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Can You Perceive the Size Change? Discrimination Thresholds for Size Changes in Augmented Reality

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Abstract. Existing psychophysical experiments show that size changes of objects could influence the human perception of objects properties (e.g., shape or weight) in the physical surroundings. On the other hand, Augmented Reality (AR) is an interactive toolkit that allows the integration of virtual objects and real-world environments. However, the absolute detection threshold of size changes on virtual objects is not clear in AR, limiting human perception and experience in AR. In this paper, we designed a pilot study and two psychophysical experiments to explore the humans' ability towards the range of the detection threshold of size changes on virtual objects in AR. Our experimental results show that the range of the detection threshold of size changes is 3.10%–5.18% (reference is a $10 * 10 * 10 \text{ cm}^3$ cube). We also calculated the value of the point of subjective equality ($PSE = 4.00\%$), which means that users react 'same' with 50% probability upon the given stimulus.

Keywords: Augmented Reality · Size discrimination

1 Introduction

A number of studies have recently investigated object perception in Virtual Reality (VR) [10] and Augmented Reality (AR) [4]. Size perception is critical for users to understand the virtual environments [22], which enhances the interaction between humans and virtual objects in both the virtual and physical surroundings. In addition, size changes of virtual objects could induce some illusions in AR, such as weight [17] or satiety [15]. Such illusions [21] have the potential to help us understand virtual object perception.

To further investigate the effect of size perception on virtual objects, Helbig and Marc explored the human's ability of size discrimination [13] by utilising a distortion lens to change the heights of objects. Their experimental results demonstrate that changing the visual stimuli could influence size discrimination performance when visual and haptic shape information was available. However,

they did not calculate or measure any thresholds in their experiments. Hence, Thomas conducted several studies [22] on users' ability of spatial size perception (i.e., width and height) for virtual objects with different colours in VR. The results reveal that the users could perceive the height and width of the virtual object very close to the reference object (height: less than 1.5mm, width: less than 2.3mm). These works show that even though human eyes are susceptible to size changes on objects, there still exists a noticeable difference in size on human observation, and those tiny differences could influence people interactive experience.

Even though some works have studied the detection threshold of size perception in virtual or physical environments, there is no current work exploring humans' ability to discriminate size in AR. However, understanding the tolerance of virtual objects size could benefit the stakeholders to help create and evaluate virtual object prototype design in AR. For example, an AR modeller or designer could design an adequate and reasonable 3D virtual push-button for users to perceive the significantly changeable size during different statuses (e.g., on/off). Hence, this paper tries to explore the humans' ability of size perception in AR. Specifically, this article investigates the following research questions:

RQ1: Is there exist some different size changes but human eyes could not distinguish in AR?

RQ2: What value or range is the detection threshold of size changes that human could not identify in AR?

To solve these two questions, we proposed two psychophysical experiments to investigate size discrimination in AR. Specifically, we designed one pilot user study and two different user-perception experiments based on the two-alternative forced-choice (2AFC) method: one experiment for narrowing down the interval of users' size discrimination gain and another experiment designed for more delicate unity gain. Our experimental results show that the point of subjective equality (PSE) value is 4.00%, indicating that the user at this point has a 50% chance to estimate the size difference.

2 Related Work

2.1 Size Perception Augmented Objects

AR could provide a direct link between physical reality and virtual information about the real world [3]. Still, the measuring perception level would become an essential indicator of how AR integrates into human life. Meanwhile, size as a very significant indicator is often defined as a study variable. Ahn et al. compared whether different AR-HMDs can affect human perceived object size [2]. Their results showed that users tend to overestimate the size of objects when using handheld displays, and people could have an estimating bias on the object size in AR scenarios. In addition to directly changing the graphics in the HMD, it

is also possible to influence the size perception by controlling the depth of the virtual object. Dey et al. demonstrated that visual clutter in AR reduces the discernibility of occluded objects and decays depth judgment [11]. Moreover, Diaz et al.'s work show that changes in object depth could influence the user's judgment of object size in AR [12]. However, in recent years, due to innovations in hardware such as LIDAR, influencing the subjective feelings of objects directly by changing the depth of the graphics has become less mainstream. Another example [14] is that the user's perception of the virtual object's size can also manipulate by distortions of FOV (field-of-view) in a video see-through AR-HMD. However, the notable disadvantage of this approach is that it could affect the user experience and even cause sickness.

