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Comparing Perceptual Thresholds of Size Perception under Different Distances in Augmented Reality

Liwen WANG* Shaoyu CAI†

School of Creative Media
City University of Hong Kong

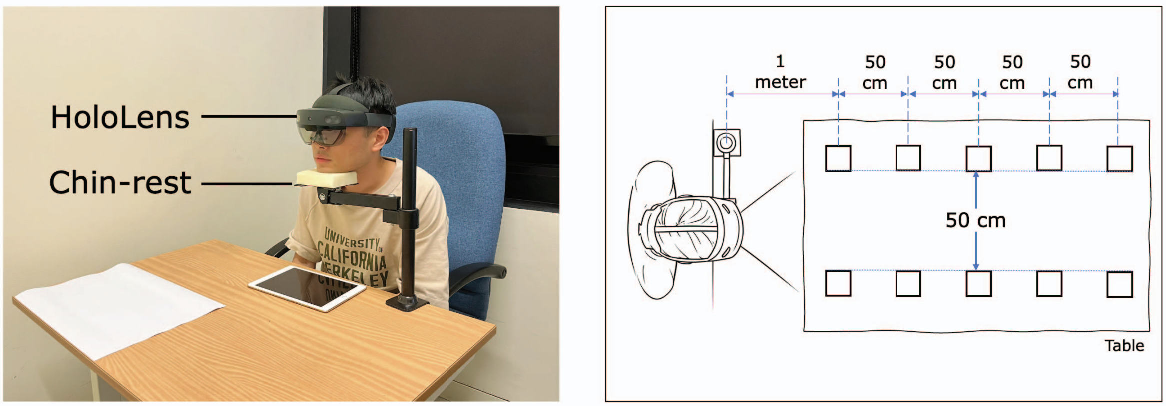

Figure 1: Left: A user wearing HoloLens placing their head on a chin-rest to watch the virtual objects. Right: Top view of our experimental setup. The squares on the table represent the virtual objects in our experiment.

Abstract

Gaining a comprehensive understanding and quantifying human perception are indispensable as they enable us to design more effective interaction and visualization techniques for augmented reality (AR). However, there is a lack of straightforward comparisons of size perception accuracy between different distances in augmented reality. In this paper, we conducted a series of psychophysical experiments to measure perceptual thresholds of size discrimination for virtual objects. Our results indicated that there was no main effect of viewing different distances between 1 meter to 3 meters. Our findings indicate that AR could effectively support training and simulation applications utilizing distances within the range tested in our study. As a result, HoloLens 2 seems to be a competent augmented reality headset for visual perception experiments with reduced bias from vergence-accommodation conflicts in future research.

Keywords: Augmented Reality, Size Perception, Psychophysical Experiment

Index Terms: H.5.1 [Information Interfaces and Presentation: Multimedia Information Systems]: Artificial, augmented, and virtual realities—; J.4 [Computer Applications: Social and Behavioral Sciences]: Psychology—

1 Introduction

Size perception has an aspect of human interaction, and numerous investigations [17, 18] have studied its effects. Taking into account size effects is important when examining the efficacy of visualization or physicalization variables in real-world settings [3, 5, 10, 15]. One important factor that can affect size perception is visual angle [13], which combines two variables: the actual size of the object and the distance between the object and the eyes. The distance between objects and the eyes is inversely proportional to the size of the object on our retina [6]. Without distance information, humans may underestimate the size of faraway objects since the retinal image is reduced [19].

Size perception of virtual objects can aid in understanding computer-generated imagery. Stefanucci et al. [16] investigated the accuracy of size perception on screen-based displays and found that displayed objects on the screen appear smaller than real-world objects. Thomas [17] investigated size perception of virtual cylinders and found the judgments to be very close to the target values in VR. Understanding size perception in AR/VR displays can enhance spatial properties and effectively convey information to users. However, the effect of distance on size perception in AR remains an open question.

