Effects of shadows and brightness on distance judgments for virtual objects

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This project was carried out to check whether the light and the shadows influence the distance judgment of an object in virtual reality. To this end, a program using Unity was developed and the experiment was conducted through Meta Quest2. In an experiment involving six participants, it was concluded that both the light and the shadow influence the distance judgment of the virtual object. The presence of shadow helps to determine the distance to the virtual object. However, I have not found which brightness increases the most accuracy, so in future studies, I should find the optimal brightness.

Additional Key Words and Phrases: virtual reality(VR), head-mounted display (HMD), light, shadow, distance

ACM Reference Format:
Junhwan Kim. 2024. Effects of shadows and brightness on distance judgments for virtual objects. 1, 1 (May 2024), 9 pages. https://doi.org/10.1145/nnnnnnn.nnnnnnn

1 INTRODUCTION

1.1 Introduction

The basic concept of virtual reality (VR) means 'an artificial environment that is similar to reality but is not real,' but generally refers to tangible digital content that uses a head-mounted display (HMD) as an output device. Among various types of HMD, VR devices, unlike augmented reality (AR) devices, have the characteristic of occupying the user's entire perspective and showing a completely new world. Because of this, in a VR device environment, users must rely only on the images provided by the VR device when judging the distance of a virtual object. Therefore, knowing the factors that affect the distance judgment of virtual objects in VR devices can enable users to accurately judge the distance to virtual objects(Westermeier et al.[7]). The reason why it is important for VR device users to determine the distance to a virtual object is that if the distance judgment is not accurate, immersion is lost, errors may occur when holding or operating an object, and obstacles in the real environment are not accurately displayed in virtual, causing safety problems that cause users to collide(Benjamin et al.[2]). In order to solve this problem, it is necessary to understand the factors that help and hinder distance judgment. Estimating the distance through stereoscopic vision, comparing the size with other virtual objects of the same size, and the presence of shadows are factors that help the user determine the distance to the virtual object(Krueger et al.[4]). Most of the factors that hinder VR device users from determining the distance to a virtual object are factors that cause optical illusion or confusion, and there are cases in which low-quality graphics, brightness, and movement of virtual objects are different from reality(Wang et al.[6]). Among them, this project presents the effect of brightness and shadow on users' distance judgment of virtual objects in a VR device environment.

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1.2 Motivation

The initial motivation for conducting this study came from two studies, Singh et al.[5] and Kunz et al.[8] on determining the distance of experimental participants on hypothetical objects. I performed partial replication and expansion in two studies, Singh et al.[5] and Kunz et al.[8]. Singh et al.[5] conducted an experiment to determine which factors influence distance judgment among focal length, age, and brightness in an AR environment. Among them, I concluded that focal length and brightness influence the distance judgment for virtual objects in AR environments. Singh et al.[5] motivated me to conduct this study with brightness as a central variable. Kunz et al.[8] concluded that the quality of graphics in a VR environment influences the user's judgment of the distance to a virtual object. In addition, Kunz et al.[8] presented an experimental method for determining the distance of a virtual object by a user in a VR environment. Through this, I was motivated to conduct this study in a VR environment.

1.3 Contribution

Focusing on brightness and shadow, a study on the distance judgment of participants in the experiment on virtual objects in a VR environment is conducted because it can give real users an improvement in distance judgment with less resources and effort than other factors that affect distance judgment. Among the factors that help users judge their distance in a VR environment, most of the parts that can be improved require a lot of resources and effort. Improving the quality of graphics has clear limitations depending on the performance of the device, and making the visual change of the object according to the user's movement similar to the actual reality also requires a lot of effort. However, changing the brightness and adding shadows does not require much effort and is not significantly affected by the performance of the device. Therefore, knowing the effect of brightness and shadow on VR device users' distance judgment on virtual objects will be of great help in improving the distance sense of VR device users, who occupy an important part of VR environment research.

1.4 Hypothesis

- `H1`: The presence of shadows will increase accuracy in determining distance to virtual objects.
- `H2`: The higher the intensity of light will increase accuracy in determining distance to virtual objects.

