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The Effects of Immersion Level, Human Characteristics, and a Virtual Scale on Exocentric Distance Perception

Tibor Guzsvinecz, Judit Szűcs, and Erika Perge

***Abstract*—Understanding spatial perception is crucial in virtual environments since it influences navigation abilities. To better understand how human characteristics combined with immersion levels influence exocentric distance estimation, this study was conducted. We have implemented a virtual environment for the desktop display and the Gear VR head-mounted display, in which we assessed these skills of 229 university students. 157 used the former, while 72 used the latter display device. The results show that human characteristics combined with the two display devices as well as a virtual scale have significant effects on exocentric distance estimation. The findings can help the development of more accessible virtual environments in the future.**

***Index Terms*—desktop display, exocentric distance estimation, Gear VR, head-mounted display, human–computer interaction, immersion, virtual environment**

I. Introduction

EXOCENTRIC distance is defined as the distance between external objects or points from the observer's perspective. Accurate distance perception in the real world is essential for various aspects of daily life, including navigation, spatial awareness, and activities (such as driving and sports). Distance estimation plays a critical role in avoiding obstacles, decision-making, and interacting with our surroundings [1–3].

In virtual reality (VR), the accurate estimation of distances is crucial for creating immersive and realistic experiences. As users navigate virtual environments (VEs), their cognitive ability to estimate distances directly impacts their interactions and decision-making during the process. The whole process can be addressed in the fields of Cognitive Aspects of Virtual Reality (cVR) and Cognitive InfoCommunications (CogInfoCom) since they primarily focus on human cognition. They aim to showcase the latest advancements in information and communication technologies (ICT) that facilitate the interaction between humans and machines [4–9]. Furthermore, it is worth mentioning that CogInfoCom and cVR are closely related [10].

However, it is important to investigate human-computer interaction regarding distance perception due to the fact that in VR applications like training simulations [11, 12], education [13, 14], and gaming [15, 16], users must rely on their distance estimation skills for navigation. According to the literature, users tend to underestimate distances in VR applications [17, 18]. While this underestimation can be decreased [19], it is influenced by several factors. The first factor is the composition of VEs, since they can be constructed differently. Consequently, distance perception can be affected by visual cues such as textures, graphics, and even avatars [20–24]. The other affecting factor is the technology used, such as display devices (especially the level of immersion), as well as the effect of binocular disparity [25–28]. The third factor is the distance itself: studies show that distances up to approximately 1 m are usually overestimated, but accurate estimates can occur up to 55 cm [29]. Lastly, the fourth factor is the 'human one' (i.e. demographic data of the users). Studies show that gender and age can significantly affect distance estimation [30–32]. We also explored the effects of human characteristics such as gender, height, dominant hand, gaming hours per week, previous VR experience, wearing glasses, and field of study in another paper. Our results showed that the latter two factors did not have significant effects on the accuracy of distance estimates or estimation time [33].

The influence of human factors has a large importance because VR redefines human-computer interfaces, and humans play a crucial role in such systems [34]. According to the literature, cognition plays an important role in interacting with virtual spaces [10], and VEs can even enhance the cognitive skills of humans [35]. Studies also emphasize the importance of focusing on humans during the development of VEs [6, 7]. Thus, it is crucial to understand these factors to enhance VR experiences while creating accessible experiences for a diverse range of users. In this study, the aim is to investigate how certain combinations of factors affect exocentric distance perception. Therefore, our research question is the following: *Do gender, height, dominant hand, gaming hours per week, previous VR experience, wearing glasses, and current studies combined with immersion levels, and a virtual scale influence exocentric distance estimates?*

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The paper has the following structure. Section II presents the materials and methods, including details of the VE, data collection, and analysis. The results are presented in Section III. Afterward, discussion is shown in Section IV, while conclusions are made in Section V.

II. Materials and Methods

This section is split into three subsections. In Subsection A, the developed VE is presented. Subsection B contains the data collection process. Lastly, the data analysis is shown in Subsection C.