Head-mounted displays (HMDs) have a vergence-accommodation conflict, which reveals a mismatch between the vergence and accommodation of the eye [8]. However, every AR HMD has an ideal distance for viewing virtual objects, under which the virtual objects have minimal vergence-accommodation conflict [9]. We assume that at the ideal distance, size perception works well and is close to the target values. Meanwhile, at other distances, size perception may suffer. The goal of our experiments is to quantify the extent to which size perception is affected at different distances.

In our paper, we used 2 meters as the ideal distance [9] for our study. We employed a step size of 50 centimeters to investigate size perception at distances of 1, 1.5, 2, 2.5, and 3 meters. Using the two-alternative forced choice method, we measured the level of size perception for each distance. By employing psychophysical techniques, we quantified the impact on size perception and obtained the detection thresholds for the various distances. In summary, the points of subjective equality (PSEs) derived from the psychophysical function curve for distances of 1-3 meters were determined as 1011,

*e-mail: liwen.wang@my.cityu.edu.hk
†e-mail: shaoyu.cai@my.cityu.edu.hk

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1008.2, 1018, 1027.7, and 1032.1 cm^3, respectively. Based on our analysis of size perception in augmented reality, we observed no significant differences in terms of perceptual thresholds for size perception or user experience across the different distance conditions.

2 Related Work

There are some factors that impact size perception, mainly: size constancy, perspective, and retinal visual view [4, 7, 13]. Size constancy refers to the phenomenon where objects of a known size appear the same, regardless of their position from the viewer [4]. To mitigate the impact of size constancy, we did not provide users with information about the object size beforehand or a constant reference frame around the stimuli. Perspective, such as converging lines, can create an illusion of size changes [7]. Additionally, the visual view of objects on the retina influences the perceived size, with larger objects subtending a larger visual view [13]. Understanding these factors that influence size perception can improve our comprehension of their impact on AR/VR displays.

Several studies have explored size perception in virtual objects in HMDs. These previous works [2, 17] have verified that humans have the ability to discriminate size in AR/VR and can perform with precision. This demonstrates that it is possible to quantify size perception in AR. However, it is unclear how accurately people can perceive size. Adams et al. [1] mentioned that shadows can affect depth perception, and distance is a key factor in our experiments. Therefore, we kept the presence of the virtual object, instead of a "ghost cube", which can be seen in more detail in Fig. 2.

Vergence–accommodation conflicts in stereo displays can affect visual discomfort and fatigue. It is a natural conflict in HMDs where the viewing distance is at the glass but the perceived distance is in the space. Shibata et al. [14] conclude a continuous zone of comfort expressed in diopters. We chose a relatively close distance that would accommodate more usage scenarios, which also fits within the "safe zone" [14].

3 Experiment

We ran an experiment to test whether size perception will suffer in augmented reality under different distances. Participants viewed the virtual cubes placed above the table in augmented reality, with all distances wearing the HoloLens. Viewing conditions (different distances with different size comparisons) was a within-subjects manipulation. We tested the following hypotheses:

H1. The farther away from the ideal distance, the more the size perception will be affected.

H2. The farther away from the ideal distance, the more eye fatigue will be experienced.

3.1 Participants

Ten participants (8 females, 2 males; mean age = 24.1, SD = 2.42) joined our experiment. All participants were right-handed and had normal or corrected-to-normal vision. We defined the levels of experience with AR as follows: 0 - never, 1 - seldom (less than once a month), 2 - often (more than once a month), and 3 - expert (developer or related engineering). The average level of user experience with AR or VR was 1.2 (SD: 0.42). Prior to participating, all individuals provided informed consent and were unaware of the experiment's purpose. Participants received compensation for their efforts.

3.2 Apparatus and Stimuli

We conducted our experiments using the Microsoft HoloLens 2, an optical see-through head-mounted display. The HoloLens 2 has a field of view of 43° x 29° and weighs approximately 566 g. The experimental objects and design were programmed in Unity (v. 2019.4.29) and ran as a standalone application on the HoloLens. A chin-rest was provided to fix the head position, and the distance between the chin-rest and the table was fixed at 45 cm. The experiment took place in a 4.5 m x 2.5 m laboratory room without any additional furniture, and the laboratory room and lighting were the same in all conditions. An iPad Air 2 was provided for participants to fill out all questionnaires used in the experiments.

