications.

Keywords: exocentric distance; head-mounted display; stereoscopic widescreen display

1. Introduction

Nowadays, more than an amusement platform, augmented reality (AR)/virtual reality (VR) can be utilized in a wide range of applications such as archeology, geography, and space tours where real-world access is not available, and to train employees where actual live training is greatly unsafe, for example, on-board offshore oil rigs, medical surgery training and diagnosis, and neuroscience [1]. In Industry 4.0, cyber–physical systems (CPS) monitor physical processes, create a virtual replica of the physical world (Digital-Twin concept), and make autonomous decisions [2]. CPSs interact and collaborate in real-time with one another and humans across the value chain throughout the Internet of Things [2]. Romero et al. [3] introduced the concept of Operator 4.0 in the context of human cyber–physical systems (H–CPS) as systems designed to improve human abilities, human physical sensing, and cognitive capabilities through different technologies, since Industry 4.0 without
human beings would be unthinkable. Posada et al. [4] elucidated that visual computing is a crucial
technology to smooth human–machine interactions on various levels of smart production, where AR/VR are the main parts of visual computing technologies to empower the operator in Industry 4.0 [2]. The integration of the human operator in Industry 4.0 nevertheless poses challenges in research, technology, and politics [3]. For example, Posada et al. [5] explained that, to train operators and support them to perform tasks, the improvement of AR/VR experiences is crucial, where difficult interactions, misalignment of real/virtual models and better integration in real-world operator workspaces are the challenges of AR/VR.

It is believed that, for any 3D-application, a VR framework should create a sensible dimension of authenticity that users can have confidence and be prepared to partake in [6]. VR innovations are, as yet, failing to give the realism that the real world can, because VR authenticity still experiences particular limitations [7], for instance, creating proper space visualizations of the environment and how selection and manipulation of objects in VR works are, thus far, the challenging problems [8]. Stefanucci et al. [9] argued that precise space visualization is critical in VR, which can enhance interaction performance and provide a virtual scene with satisfactory perceptual fidelity. Segura et al. [10] also confirmed that the use of VR in industrial applications has been hindered because of visual discomfort and incorrect geometry perception. Accordingly, it is becoming increasingly difficult to overlook the investigation of visual space accuracy in VR.

To explore the accuracy of visual space, two frames of reference are usually employed. According to a definition provided by Lin and Woldegiorgis [11], the egocentric frame of reference utilizes the subject as a focal point of reference, while an exocentric frame of reference indicates the relative separation among objects and their corresponding orientations. So far, a considerable amount of studies in the VR literature has reported accuracy considering egocentric environments, in either extrapersonal or peripersonal space. For example, egocentric distance estimations are relatively accurate [12], underestimated [13–16], and sometimes overestimated [6,16,17]. Thus far, in the exocentric space, comparatively limited numbers of studies have been reported, although researchers argued that numerous applications in a virtual environment indeed require the knowledge of exocentric distance. For example, Woldegiorgis and Lin [6] pointed out and argued that performances in manipulation, navigation, and avatar control tasks are significantly influenced by exocentric distance judgments in peripersonal space. Similarly, Wartenberg and Wiborg [18] urged that exocentric distance information is very important for numerous applications in virtual conditions.

Even though there are not many studies in the exocentric space, it seems most of them agreed on the underestimation [19–21]. Kelly et al. [22] bolstered the case that the virtual space has been compacted by indicating the underestimation of both depth and frontal extents. Similarly, Lin, Woldegiorgis and Caesaron [8] and Woldegiorgis and Lin [6] reported compression in the frontal plane in stereoscopic widescreen displays (SWDs). Moreover, Li et al. [2011] looked at egocentric and exocentric distance estimation and discovered underestimation in both cases, where compression in egocentric conditions was higher. Kelly et al. [2017] reported that modern head-mounted displays (HMDs) have improved the accuracy of space perception. However, Kelly, Hammel, Sjolund and Siegel [22] indicated that the exocentric distance judgment in VR is either underestimated when objects are oriented in both sagittal and frontal planes or sometimes veridically perceived when the objects are oriented in a frontal plane.

Researchers have discussed the possible reasons for the inaccuracy of judgment in stereoscopic exocentric spaces. For example, Waller [23] listed the display type, the geometric field of view (GFOV), scene contrast, texture, stimulus size, navigational interface, and feedback as the likely factors that affect exocentric distance estimations. Tan et al. [24] reasoned that distances are assessed more precisely in larger displays as they actuate a more grounded emotional feeling of being available in the virtual space. Aznar-Casanova et al. [25] claimed that feedback combined with a sufficiently vast GFOV could permit sensibly accurate exocentric distance estimations. Henry and Furness [19] identified that size-constancy phenomena caused misperception, whereby sizes and distances seem to be smaller when seen through a truncated field of view. Wartenberg and Wiborg [18] reported that the availability
of stereoscopic depth cues resulted in a higher estimation accuracy in the cave automatic virtual environment (CAVE). In addition, Lin, Woldegiorgis and Caesaron [8] have shown how the accuracy of judgment varies with distance because, as the exocentric distance increases, the accuracy of estimation decreases, whereas the effect of egocentric distance was not significant. Geuss et al. [26] reported the influence of VR displays on virtual space perceptions and claimed that examining it is valuable for a variety of applications.