A. Details of the virtual environment

The mentioned VE was developed in Unity game development engine (version 2018.4.36f1). Two versions were created: an immersive version for the Gear VR, and a non-immersive version for the desktop display (LG 20M37A (19.5")). Naturally, the Gear VR uses Android platform, whereas the latter one uses Windows operating system. The Windows one is also referred to as the 'PC version' in this study. Also, the smartphone used in the Gear VR was a Samsung Galaxy Edge S6+. The two versions were identical, except for the immersion level and the controls. The PC version is controlled with a keyboard and a mouse, whereas the Gear VR version can be controlled with the rotation of the user's head and by tapping its touchpad on its right side. The participants can only look around in the virtual space. It was not possible to walk in it due to technical constraints.

After starting the application, the participants are taken into the main menu. In it, they have to enter some information about themselves. Upon completion, they had to press the start button. Afterward, they are placed into the middle of the room at their actual (entered) height. The room was 12 m wide on each side, meaning that each wall was 6 m away from the participants. The room can be observed in Figs. 1 and 2.

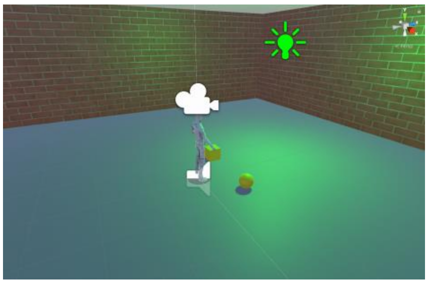

Fig. 1. The virtual environment without a scale (seen from the Unity editor).

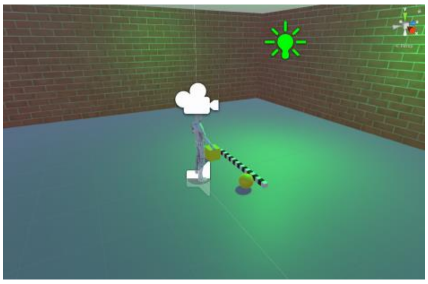

Fig. 2. The virtual environment with a scale (seen from the Unity editor).

As seen in Figs. 1 and 2, two objects were in front of the participants' avatar. Both objects had three types that were randomized. They could either be a cylinder, cube or a sphere. Their exocentric distances were also randomized between 60-150 cm at 10 cm intervals in each round. Every distance had to be encountered two times by the participant. Firstly, all without the scale, and afterward, all with the scale, but in both cases in randomized order. Therefore, the whole measurement process had 20 rounds. The scale had 19 cubes on the ground. The size of each cube on the scale was 10 cm × 10 cm × 10 cm.

B. The data collection process

The University of Pannonia and the University of Debrecen were the sites of the data collection process which occurred in the fall of 2022. The Gear VR version was used at the former university, while the PC version was used at the latter. The skills of 72 students were measured with the Gear VR ($M_{age} = 22.51, SD_{age} = 6.63$). These participants were IT students. With the desktop display, the distance perception ability of 157 students was measured ($M_{age} = 19.80$, $SD_{age} = 2.09$). Out of these, 81 were civil engineering ($M_{age} = 19.72, SD_{age} = 2.32$), 27 were mechanical engineering ($M_{age} = 20.18, SD_{age} = 2.45$) and 49 were vehicle engineering students ($M_{age} = 19.71, SD_{age} = 1.34$). All participants joined the measurements of their own volition and gave informed consent for the process. No names were gathered. However, we asked the participants to provide their following non-identifying data: gender; age; height; dominant hand; whether they wore glasses; their field of study; how many hours of video games they play per week; and whether they had any previous VR experience. This information had to be entered in the main menu of the application.

Before the measurements started, information was given about them. The participants were briefed on the following. They were instructed how to look around in the virtual space, and how to estimate distances. We also told them the dimensions of the room and the scale. On PC, participants had to enter the distances using the keyboard. It was not even necessary to click on the input box. With the Gear VR, they had to say the estimated distances to the researcher next to them, who wrote it into a file. After either was completed, the participants had to look up at the ceiling and press enter on the keyboard or the touchpad on the Gear VR. After doing so, the next round started at another distance. The first 10 rounds were without the scale, while the scale appeared for the second 10 rounds. If the participants completed all 20 rounds, the tests were over. Again, all the distances arose in both types, but in randomized order.