All cubes in AR were rendered in normal white color (Fig. 2). The reference virtual cube had a size of $10 \times 10 \times 10$ cm^3, and the stimuli size change was scaled with the volume as a whole. We created 8 stimuli with volumes ranging from 800 to 1200 cm^3, with a 5% change step. Each stimulus was repeated 6 times. For the distance, each participant experienced 5 distances (1, 1.5, 2, 2.5, 3 m) in a balanced Latin square order. Therefore, each user experienced 240 pairs of stimuli during the experiment (8 stimuli x 5 distances x 6 repetitions). The order of stimuli was randomized, and the order of reference-stimuli pairs was also randomized. For example, the cube pair (850, 1000) with (1100, 1000) randomly occurred in the list, and the cube pair (1000, 850) with (850, 1000) randomly occurred in the stimuli list.

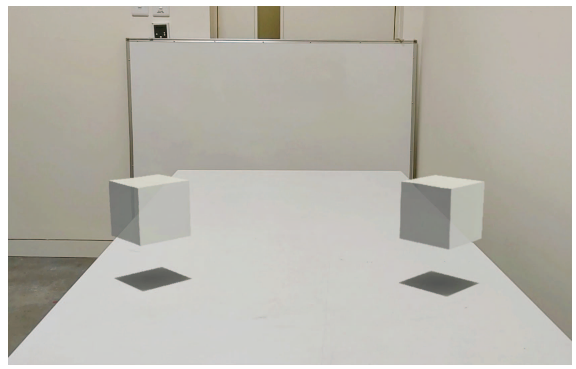

Figure 2: Two cubes were placed at a distance of 1 meter from the participants. In our experiment, the two cubes appeared in the participants' view one by one for judgement.

3.3 Procedure

We conducted a within-subject user study with a balanced Latin square order of distances in AR. The procedure was kept consistent for all conditions. To simplify, we will only emphasize the experiment process in this section and omit descriptions of the different distances.

Participants were first provided with an information sheet that explained the experiment, and signed consent forms were obtained. Demographic information was also collected. Next, participants filled in a symptom question that explored their vision state, which included eye fatigue in "How tired are your eyes?". Participants who reported moderate or severe eye strain were advised to end the experiment. Once all the necessary paperwork was complete, participants moved on to the next section, where they received assistance in putting on the HoloLens. After putting on the HoloLens, participants underwent a training session to familiarize themselves with the virtual objects and procedures. During the training, the virtual objects were placed at a fixed distance of 80 cm from the head to offset the effect of distance on subsequent performances. We presented the participants with a series of 10 pairs of virtual cubes and asked them to choose the bigger one. After the participants felt they were familiar with the process, we proceeded to the test.

Participants were asked to estimate the size of cubes that were placed above the table at distances of 1m, 1.5m, 2m, 2.5m, and 3m away from the head, six times for each stimulus in random order. In each distance, we showed the first cube on the left. We did not control the time when participants memorized the size of the cube.