Out of the previous studies, only a few of them exhibited the same 3D content through various VR displays that allowed for an examination between them, all of which had compared HMDs to a projection display—i.e., only one type of SWD. For instance, Waller [23] reported that participants using HMD have been precise, more linear, and more consistent with their exocentric distance judgments than participants who used a desktop display. On the other hand, Geuss, Stefanucci, Creem-Regehr, Thompson and Mohler [26] found no significant difference between the stereo back-projection (BackPro) display condition with a tracked viewpoint and the HMD conditions; they also found significant underestimation in the BackPro condition (when the viewpoint was not tracked). Henry and Furness [19] reported mixed results via comparing the real environment, a monitor, a fixed HMD (no head rotation), and a tracked HMD (with head rotation), and found that the underestimates in all the VR conditions were significantly lower than the real condition, and the estimates in the tracked HMD were significantly smaller than the other two display (monitor and fixed HMD) conditions.

Therefore, it is very important to further explore the effect of displays on the accuracy of exocentric distance estimation for the following reasons: First, to date, there has been little agreement on exocentric distance judgment in VR displays, whether the HMD is better than the projection display types or if there no significant difference between them, for example: HMD is better in distance judgment [23], no significant difference between the display [26], and the estimates in the tracked HMD were significantly smaller than the other two displays (monitor and fixed HMD) [19]. Second, with the advancement of VR technologies, VR systems are becoming simpler and more interactive, so that the users not only look around and experience a 3D environment, but also are able to move around the space, interact with targets in the immersive environment and provide guidance. Besides, it has been reported that more natural interactions (direct interaction) improve performance [27] and can be used as a conceivable response method [28]. Despite the fact that interaction is as important as perception, interaction performance in virtual environments, especially with regards to a direct interaction impact on VR displays, has not so far been sufficiently studied when compared to visual perception. In addition, most of the previous studies attempted to measure the accuracy of perception by using verbal, perceptual, and other visually directed techniques—probably because of the technical difficulties in implementing direct reaching tasks [16]. In this manner, the findings are expected to clarify the impact of VR displays on direct interaction or reaching performance. Third, Geuss, Stefanucci, Creem-Regehr, Thompson and Mohler [26] and Lin et al. [29] have shown the need for assessments of various display technologies, since the accessibility and the overall advancement is promising. Buck et al. [30] and Kelly et al. [31] claimed that recent HMDs have enhanced precision. Therefore, the results of this study will be noteworthy in elucidating how the recent improvements of the HMDs influence user exocentric distance estimation and how its accuracy can be compared to an SWD performance. Fourth, we endeavored to explore the impact of exocentric distance, target size, and target distance (egocentric distance) with the hope that all independent variables would influence the accuracy of exocentric distance judgment and position accuracy.

2. Materials and Methods

The examination was intended to give a reasonable comparison of accuracy among HMDs and SWDs regarding their impacts on the user’s exocentric distance judgment and position estimation by using a direct interaction or reaching technique.
2.1. Stimuli and Apparatus

A ViewSonic 3D projector and HTC Vive were chosen as an illustration of HMDs and SWDs, respectively, and were used to display the experimental task for the reasons that both VR displays have been the most widely used in VR studies [16,27,30,31] and can be grouped into HMDs and SWDs respectively. Unity 3D was used to develop the experimental tasks. A desktop that supported NVIDIA graphics for binocular vision was used to run the experimental tasks in both environments. NVIDIA 3D glasses and HTC Vive were used to look at projected virtual targets.

Three sticks of 50, 85, and 135 cm length were used for pointing. A Vive controller and a reflective marker were hooked up to the tip of the sticks in the HMD case, while only reflective markers were affixed to the tips of the sticks in the SWD case. There was no essential weight variation between the sticks; therefore, the weight effect on the pointing posture or performance may have been eliminated. A motion system with six infrared cameras was used to track reflective markers, and the data was recorded via motive (version 2.0) software at 120 frames per second. The experimental setup (Figure 1) was marked and fixed to keep up the consistency of the location and placement of the participant.

An adjustable chair was used to maintain appropriate pointing posture via adjusting the sitting height as needed. A chin rest and a dark space (3.6 m × 3.2 m × 2.5 m) fenced by black curtains were used, respectively, to decrease the impact of head movement on perception, prevent light and to supply a high fidelity.

2.2. Procedure

At the start of the experiment, the objective and strategy of the test were explained to each participant. The participant was asked to take a seat in front of the screen (Figure 2b) after the display was accustomed to the interpupillary distance of the participant (IPD). The participant was instructed to put his or her chin on the chinrest, fixate their eyes on a virtual cube and wore either NVIDIA 3D glasses or HTC Vive. Once every trial started, an endless stream of clear images of virtual spheres were shown, before disappearing (after the participant reached the target), following each other in quick succession. Participants were told to go after the virtual target and reach as quickly and precisely as could be expected under the circumstances. To reduce the effect of the order, the participants were grouped equally into two halves; half of the participants used the SWD first and the other half used

Figure 1. Illustration of experimental layout for both stereoscopic widescreen display (SWD) and head-mounted display (HMD), relative locations of the ViewSonic 3D projector, and target distance.
the HMD first. Right after this, each group was split into three more groups to counterbalance the order of trials over a three-target distance (measured from participant to virtual target). Once the target distance was allocated, in a completely randomized order, participants completed the exocentric distance and size levels. Generally, every participant had to complete all ranges of tasks, where we used a fully balanced within-subject design with two displays, three target distances, two exocentric distances, and two target sizes. Each pointing trial was recorded at a sampling rate of 120 Hz. Every participant completed 132 trials in the HMD condition and 132 trials in the SWD condition, and all combinations of experimental tasks in each display lasted from 40 to 50 s.

