Examining the Influence of Egocentric Distance on Exocentric Distance Estimation in Virtual Environments

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Abstract: Egocentric and exocentric distance estimations are crucially important in the modern world. However, these skills can often be inaccurately assessed in virtual environments. A virtual space with two versions was designed to understand this phenomenon better. One version was created for PC, and the other for VR. A desktop display was used in the PC version, while the Gear VR was employed in the VR version. The exocentric distance estimation skills of 229 university students were measured, while egocentric distances were varied. A total of 157 students used a desktop display, and 72 students used the Gear VR. According to the results, significant associations were found between accuracy, egocentric distance, and exocentric distance in both versions. However, unlike the proportions of inaccurate estimates, the proportions of accurate estimates did not differ between the various egocentric and exocentric distances across both display devices. The two distance types had significant effects on accuracy and estimation time in the PC version; these effects were not observed in the VR version. The results of this study can inform the design of future virtual environments.

Keywords: desktop display; egocentric distance; exocentric distance; Gear VR; human-computer interaction; virtual environment

1 Introduction

Egocentric distance can be defined as the distance between an object and the observer, while exocentric distance refers to the distance between two objects. These two types of distance, though different in their definitions, are closely interrelated and are fundamental to spatial perception [1, 2]. Both are critical for navigating physical spaces such as when estimating the distance to obstacles or when gauging the relative positions of objects. As such, they are integral components of navigation and are widely studied in both cognitive science and applied fields like engineering design [3-5].

Spatial perception, a key cognitive skill, is not static; it evolves and improves over time [6, 7]. Several studies have highlighted that spatial perception can be honed through practice and specific training. For example, physical exercise has been shown to enhance egocentric distance estimation [8-10]. A similar phenomenon can be found in video games' case [11]. Video games, mainly those involving complex three-dimensional environments can provide an excellent platform for enhancing spatial reasoning and visual search abilities, as they challenge players to constantly adjust their understanding of spatial relationships [12]. In this way, regular engagement with virtual environments (VEs) can significantly improve users' ability to estimate distances, not only in virtual spaces but also in the real world [9].

VEs are especially effective in enhancing distance perception. VEs often use technologies such as virtual reality (VR) to create immersive experiences that can simulate real-world scenarios [13]. In these virtual worlds, distance estimation is an essential task as users need to understand the layout of the space to navigate effectively [14]. Moreover, VR systems can promote cognitive benefits, such as improving spatial awareness and memory through interactive and immersive experiences [15, 16]. As a result, VEs are increasingly being applied in various fields from military and medical training to architectural design and should be designed with a human-centered approach [17-19]. These systems provide a platform for training distance estimation skills, allowing individuals to practice and refine their abilities in a controlled environment [20].

However, the design of VEs plays a crucial role in the accuracy of distance estimation. Compositional factors such as visual cues, surface textures, and the overall graphic quality of a virtual scene can significantly influence how distances are perceived [21, 22]. These factors interact with the perceptual abilities of the user which can also affect the accuracy of distance judgments. For instance, research by Naceri et al. showed how depth perception within the peripersonal space is influenced by the type of display used [23]. Their results show that head-mounted displays provided a more accurate sense of depth compared to standard screen-based displays.

In addition to environmental factors, human characteristics, such as individual differences in visual acuity or stereoscopic vision, can also impact distance perception [24]. For instance, binocular disparity is a key factor in how we perceive depth and distance, especially when using stereoscopic displays [25-27] Despite these advancements, studies show that both egocentric and exocentric distances are often underestimated in VEs [28-32]. This underestimation is an ongoing challenge in VR systems which has led to increased research into improving the accuracy of distance judgments in these spaces [29].

Recent studies, such as the work of Lin et al. [33], have investigated the accuracy of exocentric distance judgments in VEs, comparing different display technologies. Their research indicated that head-mounted displays tend to yield more accurate distance judgments than stereoscopic wide displays, with smaller egocentric distances (such as 65 cm) being more difficult to estimate accurately compared to larger distances (such as 150 cm).