After each round, the application wrote the data into a file with CSV type. The data looked like the following: every line was a round, and it contained all factors that were present during the measurement. This meant the human characteristics, actual and estimated distances, estimation times, et cetera.

C. Analysis of data

When the data collection process was completed, the mentioned CSV file was imported into the statistical program package R. However, before the analyses started, several groups were created based on heights and video game playtime per week. 11 groups were created of the former, whereas six were created of the latter one. Regarding height, the shortest person was 150 cm, whereas the tallest was 202 cm. Therefore, the 11 groups were created at five-centimeter intervals (150-154 cm, 155-159 cm, and so on). Regarding video game playtime per week, the following groups were made on an empirical basis: 0 hours; 1-2 hours; 3-4 hours; 5-10 hours; 11-19 hours; and 20 or more hours.

For the first step of the investigation, the estimates were deemed either accurate or inaccurate. An estimate was considered accurate if it ranged within ±10% of the actual distance. This classification yielded 1274 accurate estimates and 3306 inaccurate ones. For the investigation, an alpha value of 0.05 was chosen. The Shapiro-Wilk test was used to examine the distributions of the data. Due to the distributions, the Wilcoxon rank sum test was used when comparing the general results. To see the effects of the various objects in the VE, the Kruskal-Wallis rank sum test was used. Logistic regression analysis method was used to understand the effects of the influence of human characteristics and immersion levels with or without the scale on the probability of accurate estimates. The log-odds returned by the logistic regression analysis can be converted to percentages using Equation (1).

$$\% = (e^{LO} - 1) \cdot 100 \quad (1)$$

, where LO stands for the log-odds. The basis (intercept) variables were chosen by R automatically. Usually, the first one is chosen in the alphabet. The strengths of the effects are presented in the form of 95% confidence intervals (CIs). The basis variables are omitted from the figures.

III. Results

In this section, the results are shown within several subsections. Each details the results of a pair of factors. Before continuing to the analysis of the effects, the descriptive statistics are investigated. They can be observed in Fig 3.

Judging from Fig. 3, desktop display users were more accurate than the Gear VR users. Before comparing the accuracy of estimates on both platforms, their distributions were assessed with the Shapiro-Wilk normality test. The accurate estimates regarding the desktop display ($W = .584, p < .001$), Gear VR ($W = .489, p < .001$), with a scale ($W = .616, p < .001$), and not having a scale ($W = .458, p < .001$) did not follow Gaussian distribution. Therefore, the Wilcoxon rank sum test was used for comparison. The distances were compared between the platforms, and every difference was significant, except for 90 cm ($W = 20677, p = .140$). The remaining differences were strongly significant at each distance ($9103.5 \leq W \leq 36226, p \leq .002$).

Afterward, the effects of the scale were also compared. The accuracy was significantly different between the two groups ($W = 3169360, p < .001$). Those who used a scale were more accurate ($M = 0.382, SD = 0.486$) than those who did not ($M = 0.173, SD = 0.379$).

The last step was to assess the differences in accuracy regarding the three various objects. The Kruskal-Wallis rank sum test was used for this purpose. The results show that the various objects did not have significant effects on the results ($H(8) = 9.897, p = .272$), thus they were omitted from further analyses.

It should be noted that to conserve space, the following abbreviations are used in the forthcoming figures:

- M (Male),
- F (Female),
- DD (desktop display),
- GVR (Gear VR),
- LH (left-handed),
- RH (right-handed),
- Hx-y (height between x cm and y cm),
- G (wore glasses),
- NG (did not wear glasses),
- VGn-m (video game playtime per week between n and m hours),
- VRXP (previous VR experience),
- NVRXP (no previous VR experience).