![Figure 2. Illustration of (a) experimental task (a combination of twelve pointing trials) and the steps of reaching for the very first four targets and (b) a pointing posture of a participant in the HMD condition.](image)

2.3. Participants

Three female and thirteen male participants between the ages of 24 and 38 years of age (mean (M) = 30.33, standard deviation (SD) = 3.85), took part in the experiment. All volunteers were selected from the National Taiwan University of Science and Technology and did not get any payment or compensation of academic credits, for their participation. To meet all requirements for the inclusion, every participant needed to pass the most extreme stereo vision condition of the experiment. Two of the enrolled participants were not able to see VR targets presented at the most extreme negative parallax (at the target distance of 65 cm), so they were replaced.

2.4. Independent Variables

We pursued a repeated measure within-subject design. Two display technologies, three target distances, two exocentric distances, and two target sizes were the factors considered in the analysis. The twelve virtual targets were rendered approximately at eyes height in the frontal plane (Figure 2a) where the target distances of 65, 100, and 150 cm from the participant were used. We only considered target distances in the personal space (peripersonal and near extrapersonal spaces) for the following reasons. First, personal space is a zone immediately surrounding the observer’s head, generally within arm’s reach and slightly beyond, around which most VR applications are structured. In this region, the six information sources: occlusion, retinal disparity, relative size, convergence, accommodation, and motion information are generally effective [32,33]. All information sources are merged and coupled to produce the ability of human observers to accurately manipulate objects around them [33]. Second, in order to maintain appropriate pointing postures during direct pointing at the virtual targets (using the pole), we had to limit the range of movement in the relatively near space. In addition, the arrangement of the targets was based on the standard ISO 9241-9 [34] since the multi-direction tapping task may contribute to the difficulty of the task by considering different orientation, which could affect the performance of the reaching task. Likewise, six different exocentric distances (Figure 3), as measured...
between two consecutive targets in the pointing orders, were D1 (14.24 cm) and D2 (27.85 cm) for the targets displayed at 65 cm from the participant, D3 (21.90 cm) and D4 (42.85 cm) for the targets displayed at 100 cm, and D5 (39.63 cm) and D6 (64.28 cm) for the targets displayed at 150 cm. In addition, we also considered two different target sizes, large (2.01 cm), small (0.65 cm) for the targets displayed 65 cm from the participant, large (3.09 cm), small (0.95 cm) for the targets displayed 100 cm from the participant, and large (4.64 cm), small (1.43 cm) for the targets displayed 150 cm from the participant.

**Figure 3.** Presentation of the virtual targets (a–f) in the frontal plane of each target with the corresponding exocentric distance and target distance from the participant. The coordinates (in centimeters) are in reference to the global origin of the motion system, where it was set on the screen to the bottom right corner of the centerline of the sight of the observer.
In the SWD case, parallax (negative) was utilized to vary the target distances. Therefore, in the experiment, all the virtual targets were floating in front of the widescreen (negative parallax), where the zero parallax (target displayed at the screen) or positive parallax (target displayed behind the screen) were not included.

2.5. Dependent Variables

Visually guided direct pointing was used to estimate the exocentric distance, location data was recorded at a rate of 120 frames per second, and the accuracy was computed. Accuracy was computed by Equation (1) where it measures how near the estimate is to the position of the 3D target [8,27].

\[
\text{Accuracy} = 1 - \left( \frac{Dp - Dt}{Dt} \right)
\]  

(1)

where \(Dp\) was distance obtained from the observer’s estimate and \(Dt\) was the corresponding actual target distance. Similarly, the same equation was used to calculate the x and y position accuracies.

3. Results

Analysis based on repeated-measure ANOVA with four independent variables was conducted to assess the accuracy of exocentric distance estimates. In addition, Tukey HSD (\(\alpha = 0.05\)) post-hoc tests were used when appropriate. A Greenhouse–Geisser correction was used to rectify the degrees of freedom (DoF) when Mauchly’s test demonstrated that the presumption of sphericity had been violated.

3.1. Exocentric Distance Judgment Accuracy

The ANOVA result revealed that the effect of the display on the exocentric distance estimation was significant (\(F[1, 15] = 16.05, p < 0.01\)). The overall distance judgment results showed underestimation in the HMDs and overestimation in the SWDs, where the judgment accuracies were 0.94 (SD = 0.06) and 0.85 (SD = 0.06), respectively.

The result also showed that the main effect of target distances (\(F[1.2, 17.99] = 7.00, p = 0.01\)) and exocentric distance (\(F[1, 15] = 9.25, p < 0.01\)) were significant, whereas the effect of size (\(F[1, 15] = 0.04, p = 0.20\)) was not significant. The post-hoc analysis indicated that the exocentric distance accuracy was significantly higher at 150 than at 65 cm from the participant, where the mean and standard deviation of exocentric distance accuracies at 65, 100, and 150 cm (Figure 3a) were, respectively, 0.86 (SD = 0.12), 0.90 (SD = 0.09), and 0.92 (SD = 0.06). In addition, the result revealed that the distance judgment accuracies improved as exocentric distance increased (Figure 3b).