However, what happens in the case of a simple desktop display device and other egocentric distances? To address this question, a VE was developed for exocentric distance estimation. Additionally, the egocentric distances of objects can be adjusted between 25 cm and 160 cm, with 15 cm intervals. To examine the impact of egocentric and exocentric distances on accuracy, the following four research questions (RQs) were formulated:

- RQ1: Is there an association between accuracy, exocentric, and egocentric distances?
- RQ2: Does the proportion of accurate and inaccurate answers differ between the various exocentric and egocentric distances?
- RQ3: Do exocentric and egocentric distances have effects on the accuracy of estimates?
- RQ4: Do exocentric and egocentric distances have effects on estimation time?

Based on the research questions, four null hypotheses (Hs) were formed. These are the following:

- H1: No association exists between accuracy, exocentric, and egocentric distances.
- H2: The proportion of accurate and inaccurate answers is the same between the various exocentric and egocentric distances.
- H3: Exocentric and egocentric distances have no effects on the accuracy of estimates.
- H4: Exocentric and egocentric distances have no effects on estimation time.

Therefore, this paper is structured as follows. The materials and methods used in this study are presented in Section 2. Afterward, the results are detailed in Section 3. Then, the results are discussed in Section 4. Lastly, conclusions are made in Section 5.

2 Materials and Methods

This section is split into three subsections. The VE itself is presented in subsection 2.1. Data collection and analysis are detailed in subsections 2.2 and 2.3, respectively.

2.1 The Virtual Environment

The VE for the research was developed in Unity, using version 2018.4.36f1. Two versions of the virtual space were created: one for PC and another for VR (using the Android operating system). The VR version is immersive, as it uses the Gear VR head-mounted display. It can also be controlled through the user's head rotation and the touchpad on the side of the device. In contrast, the PC version is controlled using a keyboard and mouse. The VE tracked only the rotation of the participants' heads, not their position. Therefore, aside from the controls and the level of immersion, the two versions were identical.

A room was designed in the VE with dimensions of 12 "Unity units" along both the x and z axes. Since one "Unity unit" is equivalent to one meter, the participants were positioned in the center of the virtual room, with each wall placed 6 meters away from them. The participants' height in the VE was set to match their real-world height as they were required to input their height before the measurements began. As a result, the virtual camera was positioned at the entered height. A screenshot of the virtual room, taken from the Unity editor, is shown in Figure 1.

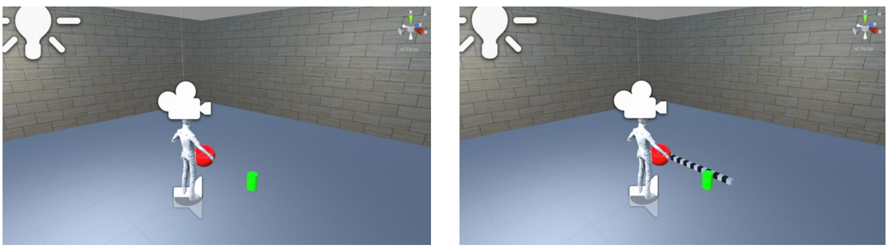

Figure 1
Screenshots of exocentric tests from the Unity editor. The first test type was without a scale (left), and the first test type was with a scale on the ground (right).

Figure 1 shows that there were two objects on the ground in front of the participants. These two objects could be placed at egocentric distances between 25 cm and 160 cm at 15 cm intervals in front of the participants. Similarly, the exocentric distances between the two objects were between 60 cm and 150 cm at 10 cm intervals. While both distance types were randomized, each had to occur twice for the participants. As each occurrence was a round, this meant 10 + 10 occurrences. The first 10 were without a scale on the ground, while the second 10 were with a scale as shown in Figure 1. 19 cubes were on the scale, and the size of all was 10 cm × 10 cm × 10 cm. The center of the scale was at the center between the two objects. Also, as the egocentric distance increased between the objects and the participants, the egocentric distance also increased between the scale and the participants.

2.2 Data Collection

The data were collected in the fall of 2022 at two universities. The University of Debrecen hosted the data collection with desktop displays, while the University of Pannonia used the Gear VR head-mounted display for the measurements. The desktop display used was the LG 20M37A (19.5”). A total of 229 students participated in the study: 157 students used the PC version, while the remaining 72 used the VR version. The mean ages of the two groups were 19.80 and 22.51, respectively. The PC version was used by engineering students, while the VR version was used by IT students. All participants voluntarily joined the study and gave verbal consent before the measurements began. No personal names were collected during the process, but participants were asked to provide demographic information, such as their age, dominant hand, and whether they wore glasses. As a result, the data alone does not allow for identification of the participants.