A. Gender and display device

As was mentioned, the first part of the investigation focused on the effects of gender and display device. On PC, the skills of

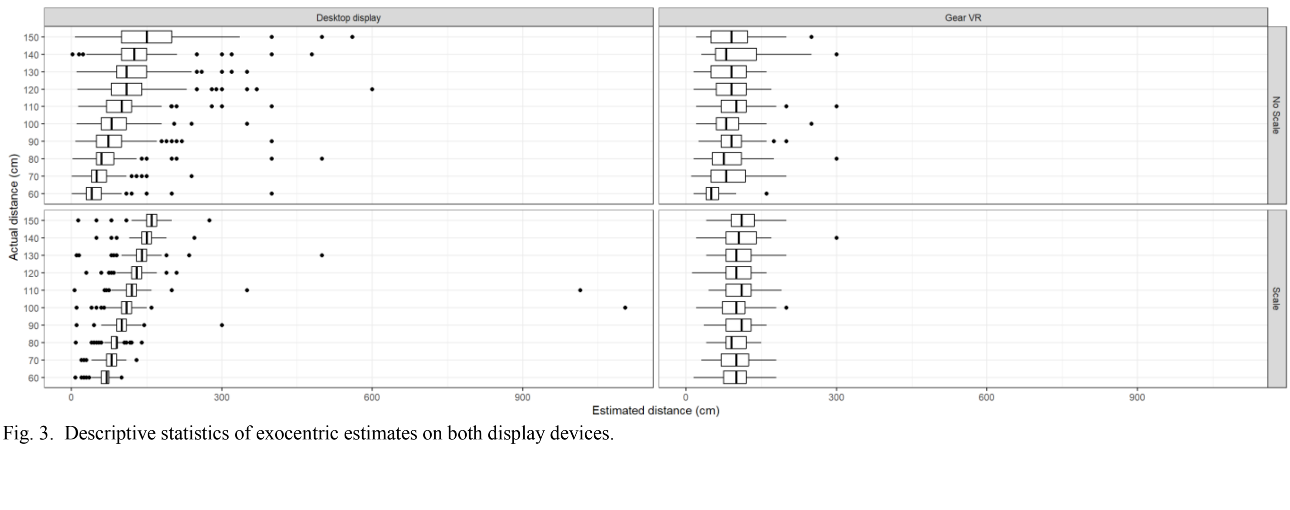

Fig. 3. Descriptive statistics of exocentric estimates on both display devices.

128 males and 29 females were measured. Contrarily, 49 males and 23 females used the Gear VR. The null-hypothesis was the following regarding this group: *The combination of gender, immersion level, and scale does not have a significant effect on the results.*

First, the accuracy of all possible combinations of groups was compared with the Kruskal-Wallis rank sum test. The results show significant differences between them ($H(7) = 407.6, p < .001$). Then, the probability of estimating accurately was compared using logistic regression analysis. The effects of each combination of variables can be seen in Figs. 4 and 5. The former presents the results when no scale was present, while the other shows them when the scale was present. In both cases, the basis variable was "female, desktop display".

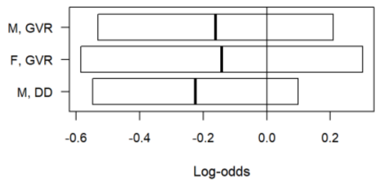

Fig. 4. 95% CIs showing the effects of the gender and display device pair when no scale was used.

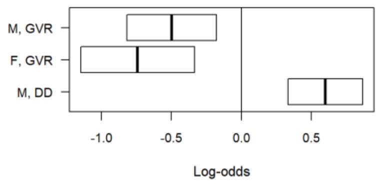

Fig. 5. 95% CIs showing the effects of the gender and display device pair when the scale was used.

When no scale was present, it can be observed that the investigated pairs of variables had no significant effects on the probability of accurate estimates. However, when the scale was present the likelihood of answering correctly significantly decreased in the case of both genders when the Gear VR was used. On average, males were less likely to answer accurately by 22.35%, while females were less likely to answer accurately by 17.53%. However, males were more likely to answer accurately by 67.07% on average, when they used the desktop display.