The interaction between environment and target distance (\(F[1.25, 18.79] = 7.97, p < 0.01\)) was significant, whereas the interaction results between environment and exocentric distance (\(F[1, 15] = 1.27, p = 0.28\)) and between environment and size (\(F[1, 15] = 2.68, p = 0.12\)) were not significant. The post-hoc analysis showed that the exocentric distance accuracy was significantly improved as target distance increase in the SWDs (Figure 4a), for which the accuracies were 0.76 (SD = 0.19), 0.86 (SD = 0.10), and 0.92 (SD = 0.04) for the target distances of 65, 100, and 150 cm from the participant, respectively. However, no significant effect of target distance on exocentric distance judgment accuracy was observed in the HMDs (Figure 4a). All the three-way interactions and the four-way interactions did not show significant difference in the exocentric distance judgment accuracy.
where the horizontal position accuracy was worsened as exocentric distance increased; whereas no
were overestimated by 0.47, 0.68, and 0.55 cm, respectively, while D3, D4, and D6 were underestimated
accuracy of 0.863 (SD = 0.06). Moreover, the main effect of both exocentric distance (F [1, 15] = 5.15,
underestimated by 0.71 and 2.8 cm, respectively.

3.2. Position Accuracy in X-Direction

The judgments of position accuracy in X-direction (horizontal position) were assessed against
the anticipated (reference) positions. The ANOVA result revealed that the difference the environment
classified as exocentric distance increased (Figure 5d) and it has improved as size decreased (Figure 5e).

In addition, the distance judgment estimations in HMD had shown mixed results as D1, D2, and D5
were overestimated by 0.47, 0.68, and 0.55 cm, respectively, while D3, D4, and D6 were underestimated
accuracy increases as exocentric distance increases.

Figure 5. Cont.
A few studies reported similar results by comparing virtual environments using HMDs to one of a number of projection display types (all fall into the same category as SWDs), and slightly underestimated (0.4 cm) in the HMDs; exocentric distance judgment was less accurate compared to the SWDs. A significant effect of exocentric distance was observed in the SWDs (Figure 5a–c), where the horizontal position accuracy was worsened as exocentric distance increases. Weber’s law could explain the phenomena where the accuracy decreases as exocentric distance increases [4,28]. The main effect of (d) exocentric distance and (e) size on horizontal position accuracy, where horizontal position accuracies improve as size and exocentric distance decreases.

3.3. Position Accuracies in Y-Direction

The judgments of position accuracy in Y-direction (vertical position) were assessed against the reference positions. The ANOVA result showed that the difference the VR displays caused to the reference positions was not significant (F [1, 15] = 0.29, p < 0.60), and the vertical position accuracies for HMDs and SWDs were, 0.90 and 0.91 respectively.

The analysis of variance showed that the effect of both target distances (F [2, 30] = 5.42, p < 0.01) and exocentric distance (F [1, 15] = 5.42, p < 0.01) were significant, whereas the effect of size (F [1, 15] = 1.13, p = 0.34) was not significant. The post-hoc analysis indicated that the exocentric distance accuracy ((Figure 6a) was significantly higher at 65 cm than at the 150 cm from the participant, where the exocentric distance accuracies were 0.92 (SD = 0.04), 0.92 (SD = 0.04), and 0.88 (SD = 0.05) for the target distances 65, 100, and 150 cm from the participant, respectively. Besides, the vertical position judgment accuracy was worsened as exocentric distance increase (Figure 6b). All the two-way interactions, three-way interactions, and the four-way interaction did not show a significant difference on the exocentric distance judgment accuracy.

4. Discussion

The results demonstrated that exocentric distance judgment (Figure 4) was more accurate (93.9%) and slightly underestimated (0.4 cm) in the HMDs; exocentric distance judgment was less accurate (85.03%) and overestimated (1.93 cm) in the SWDs. A few studies reported similar results by comparing HMDs to one of a number of projection display types (all fall into the same category as SWDs).
which are in agreement with the findings of the present study. For example, Waller [23] confirmed that immersed participants (wearing HMDs) were more precise, more linear, and less varied with their exocentric distance judgments than participants who used a desktop display. Similarly, Geuss, Stefanucci, Creem-Regehr, Thompson and Mohler [26] reported a significant difference between the BackPro display (without viewpoint tracking) and the HMD conditions, where a better accuracy of size judgment was obtained from HMDs (86%) than BackPro display (77%). Ruddle et al. [35] reasoned that the accuracy of exocentric distance judgment might be enhanced with HMDs rather than desktop displays, as HMDs are more advantageous than desktop displays in permitting information of deduced spatial relationships. In addition, the ability of HMDs to refresh the virtual target stereo information based on the tracking of the participants’ location and orientation might be a reason for their better exocentric distance judgment. For instance, Geuss, Stefanucci, Creem-Regehr, Thompson and Mohler [26] argued that display technologies with the ability to update 3D information based on the tracking of the users’ location and orientation would provide better accuracy of size judgment.

In addition, other studies reported exocentric distance judgment by comparing the real environment to a virtual environment. For instance, Henry and Furness [19] and Geuss et al. [36] both compared real environments and HMD, reported accurate and underestimated (20% lower than estimates in the real) distance judgments, respectively, in real and HMD conditions. Besides, Stefanucci, Creem-Regehr, Thompson, Lessard and Geuss [9] also revealed that sizes in the SWD were perceived smaller than in the real world. Woldegiorgis and Lin [6], Lin et al. [37], and Lin, Woldegiorgis and Caesaron [8] also reported that, under different distance and varied experimental setups, exocentric distance judgment accuracies of, respectively, 85%, 84%, and 80% in SWD, and these were perceived as smaller than in the real environment. The findings of the present study show that the exocentric distance judgment was imperceptibly improved in accordance with the past studies of VR. The possible reasons for the improvement of the judgment accuracy could be because of the direct reaching method employed in the present study and the display advancements. Indeed, accuracy results obtained using direct reaching was better as compared to the results reported in previous studies, where 86% and 77% accuracies were obtained using affordance judgment, respectively, in the HMDs and BackPro display [26]; 80% using gesture interaction [8]; 84% using perceptual matching [37]. Consequently, direct pointing could be considered as one of the reliable and promising interaction techniques in VR.