2.2 Two-Alternative Forced-Choice Method

Researchers always use three classical psychophysical methods [6] (e.g.: adjustment, serial exploration and constant stimuli) to study thresholds in psychophysical experiments. Since the subject cannot specify the threshold himself in the constant stimulus approach, the experimenter calculates the threshold based on his response probability. Therefore constant stimulus method is more respected. As a typical representative of the constant stimulus, the two-alternative forced-choice (2AFC) [7] method is well suited to explore thresholds in our experimental condition. 2AFC is that subjects were given two independent stimuli within the same trial, and they were forced to choose one between two stimuli at the end of the trial. The observer was not allowed to say "I do not know", "I am not sure", or "I did not see anything". The two-alternative forced-choice (2AFC) method could more closely approximate indistinguishable thresholds. It minimizes subjective judgments (e.g., expectations), and the series of randomly ordered, discrete values of the stimulus provides a more honest probability of the stimulus. Rolland et al. utilized the 2AFC method [18] to render virtual objects in a binocular HMD with a depth-aware manner. Their results showed that the accuracy was 2 mm and precision was 8 mm when rendering depth in the HMD. The results of those above experiments show that the 2AFC method could get relatively accurate thresholds for virtual objects.

3 Psychophysical Experiment

In this section, we performed one pilot study and two user perception experiments to identify the minimal height increase for the virtual cube and determine the detection threshold for height perception of virtual objects in augmented reality. Those two studies aimed to fit the psychometric functions that describe the detection thresholds of height increase.

We used an HTC Vive HMD with Stereolabs ZEDmini camera to observing an augmented world, and utilised a hand controller as our grasping proxy (Fig. 1). The virtual scene was developed by Unity (2018.4.30f) and running on a desktop (AMD Ryzen9 3950X 16-core 3.49 GHz, NVIDIA GTX 3080, Windows 10 Pro).

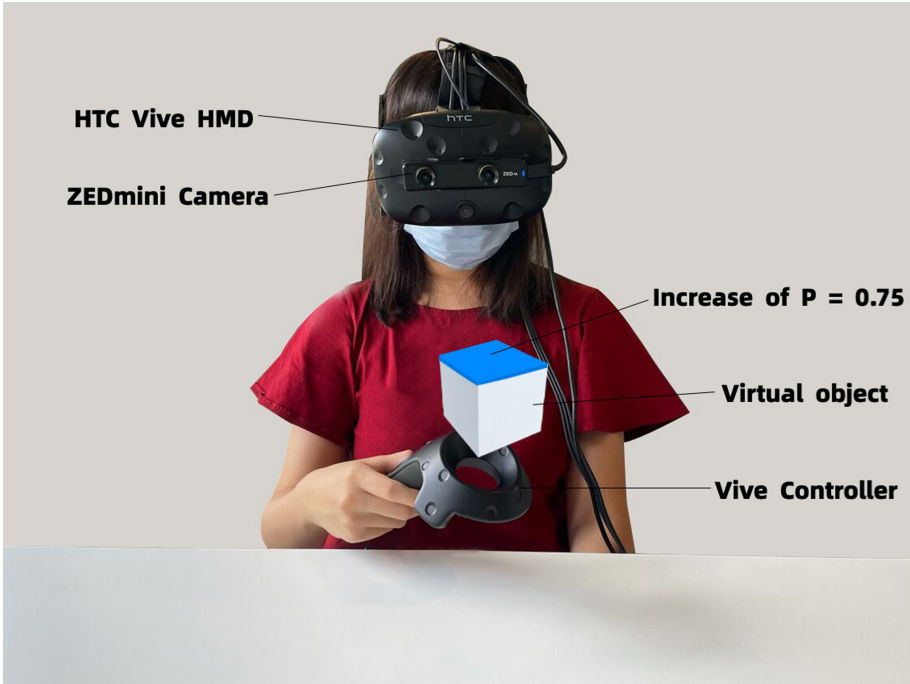


Fig. 1. The user is holding a hand controller with a virtual object above it. The blue part in the cube is the 5.18% increment, denoted as the discrimination threshold's upper boundary. (Color figure online)

The Vive HMD display resolution is 2160×1200 pixels and the field of view is 110° with 90FPS. The physical scene of surroundings was captured by a ZED mini camera with 60FPS at its default setting of 720P.

3.1 Pilot Study

In this pilot study, we applied the aforementioned two-alternative forced-choice task in [19] to test the validity of size discrimination in the augmented virtual objects. Following the experiment setup in [22], we also define changing height as the size discrimination variable.