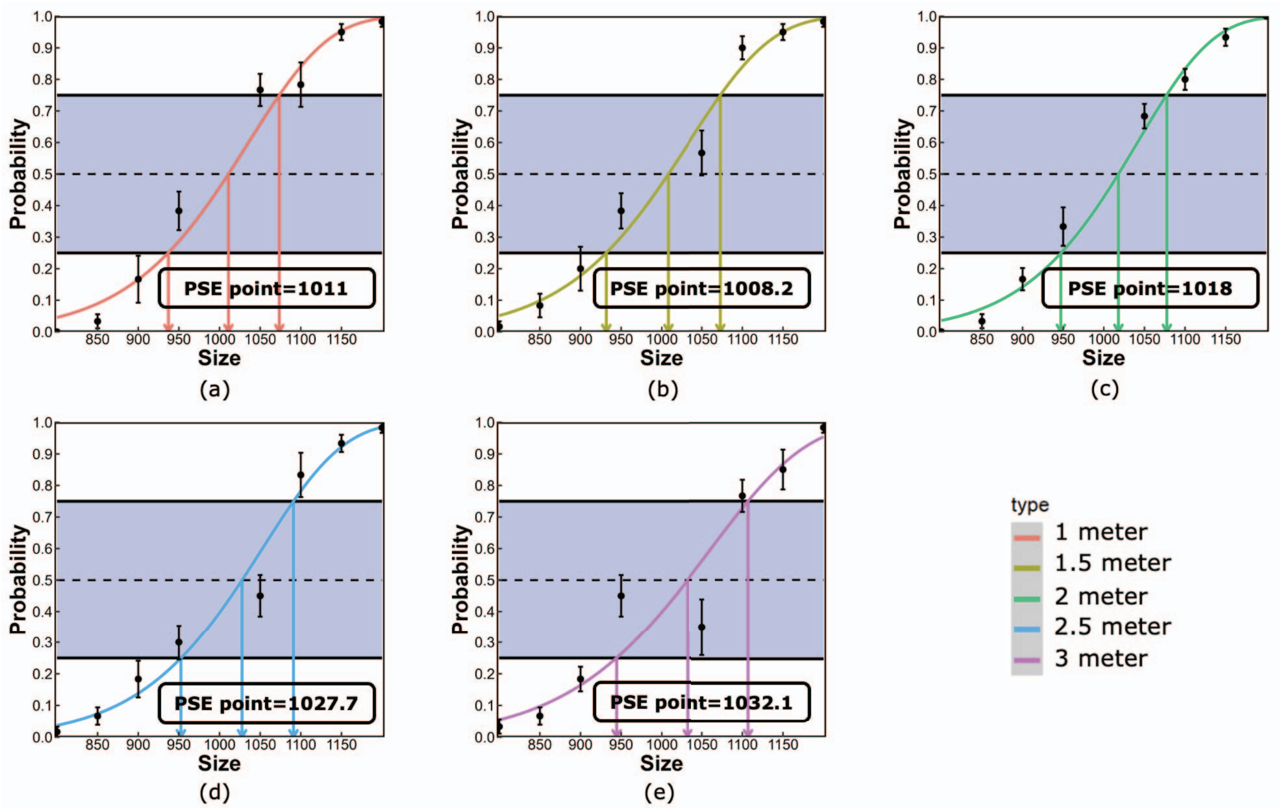

Figure 3: The psychometric functions of size discrimination at different distances are shown in the figure. The x-axis represents the different volumes of virtual cubes, and the y-axis shows the probability that users chose the "stimulus". Panels (a)-(e) represent the distance between the user and the virtual object at 1m, 1.5m, 2m, 2.5m, and 3m, respectively.

When they finished memorizing, the left cube disappeared. There was a 1-second gap during which no 3D graphics occurred in the view. Next, the second cube appeared on the right. The two cubes did not occur in the same place to remove the effect of remnant-cube, which is a kind of visual inertia [11]. The distance between the left and right cubes was 50 cm. When the second cube appeared, we asked the participants "Which one is bigger?" with no time limit to answer, but most of them answered immediately. Participants were informed that answers such as "I do not know/I cannot answer" were not allowed as we were conducting a two-alternative forced-choice task. Finally, the view followed with a 1-second no graphics period, and the next trial repeated the above process.

There were two questionnaires to be completed for each distance. One was named the "Section Symptom Questionnaire". This questionnaire was used to collect status changes of eye fatigue at each distance, with participants asked to rate their status on a scale of 1 to 5 based on the question "How tired are your eyes?". Each participant experienced 48 stimuli (8 stimuli x 6 repetitions) in one condition. We asked them to record their status from the beginning and to record it every ten pairs of stimuli. Therefore, for one user at one distance, we recorded 6 status answers. The other questionnaire was used to collect participants' physical conditions and consisted of five questions: "How tired are your eyes?", "How clear is your vision?", "How tired and sore are your neck and back?", "How do your eyes feel?" and "How does your head feel?", following the work by Shibata et al. [14] as guidance.