Generally, distance judgment in HMD condition tends to be underestimated as target distance increases, while distance judgment tends to be more overestimated in the SWDs (Figure 7b). The overestimation in the SWDs might be because of the negative parallax condition used in the experiment, where previous studies have reported that the distance judgment can be overestimated for the targets displayed at negative parallax [38,39], where targets are viewed floating in front of the screen.

Figure 7. A representative sample result of two participants showing how the estimates with respect to the reference at 65 cm distance from participants were observed. The positions judgment (a) in the HMD, a systematic shift to the right or to the left was observed. The way the HMD lens fit to the to the participant’s eye might be the possible reason for the observed result. However, (b) in the SWD, there was no systematic shift to any of the directions, instead, consistent estimates and overestimations were observed.
The previously discussed studies in peripersonal space have revealed that distance estimation was more accurate when the target was positioned nearer to the observer. For instance, Woldegiorgis and Lin [6] reported, as the target distance lengthened, the accuracy of distance judgment was found to endure more in the SWDs. However, the findings of the current study did not bolster this, and the overall exocentric distance judgment accuracy was low at 65 cm (Figure 4a) when compared to 100 and 150 cm. Waller [23] suggested that several factors that affect spatial perception are likely to affect exocentric distances judgments. Thus, this phenomenon might be explained by accommodation convergence conflict as it was reported to be one of the possible reasons for the scrutinized impact [11,32] at the nearest target distance. Similarly, Hoffman et al. [40] and Bruder, Argelaguet, Olivier and Lécuyer [39] elucidated that the user’s visual framework is stood up to conflicting visual information for targets closer to the participant as the highest accommodation–convergence mismatch observed.

Another issue considered in this study was the position accuracy, and the result showed the significant effects of the displays on estimating the position of targets in the horizontal direction of the frontal plane. In the X direction (horizontal position), the position accuracy (Figures 5a–c and 8a,b) in the SWDs was seen to be better than in the HMDs, with the accuracies of about 91.6% and 86.3% respectively. However, in the Y direction (vertical position), the position accuracy (Figure 6a) was not significantly different between the SWDs and HMDs, with the accuracy of about 90.3% and 91.3% respectively. To the best of our knowledge, none of the past related investigations have reported position accuracy comparing different VR displays. However, for example, Woldegiorgis and Lin [6] compared position accuracy in the frontal plane of real and stereoscopic environments, founded that the real environment (94% accuracy) was better than the position judgment in SWDs (89% accuracy), which was similar to the result reported in the present study.

![Figure 8](image-url) Illustration of all positions judgment from the sixteen participants with respect to the actual (reference) targets at 150 cm distance for (a) HMD and (b) SWD conditions. It shows that the overall position estimates in the SWD were better than the HMD position estimates.

Additionally, the position accuracy was significantly higher at both 65 and 100 cm than at 150 cm. The finding is in concurrence with the past investigations, for example, Woldegiorgis and Lin [6] reported that position accuracy decreases as egocentric distance increases. Similarly, the effect of the exocentric distance was significant, where precision declines as an exocentric distance increases (Figures 5d and 6b), and it might be explained by Weber’s law that, as the exocentric distance increases, the error of estimation also increases [8,37]. In addition, as shown in Figures 9–11, the position estimations of both VR displays were slightly shifted to the right side. We suspect that this might be because of the position estimations for the left sides of participants were blocked since all the participants were right-handed.
The position judgment error in the HMD was observed to pull every one of the targets towards either the right or to left (Figure 7a), which made the horizontal position estimates of both VR displays slightly shifted to the right side. We suspect that this might be because of the position estimations for the left side of participants were blocked since all the participants were right-handed.

Moreover, as Woldegiorgis, Lin and Liang [38] identified the significant effect of interpupillary distance (IPD) on size estimation, this might be one of the possible reasons for the observed results. Additionally, the position accuracy was significantly higher at both 65 and 100 cm than at 150 cm from the participants for the exocentric distances (a) D1 and (b) D2 that compared HMD and SWD.

Figure 9. Average positions judgment with respect to reference target at a target distance of 65 cm from the participants for the exocentric distances (a) D1 and (b) D2 that compared HMD and SWD.

Figure 10. Average positions judgment with respect to actual (reference) target at a target distance of 100 cm from the participants for the exocentric distances (a) D3 and (b) D4 that shows a comparison between HMD and SWD.

Figure 11. Average positions judgment with respect to actual (reference) target at a target distance of 150 cm from the participants for the exocentric distances (a) D5 and (b) D6 that shows a comparison between HMD and SWD.

Overall, better exocentric distance judgment and lower horizontal position judgment in the frontal plane was obtained in the HMD. The position judgment error in the HMD was observed to pull every one of the targets towards either the right or to left (Figure 7a), which made the horizontal position accuracy below that of the SWDs. The systematic shift could be because of the possible effects of lens position, which might be different from participant to participant and the way the participant’s eye fit to the HMD lens, which can cause an offset to the center of the twelve targets while pointing. Furthermore, to use VR displays for industrial applications, it was recommended that we used different calibration methods [10]. For example, Segura, Barandiaran, Moreno, Barandiaran and Flórez [10] developed an objective stereo display calibration application design; be that as it may, it would be premature to assume that this can be generalized to a b

- Effects of lens position, which can cause an offset to the center of the twelve targets while pointing.
- Using VR displays for industrial applications requires different calibration methods.
- Better exocentric distance judgment and lower horizontal position judgment were observed in the HMD.