Two participants, one male and one female, all right-hand, were recruited for this experiment. The average age was 22 years old. They both have limited AR using experiences. The experiment task was to answer whether two virtual objects are the same by grasping and rotating the hand controller. The order of two virtual objects shown in each trial is one in standard $10 * 10 * 10$ size cube and another in $10 * 10 * \text{height-changed}$ cube. The range of height-changing is from 1%–20%. Each height-changed trial was repeated three times. Therefore, each participant should discriminate in $20 \text{ stimuli} \times 3 \text{ repetitions} = 60$ comparison trials. The order of comparison trials is entirely random. Observation time and

interval time were consistent for every trial throughout this study. The entire experiment lasted approximately one hour.

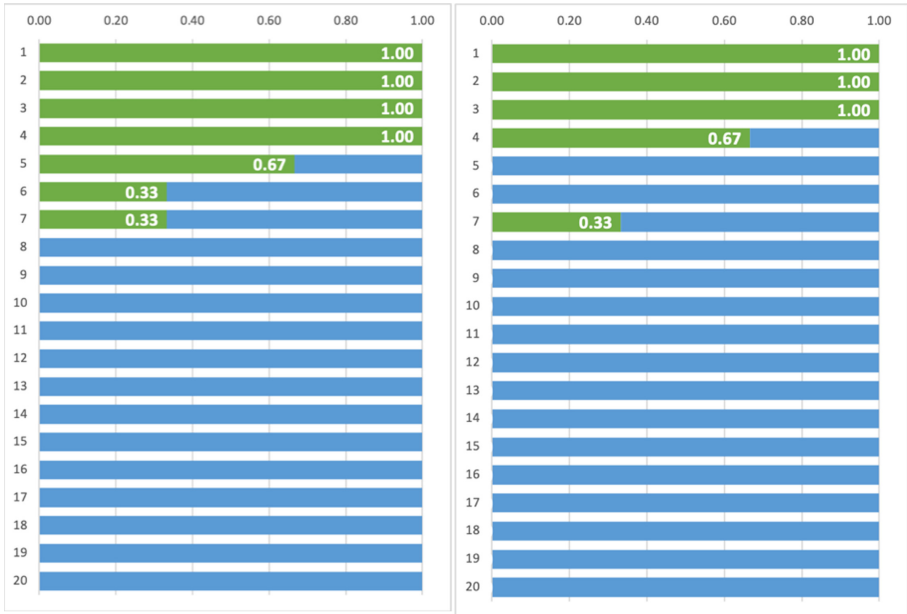


Fig. 2. The image is the analysis result of two users. The green parts are users think the probability of two objects have the same height, and the blue parts are users think the probability of two objects have different heights. (Color figure online)

The result were shown in Fig. 2. We observed that the phenomenon of size discrimination happened in all subjects, which responded to RQ1. All subjects could easily distinguish between the two virtual objects when the growth height was more than 8%. This result supports our continued exploration of RQ2 and allows us to narrow the increasing range to 0%–7%.

3.2 Experiment 1: 0–7 Range Increasing

This experiment applied a two-alternative forced-choice method to measure the participants’ ability of size discrimination towards a specific range for virtual objects in AR. Meanwhile, we want to narrow the increased range for precise threshold and determine an accuracy step through Experiment 1.

Participants and Task. Five participants, all males, all right-hand, were recruited for this experiment. The average age was 26.8 years old (SD = 0.837). We define the score of AR experience in 0-None, 1-seldom, 2-often, 3-always. Thus, the average score of AR experience is 1.8 (SD = 1.304).

The experiment task was to distinguish the height change of virtual objects through grasping and rotating the hand controller. Each participant was required to wear the HMD and grasp the hand controller, sitting on a chair with a relaxed posture. The participants could lift and rotate with free exploration to observe the virtual object's height and compare it to the reference stimuli rendered before. The height of the lift was not controlled; the participants were asked to lift the virtual objects from the surface. Upon the stimuli finished, an all-black view would be induced to the virtual scene. Then the participants were required to offer the answer in the 'same' or 'not same' orally about stimuli compared with reference as soon as possible. The experimenter would record the answer provided by the participants, and other answers, such as 'I don't know'/'I cannot answer' is not allowed.

Procedure. Before starting the experiment, participants were asked to sign the pre-questionnaire with demographic information for the experiment and agree to record data for the experiment. In the beginning, the experimenter declared the experiment task and basic procedure to participants orally to let them be familiar with the experiment. Due to the HMD sickness and limited camera resolution, participants were recommended to move the hand controller more to observe virtual objects rather than moving their heads.