B. Dominant hand and display device

The following to investigate was the effects of the dominant hand and display device. On PC, the skills of 122 right-handed and 35 left-handed participants were measured. Contrarily, 67 and 5 used the Gear VR, respectively. Here, the null-hypothesis was the following: *The combination of dominant hand, immersion level, and scale does not have a significant effect on the results.*

As in the previous subsection, the accuracy of all possible groups was compared with the Kruskal-Wallis rank sum test. The results of the previously mentioned test showed significant differences between the accuracy of groups ($H(7) = 382.16, p < .001$). Afterward, the probability of estimating correctly was assessed. The results are shown in Figs. 6 and 7. Similarly, the former presents the results when no scale was present, while the other shows them when the scale was present. In both cases, the basis variable was "left-handed, desktop display".

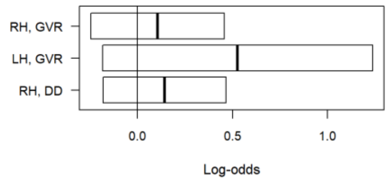

Fig. 6. 95% CIs showing the effects of the dominant hand and display device pair when no scale was used.

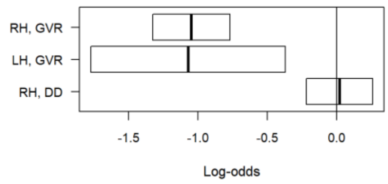

Fig. 7. 95% CIs showing the effects of the dominant hand and display device pair when the scale was used.

Similarly to gender and display device, the combination of dominant hand and display device had no significant effects on the accuracy of the participants when no scale was present. However, when the scale was present, those who used the Gear VR were less likely to accurately estimates distances. These likelihoods were 12.60% and 12.89% in the cases of left-handed and right-handed participants, respectively.

C. Height and display device

The effects of height and display device were investigated next. The distribution of students using one of each display device can be seen in Fig. 8. Here, the null-hypothesis was the following: *The combination of height groups, immersion level, and scale does not have a significant effect on the results.*

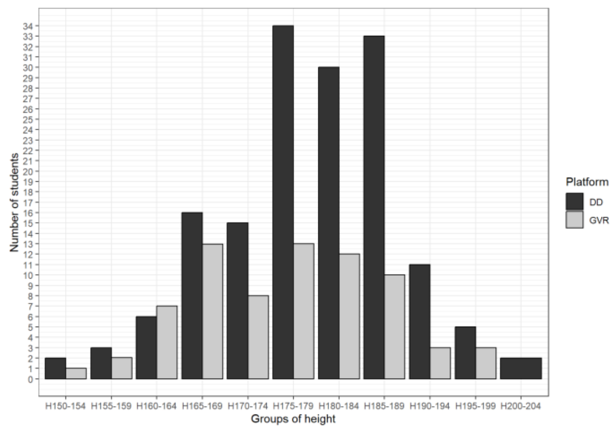

Fig. 8. Number of students using one of each display device, grouped by height.

First, as previously, the significant differences were assessed with the Kruskal-Wallis rank sum test. The results show that significant differences existed between the groups ($H(41) = 497.82, p < .001$). Next, the probability of accurate estimates was checked. The results can be seen in Figs. 9 and 10. Similarly to the previous subsections, the scale was not present in the case of the former, while it was present in the case of the latter. In both cases, the basis variable was "height of 150-154 cm and desktop display".

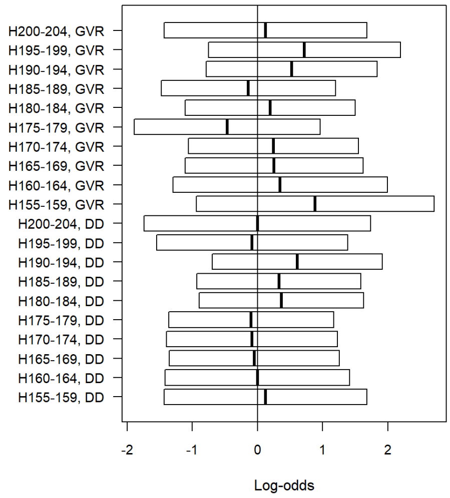

Fig. 9. 95% CIs showing the effects of the height groups and display device pair when no scale was used.