Participants were encouraged to perform to the best of their abilities and were given a full briefing on the importance of accurate estimations for the validity of the research. They were instructed on how to look around and estimate exocentric distances in the VE, and the dimensions of the room and scale were communicated to them. However, the actual egocentric and exocentric distances were not disclosed. After receiving all necessary information, participants pressed the start button to begin the measurements. Once they were placed in the center of the virtual room, the measurement process started.

For the PC version, students used the keyboard to estimate distances by pressing the corresponding keys. Afterward, they were instructed to look up at the ceiling and press Enter. Upon looking down, another round of measurements began with different egocentric and exocentric distances. In contrast, the estimation process for the VR version was different. Participants verbally estimated the exocentric distances, and the researcher recorded their responses in real-time. After providing their estimates, participants were instructed to look up at the ceiling and press the touchpad on the Gear VR. In both versions, pressing Enter or the touchpad also logged the estimation times.

Regarding data logging, the VE saved information about each round into a CSV file upon completion. Each data entry contained detail such as the actual egocentric and exocentric distances, the estimated distances, the composition of the VE, and the estimation times. In the case of the VR version, the estimated distances were later input into the file by the researchers.

2.3 Data Analysis

After the data were collected, it was imported into the statistical software package R. Two datasets were created: one for the PC version and another for the VR version. The estimates were categorized as either accurate or inaccurate. Accuracy was determined based on whether the participant's estimated distance fell within ±10% of the actual exocentric distance. Estimates outside this range were considered inaccurate. During the data analysis process, an alpha level of 0.05 was used. The data were not grouped based on the existence of the virtual scale. The analysis consisted of three main parts, as follows:

The first part of the analysis aimed to determine whether an association existed between three variables. To do this, two 3D contingency tables were created: one for the PC version and one for the VR version. The Cochran-Mantel-Haenszel chi-squared test was used to assess whether a significant association existed between exocentric accuracy (a binary variable) and the two distance types (two categorical variables). The 3D contingency tables were then split into four 2D tables: inaccurate estimates on PC, accurate estimates on PC, inaccurate estimates on VR, and accurate estimates on VR. Pearson's chi-squared test was applied to these four 2D contingency tables to determine whether there was a difference in the proportions of accurate and inaccurate estimates. Cramér's V was also used to assess the strength of the associations.

The second part of the investigation examined the effects of egocentric distance on the accuracy of exocentric distance estimation. Prior to the analysis, Shapiro-Wilk normality tests were conducted on the results from both versions. However, the data for both versions did not follow a Gaussian distribution (W_{PC} = 0.58425, $p_{PC} < 2.2*10^{-16}$, W_{VR} = 0.4898, $p_{PC} < 2.2*10^{-16}$). As a result, the Kruskal-Wallis test was used for this analysis, taking into account the interaction between the two distance types. Pairwise comparisons were performed using the Wilcoxon rank sum test with Bonferroni correction to identify which pairs yielded significant results.

The third part of the investigation focused on the effects of egocentric and exocentric distances on estimation times. As with the second part, Shapiro-Wilk normality tests were conducted on the estimation times for both versions. The data for both versions did not follow Gaussian distribution (W_{PC} = 0.68716, $p_{PC} < 2.2*10^{-16}$, W_{VR} = 0.84733, $p_{PC} < 2.2*10^{-16}$). Therefore, the Kruskal-Wallis test was used, considering the interaction between the two distance types. Pairwise comparisons were conducted using the Wilcoxon rank sum test with Bonferroni correction.

3 Results

The average accuracy and estimation times were calculated and grouped by exocentric and egocentric distances. Both were calculated in the case of both versions. The former seen in Figure 2, while the latter one can be seen in Figure 3.

Figure 2

The average accuracy in the PC (left), and the VR version (right). Both are grouped by exocentric and egocentric distances. The former is on the left and the latter is on the top. The distances are in cm.