2 RELATED WORK

2.1 A distance judgment study for virtual objects affected by the real environment

Distance judgment studies on virtual objects affected by real-world environments mainly deal with AR environments. In particular, most of them study the AR environment using HMD. Adams et al.[1] is a prime example of that. Adams et al.[1] studied the effect of shadow on distance judgment in AR environments. They show the conclusion that shadows are of significant help in determining distances to hypothetical objects. Gagnon et al.[3] studied the distance judgment of experiment participants on objects floating in AR environments that are separated by a specific distance. This study shows the conclusion that there is an error in determining the distance to the virtual object in the AR environment and that it feels closer to the experiment participant than the intended distance. There are also studies that have conducted experiments on AR without using HMD. Singh et al.[5] study the effect of focal length, brightness, and age on the distance judgment of participants in the experiment on a virtual object through a Haploscope using lenses. In this paper, I found that brightness and focal length affect the distance judgment on a virtual object, but age has no significant effect. Ziemer et al.[10] created a virtual environment by displaying images on the screen. In this experiment, whether it is more helpful to see the real environment than just the virtual environment, the experiment is conducted by changing the order of viewing the virtual environment and the real environment. In this experiment, it was confirmed that if you actually look at the virtual environment, your sense of distance becomes more accurate(Xu et al.[9]).

2.2 A distance judgment study for virtual objects that are not affected by the real environment

The study of distance judgment on virtual objects that are not affected by the actual environment is mainly conducted using VR devices among HMD devices. Kunz et al.[8] check whether the quality of graphics in a VR environment affects the distance judgment of VR device users. They found that the quality of graphics does not always affect distance judgment, but it does when walking around in a VR environment. Adams et al[1] conducted experiments in AR environments, but also in VR environments. In the same way as the experiment in the AR environment, it was confirmed whether shadows affect the distance judgment of VR device users for virtual objects, and it was concluded that they had the same effect as in the AR environment.

3 METHODOLOGY

3.1 Research Questions

The main purpose of this study is to evaluate the effects of light brightness and shadows when users judge the distance to virtual objects in a VR environment. The task of this experiment is to determine how accurately participants can guess the distance to a virtual cube depending on the intensity of light and the presence or absence of shadows. For this purpose, the distance judgments will be made for cubes with a total of 6 distances(1m, 1.2m, 1.4m, 1.6m, 1.8m, 2m) in a total of 6 environments('Light Intensity: 50%, 100%, 150%', 'Shadow: On, Off') by the participants.

Fig. 1. Program development tool

Fig. 2. HMD(Meta Quest2) for experiment

Fig. 3. Participant response record tool

3.2 Program Development

The program was developed through Unity (Fig. 1). The version of the editor used is '2022.3.22f1' and the 'Android Build Support' module was added to run on Meta Quest2 (Fig. 2). The participants' responses were recorded in Excel (Fig. 3) on a laptop. The program operates via the keyboard, and the number keys allow you to select preset light intensity and the presence or absence of shadows. For example, the number key '6' was set to 'Light Intensity: 150%, Shadow: On' (Fig. 4). The virtual cube created for distance judgment can be moved to the next cube using the right arrow key. In each environment, there are two example cubes of 1m and 2m that serve as standards that participants can see before starting the experiment to judge distance (Fig. 5, 6). The program was based on a gray floor with a black background. All virtual cubes used in the experiment had edge lengths set to 0.05m. The light intensity used in the experiment is 50%, 100%, and 150% of Unity 'Directional Light'. There are two types of shadows for a cube: exist(On) and non-exist(Off). In this program, the cubes are spaced in an order in which the experimenter randomly mixes 1m, 1.2m, 1.4m, 1.6m, 1.8m, and 2m in advance. Accordingly, there are a total of 36 cubes for which each participant judges the distance. To eliminate variables in distance judgments caused by participants moving their heads, the cube was made to float in front of the participants no matter where they were looking.