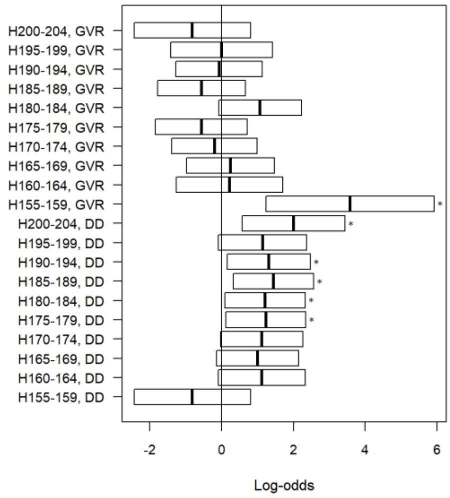

Fig. 10. 95% CIs showing the effects of the height groups and display device pair when the scale was used. To increase readability, significant effects were denoted by *.

As can be seen in Fig. 9., no significant effects were found when the scale was not present. Contrarily, Fig. 10 shows that there were six significant differences when the scale was present. Each of them had a larger likelihood of estimating accurately. These increases in the average likelihoods were observable in the following groups: H175-179, DD (126.24%); H180-184, DD (123.67%); H185-189, DD (156.34%); 190-194, DD (136.82%); H200-204, DD (273.28%); and H155-159, GVR (1324.36%). However, the larger increases may be due to the small number of participants in those groups.

D. *Whether glasses were worn and display device*

The next examination was the effects of glasses and display devices. There were 66 participants with glasses and 91 without them on PC, while these numbers were 33 and 39, respectively regarding to the Gear VR users. The null-hypothesis was the following regarding this group: *The combination of glasses, immersion level, and scale does not have a significant effect on the results.*

The Kruskal-Wallis rank sum test was used to assess whether there were significant differences between the possible combinations of groups. According to the results, significant differences exist between them ($H(7) = 383.63, p < .001$). Afterward, the effects on the probability of accuracy were investigated. The results are shown in Figs. 11 and 12. The former presents the results when no scale was present, while the latter shows them when the scale was present. In both cases, the basis variable was "wore glasses and desktop display".

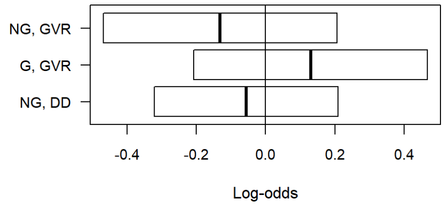

Fig. 11. 95% CIs showing the effects of the glasses and display device pair when no scale was used.

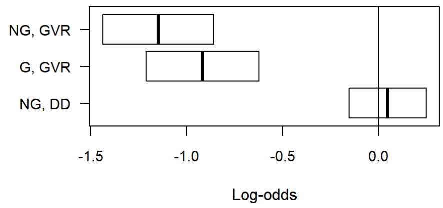

Fig. 12. 95% CIs showing the effects of the glasses and display device pair when the scale was used.

The results show that the use of the Gear VR significantly decreased the likelihood of answering correctly when the scale was used. In case of participants with glasses, the average decrease in likelihood was 14.71%, while that of those without glasses was 11.67%.

E. *Video game playtime per week and display device*

The effects of video game playtime (in hours) per week and display device were the next experiment. The distribution of students using both display devices can be seen in Fig. 13. Here, the null-hypothesis was the following: *The combination of video game playtime per week groups, immersion level, and scale does not have a significant effect on the results.*

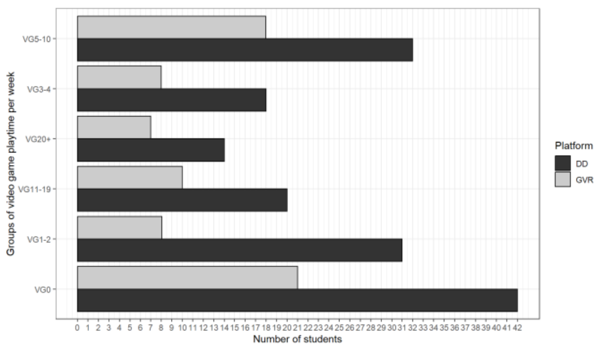

Fig. 13. Number of students using the display devices, grouped by video game playtime per week. The playtime is in hours.