The above procedure and questionnaire were repeated 5 times for each user. Therefore, each user experienced 240 pairs of stimuli: 8 (stimuli) x 5 (distances) x 6 (repetitions).

Table 1: The results of Interval of Uncertainty (25%-75%) and JND & PSE values

distance	Interval of Uncertainty (IU)		
	25%	50%	75%
1 meter	937.1	1011	1073.6
1.5 meter	931.8	1008.2	1072.9
2 meter	947.2	1018	1077.6
2.5 meter	952.5	1027.7	1091
3 meter	944.5	1032.1	1107

4 Result and Discussion

In our experiments, we asked participants to indicate whether the presented stimuli (i.e., 800, 850, 900, etc.) were perceived to be larger than the reference stimuli (i.e., 1000). We counted the results where participants chose "stimulus". The results of probabilities under different stimuli are shown in Fig. 3. We then fitted this data into psychometric functions using the quickpsy [12] toolkit. Fig. 3 (a and b) shows the psychometric curves of AR and VR for all stimuli. We included the Interval of Uncertainty (IU) part, which is the 25%-75% range of the response probabilities (shown in purple in Fig. 3). Participants could not reliably detect size changes between two stimuli in this range. Using the sigmoidal function, we calculated the upper and lower boundaries of the IU, where 75% corresponds to the upper boundary of stimuli and 25% corresponds to the lower boundary. In particular, we also calculated the point of subjective equality (PSE) values, which means that participants have a 50% probability of choosing one choice from the reference and stimuli even if they are not the same. As shown in Fig. 3, the PSE value of size discrimination are 1011 (1m), 1008.2 (1.5m), 1018 (2m), 1027.7 (2.5m), and 1032.1 (3m), respectively, when the reference stimulus is 10 $cm \times 10\ cm \times 10\ cm$. We also analyzed the answers for all stimuli and computed the data groups that fit the psychophysical curve. We then performed a two-way repeated measures ANOVA for these data groups, considering the distance and presented stimuli as the independent factors. The results showed that there was no significant difference in distance conditions ($F(4,36) = 1.881$, $p = 0.135$, $\eta_p^2 = 0.173$). We also performed a Friedman test for the questionnaire results, and the results show there were no significant differences among all conditions of distances.

These findings contradict our hypotheses. In other words, we did not find any significant differences in terms of perceptual thresholds of size perception or user experience across different distance conditions. We suspect the possible reasons may be caused by the small-scale range of distances in our experiment (i.e., 1m to 3m). Notably, the ideal viewing distance of Microsoft HoloLens 2 is 2m, where users suffer least from vergence-accommodation conflicts. However, we verified that users could still achieve considerable size perception performance and user experience within a small range of distance centered around 2m (i.e., from 1m to 3m) using HoloLens 2. In other words, we think size perception would not be significantly affected by vergence-accommodation conflicts within this range of distances. As a result, HoloLens 2 seems to be a competent augmented reality headset for visual perception experiments with reduced bias from vergence-accommodation conflicts in future research.

5 Conclusion

Understanding and quantifying human perception has garnered more attention among researchers, as it carries the potential to influence the progression of more efficient interaction and visualization methodologies for AR. Nonetheless, there is a deficiency of direct studies that specifically tackle the precision of size perception at varying distances in AR. In our research, we performed a sequence of psychophysical tests designed to measure the perceptual thresholds for distinguishing the size of digital objects. Our observations unveiled that observing objects at varying distances from 1 meter to 3 meters did not significantly influence size perception. These insights imply that augmented reality can efficiently facilitate training and simulation applications within the examined distance spectrum. Moreover, our study suggests that HoloLens 2, having lesser bias from vergence-accommodation conflicts, displays potential as a competent augmented reality headset for carrying out visual perception experiments in prospective studies. In the future, we also plan to explore the impact of varying horizontal distances on object size perception, particularly in relation to its potential implications for data visualization.

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