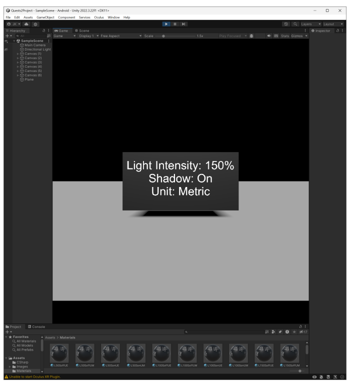

Fig. 4. Experiment environment example(Light Intensity: 150%, Shadow: On

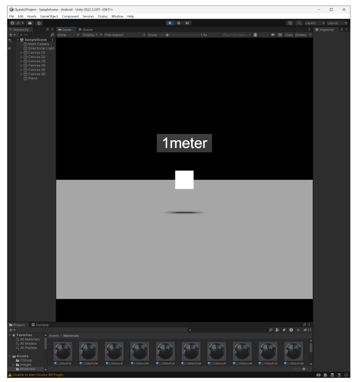

Fig. 5. 1m example cube

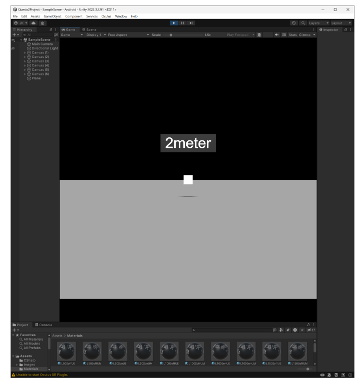

Fig. 6. 2m example cube

3.3 Participants

The experiment was conducted with six CSU undergraduate students. All participants were selected as people familiar with the Metric unit. The average age of the participants was about 25.33, the youngest was 24 years old and the oldest was 29 years old. The gender of the participants was 4 male and 2 female. All participants had normal vision, and those who needed vision correction wore contact lenses instead of glasses to comfortably wear HMD. No compensation was made for the experiment, and all participated as volunteers.

3.4 Experiment

The independent variables for this experiment are the 'Light Intensity', 'Shadow', and 'Distance' of the virtual cube. The dependent variable is the distance estimate to the virtual target verbally reported by the participants(Fig. 8). The experiment is to find out the effect of brightness and shadow on distance judgment in a VR environment through participants using a prepared program. In the experiment, participants wear HMD and there is nothing additional to manipulate. All cubes viewed by participants are managed by the experimenter through keyboard manipulation(Fig. 7). When the experiment begins, first, participants look at the 1m example cube and the 2m example cube in the environment randomly ordered by the experimenter (Fig. 9,10,11). The time to see the two example cubes was conducted until the participant became comfortable with determining the distance. Participants were not allowed to know how far away the cubes prepared in advance other than the example cubes were. At the end of the previous preparation process, the participant of the experiment expressed the distance to the cube shown by the experimenter verbally. The six types of environments that the experimenter shows are random. The distance expressed by the participants and the

						Respond - Answer					
Student	Age	Gender	Unit	Shadow	Light	Answer: 1	Answer: 1.2	Answer: 1.4	Answer: 1.6	Answer: 1.8	Answer:2
A	25	Male	Meter	Off	50%	0.1	0.1	-0.1	0.2	0.2	0
A	25	Male	Meter	Off	100%	0	0.2	0.2	-0.2	0	0
A	25	Male	Meter	Off	150%	0	-0.1	-0.2	-0.2	-0.2	0
A	25	Male	Meter	On	50%	0	0	0.1	0	0.2	0
A	25	Male	Meter	On	100%	0	0	0.1	-0.1	0	0
A	25	Male	Meter	On	150%	0	0	0	-0.2	-0.2	0
B	24	Male	Meter	Off	50%	0	0.1	0.2	0.2	0.2	0
B	24	Male	Meter	Off	100%	0	-0.1	0.2	0.2	0.2	0
B	24	Male	Meter	Off	150%	0	-0.1	-0.3	-0.1	0.2	-0.2
B	24	Male	Meter	On	50%	0	0.1	0.1	0.1	0.2	0
B	24	Male	Meter	On	100%	0	0	-0.2	0.2	0	0
B	24	Male	Meter	On	150%	0	-0.1	-0.1	-0.2	-0.1	0
C	25	Male	Meter	Off	50%	0	0.2	0.2	0.3	0	0
C	25	Male	Meter	Off	100%	0	0.3	0.2	0.2	0	0
C	25	Male	Meter	Off	150%	0	0	-0.3	-0.3	-0.2	0
C	25	Male	Meter	On	50%	0	0.2	0	0.2	0	0
C	25	Male	Meter	On	100%	0	0	0	0	0.1	0
C	25	Male	Meter	On	150%	0	-0.1	-0.2	-0.1	0	0
D	29	Male	Meter	Off	50%	0	0.1	0.3	0.2	0	0
D	29	Male	Meter	Off	100%	0	-0.1	0.1	0.1	0	0
D	29	Male	Meter	Off	150%	0	-0.2	0	0	0.2	0
D	29	Male	Meter	On	50%	0	0	-0.3	-0.1	0	-0.1
D	29	Male	Meter	On	100%	0.1	-0.2	0	0.2	0.1	-0.1
D	29	Male	Meter	On	150%	0	0.1	0	0.1	0	0
E	24	Female	Meter	Off	50%	0	0.1	0.1	0.3	-0.1	0
E	24	Female	Meter	Off	100%	0	0.2	0.3	0.2	0.1	0
E	24	Female	Meter	Off	150%	0	0	-0.2	-0.2	-0.3	-0.1
E	24	Female	Meter	On	50%	0	0.1	0	0	0	0
E	24	Female	Meter	On	100%	0	0	0	0	0	0
E	24	Female	Meter	On	150%	0	0	0	0.1	-0.2	0
F	25	Female	Meter	Off	50%	0	0.1	0.1	0	0.2	0
F	25	Female	Meter	Off	100%	0	0.2	0.3	0.2	0.1	0
F	25	Female	Meter	Off	150%	0	0	-0.2	-0.2	0	-0.1
F	25	Female	Meter	On	50%	0	0.1	0	0	0	0
F	25	Female	Meter	On	100%	0	0	0.1	0	0	0
F	25	Female	Meter	On	150%	0	0.1	0	-0.1	-0.1	0