Similarly, the Kruskal-Wallis rank sum test was used to assess the significant differences between the groups. The results show that there were significant differences between them ($H(23) = 425.05, p < .001$). Next, the effects on the probability of accurate estimates were investigated. The results can be observed in Figs. 14 and 15. The former presents the results when no scale was present, while the latter shows them when the scale was present. In both cases, the basis variable was "zero hours and desktop display".

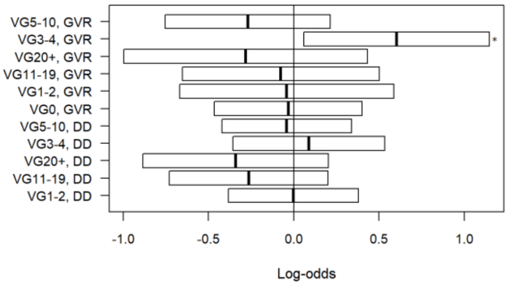

Fig. 14. 95% CIs showing the effects of the video game playtime per week groups and display device pair when no scale was used. To increase readability, significant effects were denoted by *.

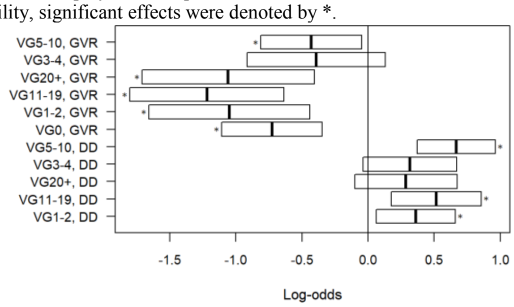

Fig. 15. 95% CIs showing the effects of the video game playtime per week groups and display device pair when the scale was used. To increase readability, significant effects were denoted by *.

Here, one significant effect could be found when no scale was present. The likelihood of the "VG3-4, GVR" group estimating correctly is significantly increased by 67.18% on average. When the scale was present, the likelihood significantly decreased in the case of five groups (VG5-10, GVR (23.88%); VG20+, GVR (12.75%); VG11-19, GVR (10.87%); VG1-2, GVR (12.87%); and VG0, GVR (17.76%)), and significantly increased in the case of three groups (VG5-10, DD (71.61%); VG11-19, DD (61.62%); and VG1-2, DD (52.77%)).

F. Previous VR experience and display device

The next to assess was the effects of the pair of previous VR experience and display devices. On PC, 57 participants had such experience, whereas 100 did not. Regarding the Gear VR users, 29 had such experience and 43 did not. Here, the null-hypothesis was the following: *The combination of previous VR experience, immersion level, and scale does not have a significant effect on the results.*

The possible groups were investigated with the Kruskal-Wallis rank sum test: there were significant differences between them ($H(3) = 253.18, p < .001$). Afterward, the probability of accurate estimates was investigated. The results can be observed in Figs. 16 and 17. The former presents the results when no scale was present, while the latter shows them when the scale was present. The basis variable was "no VR experience and desktop display" in both cases.

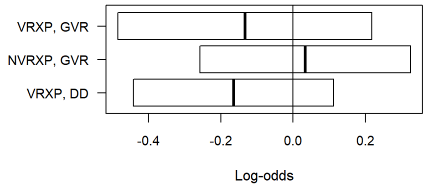

Fig. 16. 95% CIs showing the effects of the previous VR experience and display device pair when no scale was used.

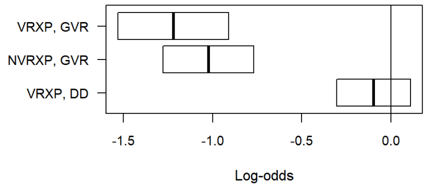

Fig. 17. 95% CIs showing the effects of the previous VR experience and display device pair when the scale was used.

There were no significant differences when no scale was used. However, when there was a scale in the VE, two significant decreases could be found in the likelihood of answering accurately. These occurred in the case of the VRXP, GVR (10.85%) as well as NVRXP, GVR (13.21%) groups.