As shown in Figure 2, the minimum exocentric accuracy for the PC version was 3%, while for the VR version, it was 0%. The maximum accuracies were 64% for the PC version and 56% for the VR version. It is evident that the average accuracy was higher in the PC version when grouped by these distances.

Figure 3

The average estimation times in the PC (left), and the VR version (right). Both are grouped by exocentric and egocentric distances. The former is on the left and the latter is on the top. The distances are in cm, and the average estimation times are in seconds.

In Figure 3, the minimum exocentric distance estimation times were 9.47 seconds for the PC version and 6.82 seconds for the VR version. Participants were quickest when estimating the nearest objects in the PC version. The maximum estimation times were 27.27 seconds for the PC version and 18.28 seconds for the VR version. Based on the data shown in Figure 3, it appears that participants using the VR version tended to be faster in estimating exocentric distances compared to those using the PC version. However, the participants using the VR version were the slowest when estimating distances to the nearest objects.

The next step involves analyzing the data, which is divided into three subsections. Subsection 3.1 presents the relationships between the variables examined. Subsection 3.2 discusses whether the investigated distances (both egocentric and exocentric) had a significant impact on exocentric distance estimation accuracy. Lastly, subsection 3.3 focuses on the effects of these distances on exocentric distance estimation times.

3.1 The Association between Exocentric Accuracy, Egocentric and Exocentric Distances

Thus, the association between exocentric accuracy, egocentric and exocentric distances was the first to be analyzed. First, contingency tables were created. Later, these tables were plotted as mosaic plots to allow for better understanding of data. These are shown in Figures 4 and 5.

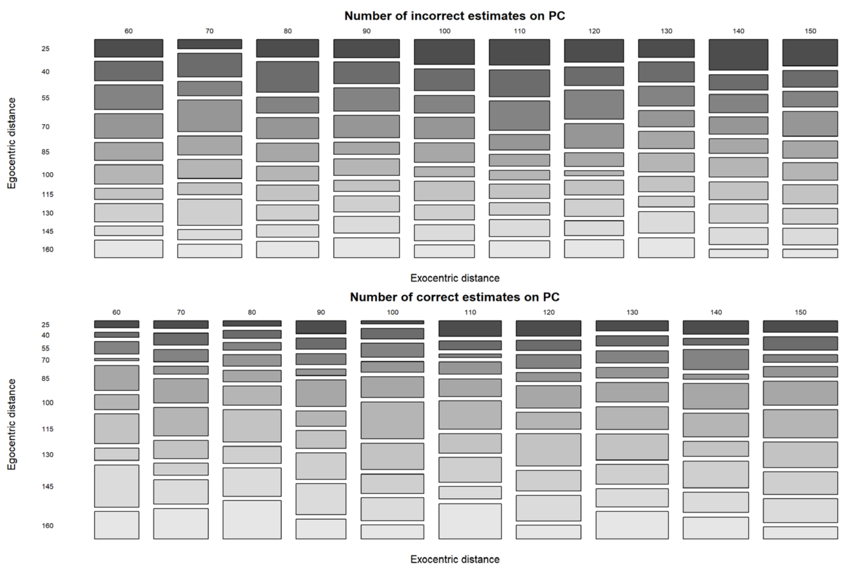

Figure 4

The number of inaccurate (top) and accurate (bottom) estimates on PC

As shown in Figure 4, students had more inaccuracies in exocentric distance estimation on the PC version than accurate estimates. Out of a total of 3140 estimates, 2154 were inaccurate and 986 were accurate. The results indicate a significant association between exocentric accuracy, and both egocentric and exocentric distances on the PC version, $X^2(9, N = 3140) = 182.97$, $p < 2.2*10^{-16}$. Similarly, a significant, but moderate association can be found between exocentric accuracy and exocentric distances on PC, $X^2(9, N = 3140) = 184.01$, $p < 2.2*10^{-16}$, $V = 0.24208$. A significant, but weaker association can also be observed between exocentric accuracy and egocentric distances on PC, $X^2(9, N = 3140) = 30.462$, $p = 0.00036$, $V = 0.09849$.