Fig. 7. Data for the project include 'Age', 'Gender', 'Shadow', 'Light Intensity', 'Respond - Answer'

Independent Variables	
Item	Value
Light Intensity	50%, 100%, 150%
Shadow	On, Off
Cube Distance	1m, 1.2m, 1.4m, 1.6m, 1.8m, 2m
Dependent Variables	
Item	Value
Verbal responses to participants' distance judgments for virtual cubes.	

Fig. 8. Independent Variables:'Light Intensity', 'Shadow', and 'Cube Distance', Dependent Variable: the distance estimate to the virtual target verbally reported by the participants

information about the corresponding cube (intensity of light, presence or absence of shadow, distance to the cube) were recorded through Excel(Fig. 11).

Fig. 9. During the experiment, participants did not use any input tools. The PathThrough function, which allows viewing outside of Meta Quest2, is turned off, so participants cannot see outside information.

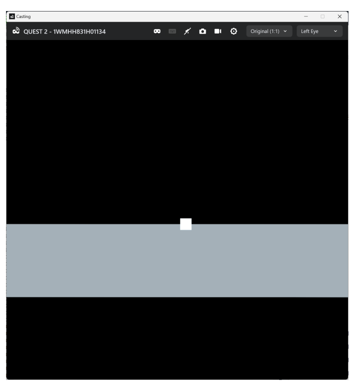

Fig. 10. This is the actual screen the participant is looking at. The information on the cube on the screen is Light Intensity: 150%, Shadow: Off, and Distance: 1.2m.

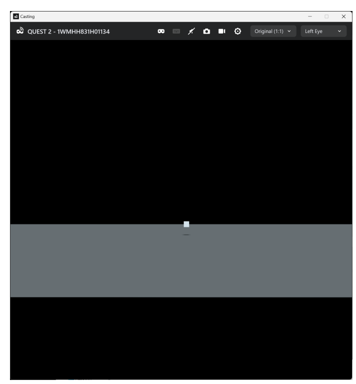

Fig. 11. This is the actual screen the participant is looking at. The information on the cube on the screen is Light Intensity: 50%, Shadow: On, and Distance: 1.8m.

4 RESULTS

4.1 t-test

The t-test is a statistical test method that evaluates whether the mean difference between two groups is statistically significant. Here, an independent samples t-test was used to compare the means between two different groups. Excel was used as the program for t-test. The two groups that conducted the t-test were 'Shadow: Off' and 'Shadow: On'. Before conducting the t-test, an f-test was performed to check whether the two groups had equal or heteroscedasticity (Fig. 12). As a result of the f-test, the P value was approximately 2.73E-07, which was less than 0.05, confirming equal variance. Accordingly, the t-test was conducted as t-test: Two-Sample Assuming Equal Variances(Fig. 13). As a result of the t-test, the P value was about 0.038. As the P value of the t-test was less than 0.05, it was considered that the difference in the presence or absence of the shadow had a significant effect on the participants' distance judgment.