G. Current studies and display device

The last to assess was the effects of the pair of current studies and display devices. There were 72 IT, 81 civil engineering, 27 mechanical engineering, and 49 vehicle engineering students. Here, the null-hypothesis was the following: *The combination of current studies, immersion level, and scale does not have a significant effect on the results.*

The accuracy of all possible groups was compared with the Kruskal-Wallis rank sum test. The results showed significant differences between the accuracy of groups ($H(7) = 384.15, p < .001$). Afterward, the probability of estimating correctly was assessed. The results are shown in Figs. 18 and 19. The former presents the results when no scale was present, while the other shows them when the scale was present. In both cases, the basis variable was "civil engineering, desktop display".

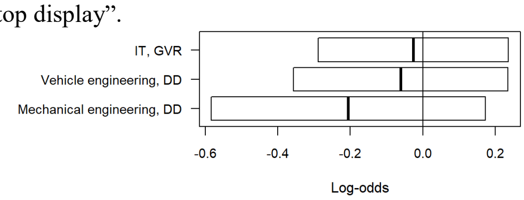

Fig. 18. 95% CIs showing the effects of the previous VR experience and display device pair when no scale was used.

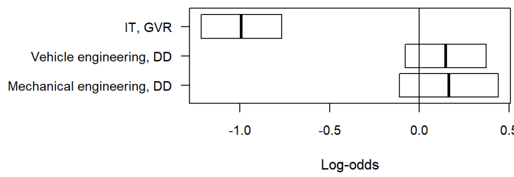

Fig. 19. 95% CIs showing the effects of the previous VR experience and display device pair when the scale was used.

In this case, there was only one significant decrease in the likelihood of estimating accurately. It is observable in the case of IT students who used the Gear VR (13.64%). However, it should be noted that it was with another display device compared to the others.

IV. Discussion

According to the findings, the research question was answered. In the literature, it is shown that display devices can influence distance estimation [24, 25, 27]. Combined with the immersion levels, every human characteristic had a significant effect on exocentric distance estimation when a scale was present. In the case of height and video game playtime per week, we did not find any patterns that could cause the significance in the differences.

It should also be noted that significant decreases in the likelihood of estimating correctly occurred with the Gear VR when the scale was present. This did not occur in the case of the desktop display. The results also show that the latter provided more accurate results and less deviation in the estimates.

As with every study, this one had limitations as well. The first limitation was the number of students with certain characteristics. For example, there were only five left-handed students on the Gear VR. Therefore, increasing the sample size could increase the value of the results as well. The second limitation was technological since we used the Gear VR head-mounted display. This device does not allow movement in 3D as it only follows the rotation of the user's head. By porting the Gear VR to PC as well and measuring with a newer head-mounted display could also produce more accurate results. The third limitation was the investigated distances. As was mentioned, the investigated distances were between 60 cm and 150 cm at 10 cm intervals. To provide a better understanding in the future, smaller or larger distances could be investigated. Since overestimation occurred at the investigated smaller distances, it would be interesting to study this trend at even smaller distances. Future research directions include studying the compositional elements in the VE, such as textures, lighting, and object size.

V. Conclusions

A VE was developed and the exocentric distance estimation skills of 229 students were assessed with it. Among them, 157 used a desktop display, whereas 72 used the Gear VR head-mounted display. During the measurements, several human characteristics were logged: gender; age; height; dominant hand; whether they wore glasses; their field of study; how many hours of video games they play per week; and whether they had any previous VR experience. After gathering the data, the statistical program package R was used for evaluation.

According to the results, when the human factors were combined with the display devices with various immersion levels, significant effects could be found. In almost all cases, significant effects only occurred when the scale was present. Therefore, based on these results, it is possible to conclude that while the desktop display was more accurate in exocentric distance estimation, the existence of a scale could change the probabilities of accurate exocentric distance estimates.

In conclusion, human factors combined with immersion level and a virtual scale have significant effects on exocentric distance estimation. Since both are integral components of VR systems, it is possible for them to interact with each other as shown by the results. These findings can be considered by developers when they design and implement new VEs to create a more accessible experience in the future.

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