Overall, better exocentric distance judgment and lower horizontal position judgment in the frontal plane was obtained in the HMD. The position judgment error in the HMD was observed to pull every one of the targets towards either the right or to left (Figure 7a), which made the horizontal position accuracy below that of the SWDs. The systematic shift could be because of the possible effects of lens position, which might be different from participant to participant and the way the participant’s eye fit to the HMD lens, which can cause an offset to the center of the twelve targets while pointing.

Furthermore, to use VR displays for industrial applications, it was recommended that we used different calibration methods [10]. For example, Segura, Barandiaran, Moreno, Barandiaran and Flórez [10] developed an objective stereo display calibration application design; be that as it may, it would be premature to assume that this can be generalized to

Overall, better exocentric distance judgment and lower horizontal position judgment in the frontal plane was obtained in the HMD. The position judgment error in the HMD was observed to pull every one of the targets towards either the right or to left (Figure 7a), which made the horizontal position accuracy below that of the SWDs. The systematic shift could be because of the possible effects of lens position, which might be different from participant to participant and the way the participant’s eye fit to the HMD lens, which can cause an offset to the center of the twelve targets while pointing. Furthermore, to use VR displays for industrial applications, it was recommended that we used different calibration methods [10]. For example, Segura, Barandiaran, Moreno, Barandiaran and Flórez [10] developed an objective stereo display calibration application design; be that as it may, it would be premature to assume that this can be generalized to
position, which might be different from participant to participant and the way the participant’s eye fit to the HMD lens, which can cause an offset to the center of the twelve targets while pointing. Moreover, as Woldegiorgis, Lin and Liang [38] identified the significant effect of interpupillary distance (IPD) on size estimation, this might be one of the possible reasons for the observed results. Therefore, it is possible that the HMD could give a better precision in both the exocentric distance and the position estimates in the frontal plane, if the HMD had been impeccably mounted and flawlessly fit the participant’s eyes. Furthermore, to use VR displays for industrial applications, it was recommended that we used different calibration methods [10]. For example, Segura, Barandiaran, Moreno, Barandiaran and Flórez [10] developed an objective stereo display calibration method and got a more precise perception.

Furthermore, the results revealed that the intermediate target distance might be the fitting or ideal distance for the design and structure of 3D applications, as the highest performance in both distance judgment and position accuracy in the frontal plane (about 90.9% average accuracy) was obtained at a target distance of 100 cm from the participant. However, to our knowledge, no comparable investigations have been reported regarding the optimum distance for locating 3D application design; be that as it may, it would be premature to assume that this can be generalized to all VR conditions just yet. Generally, HMD can be used and recommended for tasks which need exocentric distance judgment accuracy, such as architecture [19], medical visualization [9], and geography, while SWD can be utilized for tasks which need location or position accuracy, such as military training.

5. Conclusions

In this study, we have shown the effects of VR displays on exocentric distance judgment and position accuracy, in a frontal plane. The effects of target distance, exocentric distance, and target size were also explained.

The results showed that participants were more accurate in exocentric distance estimation while using an HMD than using an SWD. In addition, a significant effect of target distance on exocentric distance judgment accuracy was observed in the SWDs, where accuracy was lower at a target distance of 65 cm from the participant than for the targets displayed at 150 cm from the participant. However, exocentric distance judgment was not affected by the exocentric distance and the target size. Furthermore, the distance judgment appears to be underestimated in the HMDs, whereas distance judgment was overestimated in the SWDs.

Similarly, the horizontal position accuracy in the SWD was seen to be better than in the HMD, whereas no significant difference was observed in the Y-position accuracy. The horizontal position accuracy was worsened as the exocentric distance increased, while the effect of exocentric distance on the vertical position accuracy was not significant. It seems that the HMD was superior to the SWD with respect to exocentric distance judgment, which, on the other hand, suffered from the systematic shift that made the horizontal position accuracy less accurate. Further studies are necessary to conclude whether the systematic shift in HMD was because of either an error in fitting the center of the lens of the displays to the center of the eyes of participants or interpupillary distance.

Current trends in commercial technology, though, are likely to result in VR displays for environments that have several shortcomings. The results also confirmed that VR displays have yet to be improved to provide proper space visualization of the environment. Accordingly, the findings are of great significance since the result can give information how VR displays affect the overall accuracy of exocentric distance judgment, and how size, target distance, and exocentric distance influence the accuracy of distance judgment. The results also can help to choose VR displays for a specific application. Quite possibly, the study is one of the first to report exocentric distance accuracy in virtual environments, especially focusing on a comparison between HMD and SWD.

This paper concentrated on exocentric distance judgment in the frontal plane under three target distance (depth) conditions, which may have restricted the full explanation to just the frontal plane. Furthermore, a fixed chinrest was employed to avoid head movement, which presumably would not
be expected in real-world applications. Along these lines, further study will be required to address the influences of displays on exocentric distance judgment in the sagittal and transverse planes.

**Author Contributions:** Conceptualization, C.J.L. and B.H.W.; methodology, B.T.A., D.C. and B.H.W.; data collection, B.T.A. and D.C.; statistical analysis, B.T.A.; writing—original draft preparation, B.T.A., C.J.L. and B.H.W.; supervision, C.J.L. and B.H.W.; funding acquisition, C.J.L. and D.C. All authors have read and agreed to the published version of the manuscript.

**Acknowledgments:** This paper was partially funded by the Ministry of Science and Technology, Taiwan grant number MOST-107-2218-E-011-019-MY3 and the APC was funded by Chiuhsiang J. Lin and Dino Caesaron.