F-Test Two-Sample for Variances

	Shadow: Off	Shadow: On
Mean	0.028703704	-0.000925926
Variance	0.021878678	0.008129976
Observations	108	108
df	107	107
F	2.691112294	
P(F<=f) one-tail	2.73E-07	
F Critical one-tail	1.376364479	

Fig. 12. f-test result. P value is below 0.05

t-Test: Two-Sample Assuming Equal Variances

	Shadow: Off	Shadow: On
Mean	0.028703704	-0.000925926
Variance	0.021878678	0.008129976
Observations	108	108
Pooled Variance	0.015004327	
Hypothesized Mean Difference	0	
df	214	
t Stat	1.777521433	
P(T<=t) one-tail	0.038451345	
t Critical one-tail	1.652005156	
P(T<=t) two-tail	0.076902689	
t Critical two-tail	1.971111258	

Fig. 13. t-test result. P value is below 0.05

4.2 Anova

Analysis of Variance (ANOVA) is a statistical method used to determine whether differences in means between three or more groups are statistically significant. ANOVA tests whether there are substantial differences between groups by analyzing how much data from different groups deviates from a single overall mean. In this project, one-way ANOVA was used to determine whether there was a significant difference in the accuracy of participants' distance judgments depending on three types of light intensity (50%, 100%, 150%) (Fig. 14,15). One-way ANOVA analyzes the difference in means of multiple groups (levels) on one independent variable (factor). As a result, the P value was about 3.71E-11. This is a number significantly smaller than 0.05, which was interpreted as a statistically significant difference between the differences in light intensity.

4.3 Mean Absolute Error(MAE)

MAE was used to measure the accuracy of participants' answers, and the closer the value is to 0, the higher the accuracy. In a t-test to determine whether the presence or absence of a shadow makes a significant difference in the results, the result was that the P value was less than 0.05 and was significant, and the results of 'Light Intensity' (50%, 100%, 150%) were based on the results of ANOVA showing that the P value was less than 0.05, MAE was used to compare accuracy according to the presence or absence of shadows and 'Light Intensity'. MAE is the average of the values obtained by

Student	Light Intensity: 50%	Light Intensity: 100%	Light Intensity: 150%
A	0.1	0	0
A	0.1	0.2	-0.1
A	-0.1	0.2	-0.2
A	0.2	-0.2	-0.2
A	0.2	0	-0.2
A	0	0	0
A	0	0	0
A	0	0	0
A	0.1	0.1	0
A	0	-0.1	-0.2
A	0.2	0	-0.2
A	0	0	0

Fig. 14. Error in distance judgment according to 'Light Intensity' from Student A (Respond - Answer)

Anova: Single Factor

SUMMARY

Groups	Count	Sum	Average	Variance
Light Intensity: 50%	72	4.2	0.058333	0.011479
Light Intensity: 100%	72	3.4	0.047222	0.012387
Light Intensity: 150%	72	-4.6	-0.06389	0.012762

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	0.657778	2	0.328889	26.93783	3.72E-11	3.038264
Within Groups	2.600556	213	0.012209			
Total	3.258333	215				

Fig. 15. ANOVA results according to the intensity of debt (50%, 100%* 150%) of all participants. Since the P value is less than 0.05, it can be said that there is a significant difference between the means of each group.

subtracting the correct answer from the participants' responses (Fig. 16) and then adding the absolute value. These values were expressed as a bar graph for easy comparison (Fig. 17). According to the graph, the presence or absence of a shadow had a significant effect on the accuracy of participants' responses to distance judgments. In the bar graph (Fig. 17), the MAE for the 'Shadow: Off' environment, expressed in orange, can be seen to be noticeably different compared to the 'Shadow: On' environment, expressed in blue. In particular, in the case of 'Shadow: Off', the MAEs are all over 0.1, however in the case of 'Shadow: On', they are all below 0.1. This means that participants were more accurate in judging distance when the shadow was present than when it was not. In contrast, it is difficult to find trends in 'Light Intensity'. When in 'Shadow: Off', the MAE was lowest when the 'Light Intensity' was 50%, but when in 'Shadow: On', the MAE was lowest when the 'Light Intensity' was 100%. This shows that the accuracy of participants' distance judgments varies depending on 'Light Intensity', but it is unknown which 'Light Intensity increases accuracy the most.