Regarding inaccurate estimates, while having a weak association, significant differences can be observed between their numbers, $X^2(81, N = 2154) = 122.48$, $p = 0.00201$, $V = 0.07948$. On the contrary, no significant differences were found between accurate exocentric estimates, $X^2(81, N = 986) = 83.454$, $p = 0.4039$, $V = 0.09697$. These results show that the proportion of accurate exocentric distance estimates was the same between egocentric and exocentric distances. Regarding the strength of their association, it was also weak when the exocentric accurate estimates were assessed. However, compared to the inaccurate ones, it was slightly stronger in this case.

Next, the associations were analyzed between the same three variables in the VR version. The results can be observed in Figure 5.

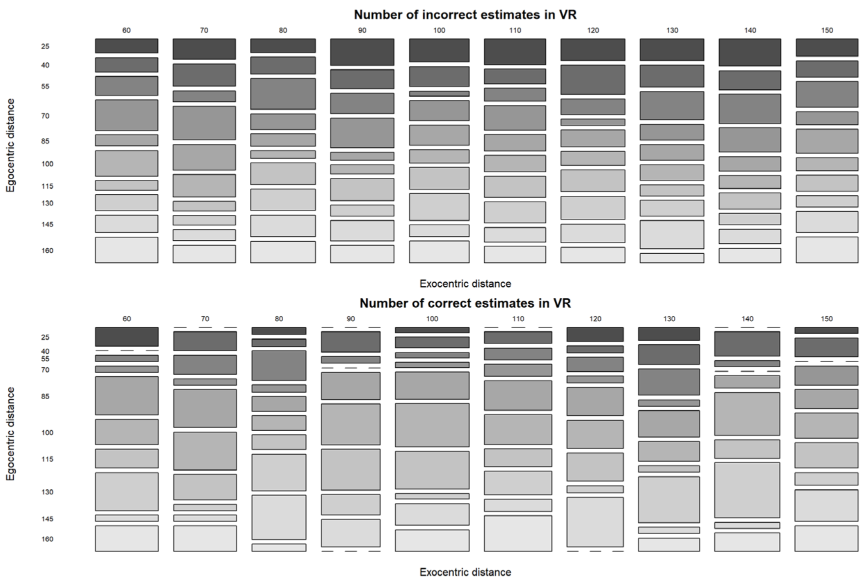

Figure 5

The number of inaccurate (top) and accurate (bottom) estimates in VR

Figure 5 presents results similar to those in Figure 4. In the VR version, students were again more inaccurate than accurate in their exocentric distance estimations. Out of 1440 estimates, 1152 were inaccurate, and 288 were accurate. The results indicate a significant association between accuracy, and both egocentric and exocentric distances in the VR version, $X^2(9, N = 1440) = 66.677$, $p = 6.801*10^{-11}$. Similarly, a significant, but moderate association can be found between exocentric accuracy and exocentric distances on VR, $X^2(9, N = 1440) = 67.766$, $p = 4.168*10^{-11}$, $V = 0.21693$. However, the moderate effect size suggests that while the association is significant, its practical impact is not overwhelming. The users' ability to estimate exocentric distances appears to be somewhat dependent on the specific distance being estimated, although the effect is not as strong as might be expected in a fully immersive system. On the contrary, the weaker association between exocentric accuracy and egocentric distances on VR was not significant, $X^2(9, N = 1440) = 2.6074$, $p = 0.9779$, $V = 0.04255$.

In case of inaccurate estimates, significant differences can be found between their numbers, $X^2(81, N = 1152) = 113.73$, $p = 0.009639$, $V = 0.10473$. While significant, its level was less strong than on the PC version. As can be observed, their association was also weak in this case, although stronger than in the PC version. Regarding accurate estimates, no significant differences could be found between their numbers, $X^2(81, N = 288) = 94.745$, $p = 0.141$, $V = 0.19118$. In this case, however, the *p*-value was stronger than on PC. Still, it was not significant. This result suggests that the perceived egocentric distance or the distance relative to the user's own body does not significantly influence their ability to accurately estimate exocentric distances in the VR environment. The very high p-value and the very small effect size indicate that this relationship is negligible.