**Conflicts of Interest:** The authors declare no conflict of interest.

**References**

1. Cipresso, P.; Gigliosli, I.A.C.; Raya, M.A.; Riva, G. The Past, Present, and Future of Virtual and Augmented Reality Research: A Network and Cluster Analysis of the Literature. *Front. Psychol.* 2018, 9, 2086. [CrossRef] [PubMed]
2. Segura, Á.; Diez, H.V.; Barandiaran, I.; Arbelaitz, A.; Álvarez, H.; Simões, B.; Posada, J.; García-Alonso, A.; Ugarte, R. Visual computing technologies to support the Operator 4.0. *Comput. Ind. Eng.* 2020, 139, 10550. [CrossRef]
3. Romero, D.; Bernus, P.; Noran, O.; Stahre, J.; Fasth, F.-B.A. The Operator 4.0: Human Cyber-Physical Systems & Adaptive Automation towards Human-Automation Symbiosis Work Systems; Springer: Cham, Switzerland, 2016. [CrossRef]
4. Posada, J.; Toro, C.; Barandiaran, I.; Oyarzun, D.; Stricker, D.; Amicis, R.D.; Pinto, E.B.; Eisert, P.; Döllner, J.; Vallarino, I. Visual Computing as a Key Enabling Technology for Industrie 4.0 and Industrial Internet. *IEEE Comput. Graph. Appl.* 2015, 35, 26–40. [CrossRef]
5. Posada, J.; Zorrilla, M.; Dominguez, A.; Simoes, B.; Eisert, P.; Stricker, D.; Rambach, J.; Döllner, J.; Guevara, M. Graphics and Media Technologies for Operators in Industrie 4.0. *IEEE Comput. Graph. Appl.* 2018, 38, 119–132. [CrossRef] [PubMed]
6. Woldegiorgis, B.H.; Lin, C.J. The accuracy of distance perception in the frontal plane of projection-based stereoscopic environments. *J. Soc. Inf. Disp.* 2017, 25, 701–711. [CrossRef]
7. Naceri, A.; Chellali, R. Depth perception within peripersonal space using head-mounted display. *Presence Teleoper. Virtual Environ.* 2011, 20, 254–272. [CrossRef]
8. Lin, C.J.; Woldegiorgis, B.H.; Caesaron, D. Distance estimation of near-field visual objects in stereoscopic displays. *J. Soc. Inf. Disp.* 2014, 22, 370–379. [CrossRef]
9. Stefanucci, J.K.; Creem-Regehr, S.H.; Thompson, W.B.; Lessard, D.A.; Geuss, M.N. Evaluating the accuracy of size perception on screen-based displays: Displayed objects appear smaller than real objects. *J. Exp. Psychol.* 2015, 21, 215–223. [CrossRef]
10. Segura, Á.; Barandiaran, J.; Moreno, A.; Barandiaran, I.; Flórez, J. Improved virtual reality perception with calibrated stereo and variable focus for industrial use. *Int. J. Interact. Des. Manuf. (IJIDeM)* 2018, 12, 95–103. [CrossRef]
11. Lin, C.J.; Woldegiorgis, B.H. Interaction and visual performance in stereoscopic displays: A review. *J. Soc. Inf. Disp.* 2015, 23, 319–332. [CrossRef]
12. Armbrüster, C.; Wolter, M.; Kuhlen, T.; Spijkers, W.; Fimm, B. Depth Perception in Virtual Reality: Distance Estimations in Peri- and Extrapersonal Space. *Cyberpsychol. Behav.* 2008, 11, 9–15. [CrossRef] [PubMed]
13. Lin, C.J.; Chen, H.J.; Cheng, P.Y.; Sun, T.L. Effects of Displays on Visually Controlled Task Performance in Three-Dimensional Virtual Reality Environment. *Hum. Factors Ergon. Manuf. Serv. Ind.* 2015, 25, 523–533. [CrossRef]
14. Grechkin, T.Y.; Nguyen, T.D.; Plumert, J.M.; Cremer, J.F.; Kearney, J.K. How does presentation method and measurement protocol affect distance estimation in real and virtual environments? *ACM Trans. Appl. Percept.* 2010, 7, 1–18. [CrossRef]
15. Knapp, J.M.; Loomis, J.M. Limited field of view of head-mounted displays is not the cause of distance underestimation in virtual environments. *Presence Teleoper. Virtual Environ.* 2004, 13, 572–577. [CrossRef]
16. Lin, C.J.; Abreham, B.T.; Woldegiorgis, B.H. Effects of displays on a direct reaching task: A comparative study of head mounted display and stereoscopic widescreen display. *Int. J. Ind. Ergon.* **2019**, *72*, 372–379. [CrossRef]

17. Alexandrova, I.V.; Teneva, P.T.; De La Rosa, S.; Kloos, U.; Blthoff, H.H.; Mohler, B.J. Egocentric distance judgments in a large screen display immersive virtual environment. In Proceedings of the 7th Annual Symposium on Applied Perception in Graphics and Visualization, APGV 2010, Los Angeles, CA, USA, 23–24 July 2010; pp. 57–60.

18. Wartenberg, C.; Wiborg, P. Precision of Exocentric Distance Judgments in Desktop and Cube Presentation. *Presence* **2003**, *12*, 196–206. [CrossRef]

19. Henry, D.; Furness, T. Spatial perception in virtual environments: Evaluating an architectural application. In Proceedings of the IEEE Virtual Reality Annual International Symposium, Seattle, WA, USA, 18–22 September 1993; pp. 33–40.