	Light Intensity: 50%, Shadow: Off	Light Intensity: 100%, Shadow: Off	Light Intensity: 150%, Shadow: Off	Light Intensity: 50%, Shadow: On	Light Intensity: 100%, Shadow: On	Light Intensity: 150%, Shadow: On
MAE	0.102777778	0.108333333	0.113888889	0.052777778	0.041666667	0.058333333
Student						
A	0.1	0	0	0	0	0
A	0.1	0.2	-0.1	0	0	0
A	-0.1	0.2	-0.2	0.1	0.1	0
A	0.2	-0.2	-0.2	0	-0.1	-0.2
A	0.2	0	-0.2	0.2	0	-0.2
A	0	0	0	0	0	0
B	0	0	0	0	0	0
B	0.1	-0.1	-0.1	0.1	0	-0.1
B	0.2	0.2	-0.3	0.1	-0.2	-0.1
B	0.2	0.2	-0.1	0.1	0.2	-0.2
B	0.2	0.2	0.2	0.2	0	-0.1
B	0	0	-0.2	0	0	0
C	0	0	0	0	0	0
C	0.2	0.3	0	0.2	0	-0.1
C	0.2	0.2	-0.3	0	0	-0.2
C	0.3	0.2	-0.3	0.2	0	-0.1
C	0	0	-0.2	0	0.1	0
C	0	0	0	0	0	0
D	0	0	0	0	0.1	0
D	0.1	-0.1	-0.2	0	-0.2	0.1
D	0.3	0.1	0	-0.3	0	0
D	0.2	0.1	0	-0.1	0.2	0.1
D	0	0	0.2	0	0.1	0
D	0	0	0	-0.1	-0.1	0
E	0	0	0	0	0	0
E	0.1	0.2	0	0.1	0	0
E	0.1	0.3	-0.2	0	0	0
E	0.3	0.2	-0.2	0	0	0.1
E	-0.1	0.1	-0.3	0	0	-0.2
E	0	0	-0.1	0	0	0
F	0	0	0	0	0	0
F	0.1	0.2	0	0.1	0	0.1
F	0.1	0.3	-0.2	0	0.1	0
F	0	0.2	-0.2	0	0	-0.1
F	0.2	0.1	0	0	0	-0.1
F	0	0	-0.1	0	0	0

Fig. 16. Data for calculating MAE according to each environment (Light Intensity, Shadow).

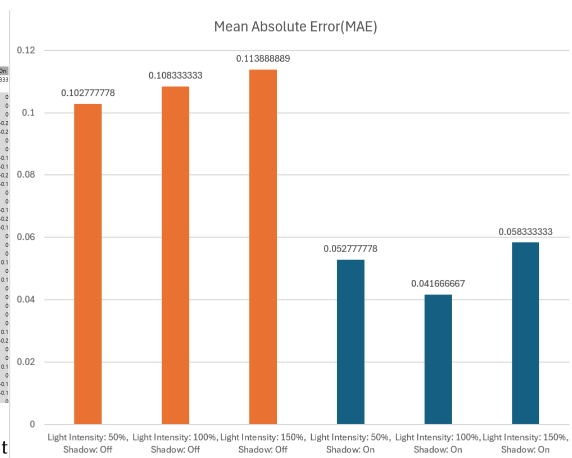

Fig. 17. Bar graph expressing MAE values obtained according to each environment (Light Intensity, Shadow)

5 DISCUSSIONS

5.1 Significance

Through a t-test, I found that the presence or absence of shadows had a significant effect on HMD users' distance judgment. This proves that the hypothesis 'H1: The presence of shadows will increase accuracy in determining distance to virtual objects' is correct. Through ANOVA, I found that differences in light intensity also had a significant impact on HMD users' distance judgments in the VR environment. Through MAE, I found that the presence of a shadow significantly increases the accuracy of HMD users' distance judgment compared to when there is no shadow. Also, through MAE, I found that there is no significant relationship between 'Light Intensity' and 'Distance determined to virtual object'. This proves that the hypothesis 'H2: The higher the intensity of light will increase accuracy in determining distance to virtual objects' is wrong. Through this, I learned that there are factors that affect users' distance judgment in a VR environment. This is expected to greatly reduce problems caused by users' sense of distance when conducting future research on VR environments.

5.2 Limitation

Through ANOVA, I found that brightness had a significant effect on HMD users' distance judgment in the HMD VR environment, but I was unable to determine which brightness was most appropriate through MAE analysis. Additionally, through the given data, it is possible to analyze whether virtual objects appear closer or farther away than they actually are depending on the brightness, but this was not done in this project. Additionally, this study did not consider the participants' level of familiarity with VR devices. This should be taken into consideration as the more familiar you are with VR devices, the more accurate your judgment of distance to virtual objects will be. Additionally, the number and background of the trial participants is narrow. There were only six participants in the experiment, and their educational background was limited to CSU Undergraduate.