3.2 The Effects of Egocentric and Exocentric Distances on Exocentric Accuracy

The following to be assessed were the effects of egocentric and exocentric distances on exocentric accuracy. The first to examine was the PC version. The results of the Kruskal-Wallis test show that significant effects exist on accuracy, $H(99) = 305.19$, $p < 2.2*10^{-16}$. This also strongly supports the hypothesis that the accuracy of exocentric distance estimations is not randomly distributed and is instead significantly associated with the different distance categories. Following the Kruskal-Wallis test, pairwise comparisons were performed to identify specific groups that differed significantly from each other. The results of these comparisons are summarized in Table 1, although only the significant differences between the investigated groups are shown in it. This also shows the complexity of the relationship between exocentric accuracy and distance categories where only specific combinations of distances lead to measurable differences in accuracy.

Table 1
The *p*-values of significant differences between the exocentric accuracies of groups. The distances are in cm.

	Exo: 60 Ego: 85	Exo: 70 Ego: 25	Exo: 70 Ego: 55	Exo: 80 Ego: 100	Exo: 90 Ego: 25	Exo: 90 Ego: 40	Exo: 90 Ego: 70
Exo: 110 Ego: 85	0.00817	0.03512	0.00486	0.00140	0.00078	0.00256	0.03540
Exo: 110 Ego: 100	-	-	-	0.01375	0.00698	0.03028	-
Exo: 110 Ego: 115	-	-	-	0.03318	0.01418	-	-
Exo: 120 Ego: 115	-	-	-	0.04611	0.02385	-	-
Exo: 140 Ego: 25	-	-	-	0.02233	0.01142	0.04892	-
Exo: 150 Ego: 55	-	-	-	-	0.04503	-	-
Exo: 150 Ego: 100	-	-	-	-	0.04503	-	-
Exo: 150 Ego: 145	-	-	-	-	0.02544	-	-

As shown in Table 1, the greatest number of significant differences occurred when one group had an exocentric distance of 90 cm and an egocentric distance of 25 cm, resulting in eight significant differences. Similarly, when a group had exocentric distances of 80 cm and 100 cm, five significant differences were observed. Additionally, with an exocentric distance of 90 cm and an egocentric distance of 25 cm, three significant differences were found. The remaining significant groups each had only one significant difference.

Next, the effects were examined in the case of the VR version. Similarly to the PC version, significant effects can be observed on accuracy, $H(99) = 155.58$, $p = 0.0002466$. However, when searching for exact significant pairs of distances with pairwise comparisons, no such pairs were found.

3.3 The Effects of Egocentric and Exocentric Distances on Exocentric Distance Estimation Time

The last to examine were the effects of egocentric and exocentric distances on exocentric distance estimation time. This analysis was done first in the case of the PC version. The results of the Kruskal-Wallis test showed that the distances had significant effects on estimation times, $H(99) = 187.3$, $p = 2.07*10^{-7}$. With pairwise comparisons, significant differences could be observed between the following groups as shown in Table 2. No other significant differences were detected in the data.

Table 2

The *p*-values of significant differences between exocentric distance estimation times of groups. The distances are in cm.

	Exo: 60 Ego: 25	Exo: 60 Ego: 130
Exo: 130 Ego: 70	-	0.03054
Exo: 140 Ego: 40	-	0.03232
Exo: 150 Ego: 40	0.022608	0.00391

Compared to Table 1, the number of significant differences was smaller. If one group contained 60 cm and 130 cm of exocentric and egocentric distances, respectively, three significant differences could be found. With an exocentric distance of 60 cm and an egocentric distance of 25 cm, only one significant difference was observable regarding estimation times in the PC version.

Finally, the effects of the two distance types on estimation time were examined in the VR version. According to the results of the Kruskal-Wallis test, significant effects were found, $H(99) = 133.99$, $p = 0.01105$. However, when assessing the differences between each group with pairwise comparisons, no significant differences could be observed between them.

4 Discussion

This study aimed to investigate the accuracy and time of exocentric distance estimation under varying egocentric distances and using two different display devices: PC and the Gear VR head-mounted display. The results showed a deeper understand of how exocentric and egocentric distances effect estimation accuracy and response times. Each of the research questions was addressed, leading to the evaluation of the null hypotheses. While some null hypotheses were rejected, others were only partially accepted, indicating mixed outcomes. These results are discussed in detail below.