20. Aznar-Casanova, J.A.; Matsushima, E.H.; Ribeiro-Filho, N.P.; Da Silva, J.A. One-Dimensional and Multi-Dimensional Studies of the Exocentric Distance Estimates in Frontoparallel Plane, Virtual Space, and Outdoor Open Field. *Span. J. Psychol.* **2014**, *9*, 273–284. [CrossRef]

21. Li, Z.; Phillips, J.; Durgin, F.H. The underestimation of egocentric distance: Evidence from frontal matching tasks. *Atten. Percept. Psychophys.* **2011**, *73*, 2205. [CrossRef]

22. Kelly, J.W.; Hammel, W.; Sjolund, L.A.; Siegel, Z.D. Frontal extents in virtual environments are not immune to underperception. *Atten. Percept. Psychophys.* **2015**, *77*, 1848–1853. [CrossRef]

23. Waller, D. Factors Affecting the Perception of Interobject Distances in Virtual Environments. *Presence* **1999**, *8*, 657–670. [CrossRef]

24. Tan, D.S.; Gergle, D.; Scupelli, P.G.; Pausch, R. Physically large displays improve path integration in 3D virtual navigation tasks. In Proceedings of the SIGCHI Conference on Human Factors in Computing Systems, Vienna, Austria, 24–29 April 2004; pp. 439–446.

25. Aznar-Casanova, J.A.; Matsushima, E.H.; Da Silva, J.A.; Ribeiro-Filho, N.P. Can exocentric direction be dissociated from its egocentric distance in virtual environments? *Percept. Psychophys.* **2008**, *70*, 541–550. [CrossRef] [PubMed]

26. Geuss, M.N.; Stefanucci, J.K.; Creem-Regehr, S.H.; Thompson, W.B.; Mohler, B.J. Effect of Display Technology on Perceived Scale of Space. *Hum. Factors* **2015**, *57*, 1235–1247. [CrossRef] [PubMed]

27. Lin, C.J.; Woldegiorgis, B.H. Egocentric distance perception and performance of direct pointing in stereoscopic displays. *Appl. Ergon.* **2017**, *64*, 66–74. [CrossRef] [PubMed]

28. Swan, J.E.; Singh, G.; Ellis, S.R. Matching and Reaching Depth Judgments with Real and Augmented Reality Targets. *IEEE Trans. Vis. Comput. Graph.* **2015**, *21*, 1289–1298. [CrossRef]

29. Lin, C.J.; Caesaron, D.; Woldegiorgis, B.H. The accuracy of the frontal extent in stereoscopic displays. *Presence* **2013**, *21*, 1235–1247. [CrossRef]

30. Buck, L.E.; Young, M.K.; Bodenheimer, B. A comparison of distance estimation in HMD-based virtual environments with different HMD-based conditions. *ACM Trans. Appl. Percept.* **2018**, *15*. [CrossRef]

31. Kelly, J.W.; Cherop, L.A.; Siegel, Z.D. Perceived Space in the HTC Vive. *ACM Trans. Appl. Percept.* **2017**, *15*. [CrossRef]

32. Renner, R.S.; Velichkovsky, B.M.; Helmer, J.R. The Perception of Egocentric Distances in Virtual Environments—A Review. *ACM Comput. Surv.* **2013**, *46*. [CrossRef]

33. Cutting, J.E.; Vishton, P.M. Perceiving layout and knowing distances: The integration, relative potency, and contextual use of different information about depth. In *Perception of Space and Motion*; Academic Press: San Diego, CA, USA, 1995; pp. 69–117. [CrossRef]

34. ISO. Reference Number: ISO 9241-9: Ergonomic Requirements for Office Work with Visual Display Terminals (VDTs)-Part 9-Requirements for Non-Keyboard Input Devices. 1st ed.; International Organization for Standardisation: Geneva, Switzerland, 2000; p. 57.

35. Ruddle, R.A.; Payne, S.J.; Jones, D.M. Navigating Large-Scale Virtual Environments: What Differences Occur between Helmet-Mounted and Desk-Top Displays? *Presence* **1999**, *8*, 157–168. [CrossRef]

36. Geuss, M.; Allen, G.; Stefanucci, J.; Creem-Regehr, S.; Thompson, W. The Role of Depth and Frontal Planes in Perceiving Distances in a Virtual Environment. *J. Vis.* **2011**, *11*, 75. [CrossRef]

37. Lin, C.J.; Woldegiorgis, B.H.; Caesaron, D.; Cheng, L.Y. Distance estimation with mixed real and virtual targets in stereoscopic displays. *Displays* **2015**, *36*, 41–48. [CrossRef]
38. Woldegiorgis, B.H.; Lin, C.J.; Liang, W.-Z. Impact of parallax and interpupillary distance on size judgment performances of virtual objects in stereoscopic displays. *Ergonomics* 2019, 62, 76–87. [CrossRef] [PubMed]

39. Bruder, G.; Argelaguet, F.; Olivier, A.-H.; Lécuyer, A. CAVE Size Matters: Effects of Screen Distance and Parallax on Distance Estimation in Large Immersive Display Setups. *Presence Teleoper. Virtual Environ.* 2016, 25, 1–16. [CrossRef]

40. Hoffman, D.M.; Girshick, A.R.; Akeley, K.; Banks, M.S. Vergence–accommodation conflicts hinder visual performance and cause visual fatigue. *J. Vis.* 2008, 8, 33. [CrossRef]

© 2020 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (http://creativecommons.org/licenses/by/4.0/).