6 CONCLUSION AND FUTURE WORK

In conclusion, through this project, I found that various factors affect the judgment of distance to virtual objects in a VR environment. In particular, I realized that it is important in a VR environment to have factors that help judge distance, such as the presence or absence of shadows. In future research, I plan to conduct research by adding various conditions such as the presence or absence of an object whose size can be compared and the presence or absence of a background. Considering the level of familiarity with VR devices, which was disappointing in this study, it is recommended that participants experience the 'Meta Quest2' tutorial to help them adapt to the VR environment. Objects appear distant depending on the intensity of light. It is recommended that you also analyze the tendency to see if they seem close.

7 ACKNOWLEDGEMENTS

I would like to thank the Department of Natural Sciences and Computer Science at Colorado State University for their support in conducting this research. Additionally, I would like to express my sincere gratitude to all professors and fellow students who provided advice and support regarding this study.

REFERENCES

[1] H. Adams, J. Stefanucci, S. Creem-Regehr, G. Pointon, W. Thompson, and B. Bodenheimer. 2022. Shedding Light on Cast Shadows: An Investigation of Perceived Ground Contact in AR and VR. *IEEE Transactions on Visualization amp; Computer Graphics* 28, 12 (dec 2022), 4624–4639. https://doi.org/10.1109/TVCG.2021.3097978

[2] J. Benjamin, A. Erickson, M. Gottsacker, G. Bruder, and G. Welch. 2024. Evaluating Transitive Perceptual Effects Between Virtual Entities in Outdoor Augmented Reality. (mar 2024), 619–629. https://doi.org/10.1109/VR58804.2024.00082

[3] Holly C. Gagnon, Carlos Salas Rosales, Ryan Mileris, Jeanine K. Stefanucci, Sarah H. Creem-Regehr, and Robert E. Bodenheimer. 2021. Estimating Distances in Action Space in Augmented Reality. *ACM Trans. Appl. Percept.* 18, 2, Article 7 (may 2021), 16 pages. https://doi.org/10.1145/3449067

[4] Matheus L. Krueger, Manuel M. Oliveira, and Airton L. Kronbauer. 2016. Personalized Visual Simulation and Objective Validation of Low-Order Aberrations of the Human Eye. (2016), 64–71. https://doi.org/10.1109/SIBGRAPI.2016.018

[5] Gurjot Singh, Stephen R. Ellis, and J. Edward Swan. 2020. The Effect of Focal Distance, Age, and Brightness on Near-Field Augmented Reality Depth Matching. *IEEE Transactions on Visualization and Computer Graphics* 26, 2 (2020), 1385–1398. https://doi.org/10.1109/TVCG.2018.2869729

[6] Zhimin Wang, Yuxin Zhao, and Feng Lu. 2022. Gaze-Vergence-Controlled See-Through Vision in Augmented Reality. *IEEE Transactions on Visualization and Computer Graphics* 28, 11 (2022), 3843–3853. https://doi.org/10.1109/TVCG.2022.3203110

[7] Latoschik ME. Assessing Depth Perception in VR Westermeier Brubach L, Wienrich C, Performance Video See-Through AR: A Comparison on Distance Judgment, and Preference. IEEE Trans Vis Comput Graph. 2024;30(5):2140-2150. doi:10.1109/TVCG.2024.3372061. [n. d.]. ([n. d.]).

[8] Kunz B.R Smith D. et al. Revisiting the effect of quality of graphics on distance judgments in virtual environments: A comparison of verbal reports Wouters, L. and Psychophysics 71 1284–1293 (2009). https://doi.org/10.3758/APP.71.6.1284 blind walking. Attention, Perception. [n. d.]. ([n. d.]).

[9] Feng Xu and Dayang Li. 2018. Software Based Visual Aberration Correction for HMDs. (2018), 246–250. https://doi.org/10.1109/VR.2018.8447557

[10] Plumert J.M. Cremer J.F. et al. Estimating distance in real Ziemer, C.J. and Psychophysics 71 1095–1106 (2009). https://doi.org/10.3758/APP.71.5.1096 virtual environments: Does order make a difference?. Attention, Perception. [n. d.]. ([n. d.]).