The results for RQ1, which focused on whether there is an association between accuracy, exocentric, and egocentric distances, shows important results. A clear association was found between exocentric accuracy and both exocentric and egocentric distances across both display devices. Specifically, the associations between these distance types were stronger for accurate estimates. This indicates that the participants' ability to accurately estimate exocentric distances in the VE was influenced by both egocentric and exocentric distances. Notably, however, the association between exocentric accuracy and egocentric distances was weaker in the VR version and did not reach statistical significance. This mixed result suggests that while both types of distances are important in determining exocentric accuracy, the VR version may involve additional factors that moderate this relationship. As a result, H1 was partially rejected, but the association in the VR condition warrants further exploration.

For RQ2, which examined whether the proportion of accurate and inaccurate answers differed between various exocentric and egocentric distances, the results revealed mixed effects across the two display devices. In the PC version, significant differences were found in the proportions of accurate and inaccurate answers between various distance pairs. In contrast, no significant differences were observed in the VR version where the proportions remained consistent across the different exocentric and egocentric distances. These results suggest that participants' perception of distances may be altered by the immersive nature of the VR environment, possibly due to the heightened sense of presence and the reliance on different perceptual cues compared to traditional desktop setups. Consequently, H2 was partially rejected. This indicates that the display device had a moderating effect on how participants perceived and estimated distances.

For RQ3 and RQ4, which assessed the effects of exocentric and egocentric distances on estimation accuracy and time, the results highlighted a significant difference between the two display devices. In the PC version, both exocentric and egocentric distances significantly affected estimation accuracy and time, suggesting that these distance variables played a crucial role in the estimation process. This observation likely reflects the nature of traditional desktop-based setups where participants may rely more on visual cues and cognitive processing to judge distances. In the VR version, however, the immersive environment seemed to alter participants' reliance on such cues, making them more dependent on the VE's inherent spatial properties. The significant effects of exocentric and egocentric distances in the PC version and the absence of such effects in the VR version indicate that the immersive nature of VR might change how distances are perceived and estimated. These results suggest that while the PC version relies more heavily on cognitive processing of visual cues, the VR version's immersive nature may lead to different strategies for distance estimation. As a result, both H3 and H4 were partially rejected.

While this study provides a deeper understanding of the role of exocentric and egocentric distances in distance estimation across different display devices, several limitations should be considered. First, the sample consisted primarily of university students which may not fully represent the broader population. Future studies should consider a more diverse sample to assess whether the findings are generalizable to different demographic groups. Second, the study did not explore the role of individual differences, such as prior experience with VR, cognitive styles, or spatial abilities, which could influence exocentric distance estimation. Further research could investigate how these factors affect the participants' ability to estimate distances in VEs. Additionally, the study did not examine the cognitive processes involved in distance estimation and future studies should examine how participants mentally process and navigate distances in virtual spaces.

Conclusions

To assess the exocentric distance estimation skills of participants while changing egocentric distance to the objects, a virtual space with two versions was designed. A desktop display was used in the PC version, while the Gear VR was used in the VR version. The two versions were identical. 229 university students participated in the study. 157 used the former version, while 72 used the latter. Four research questions were formed for the study, and all were answered.

Based on the results, there were significant associations between exocentric accuracy, egocentric distances, and exocentric distances in both versions. However, the associations between exocentric accuracy and egocentric distances were weaker than in the case of exocentric distances. This association was not significant in the VR version. Also, the proportions of accurate exocentric distance estimates were not different between various egocentric and exocentric distances on both display devices. The proportions of inaccurate ones were significantly different. However, the associations between accurate estimates and the distances were stronger than between inaccurate estimates and the distances. Furthermore, the two types of distances had a significant effect on exocentric accuracy and distance estimation time in the PC version, while such effects were not observable in the VR version.

In conclusion, our findings have implications for the design of future virtual spaces. Understanding how users estimate distances and the importance of display devices regarding these estimations is crucial for creating immersive and effective virtual experiences. The designers of these virtual spaces should consider the potential differences in distance perception between desktop and head-mounted displays.

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