Each experiment includes two parts, a training session and a testing session. The goal of the training session is to help the participants fully understand our experimental setup and procedure, so the data would not be recorded in the training session. Each trial in the training section is divided into four parts: reference observing, rest, new-stimuli observing, and end-trial rest. The reference observing section asked the users to memorize the size of virtual objects; therefore, the time is no limit. After the participants think they remembered the virtual object size, the all-black view was rendered in the virtual scene to allow the participants to rest for 5 s and then a new stimulus would appear on the hand controller. The participants were allowed to observe the new stimulus for only 5 s, and after 5 s, the all-black view would back. Next, the experimenter would ask the participants, "Do you think this stimulus is the same with reference?" After got the 'same' or 'not same' answer from participants, they were allowed to rest for 10 s until the subsequent trial. The training section would repeat six trials. After the 6-trials training section, Participants still have the right to repeat it until they agree to enter the testing section. The procedure of each trial in the testing section is the same as the training section. The only difference is that the 'same' or 'not same' answer would be recorded.

Stimuli. In this study, we provided eight different visual (from 0 to 7) stimuli for object sizes to users and allowed them to compare with the reference cube size. The reference size set as 10 cm, and the other seven virtual cube size augmented in 1%-step levels of extends (i.e., from 1% to 7%). In addition, we implemented six repetitions for each of the eight stimuli. Therefore, each participant should discriminated in total $8 \text{ stimuli} \times 6 \text{ repetitions} = 48$ comparison trials.

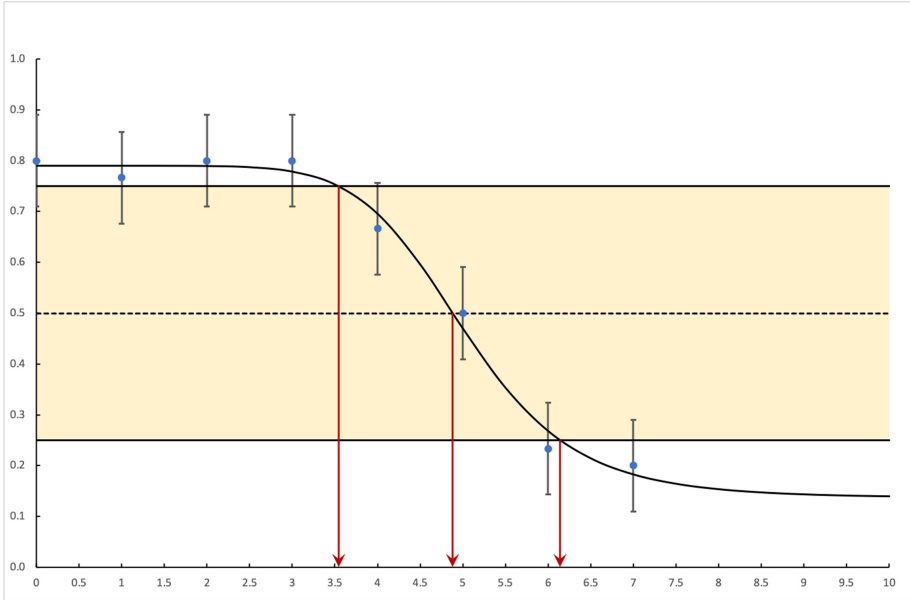


Fig. 3. The result of our pilot study. The size of referenced cuboid is 10 cm and the stimuli with augmented size is from 1% to 7% with 1% as the interval. The error bars show the standard deviation. The dashed line shows equivalent probability (50%) for the perceived stimuli were reacted by the participants as ‘same’ or ‘not same’, comparing to the reference. The yellow shady shows the range of 25%–75% discrimination gain for size discrimination by the participants. (Color figure online)

The order for stimuli was randomized, and the total duration of the experiment was approximately 30 min.

Results and Analysis. Based on our above experiment, the results are showing in Fig. 3. The x-axis shows the percentage of virtual object size increased from 0% to 7%. The y-axis shows the probability that subjects perceive the stimuli as the same as the reference, denoted as P_s . The solid line shows the fitted symmetrical psychometric function. The average of $P_s = 0.596$ (SD = 0.255), and the PSE value is 4.88%. The blue shady part in the figure shows that the range of 25%–75% for the possible discrimination gains is 3.55%–6.14%.

Based on the results of our Experiment 1, we noticed that the previous four stimuli (0%, 1%, 2% and 3%) yield similar level in some extent. Specifically, the probability of perceived stimuli were reacted by the participants as ‘same’ among four stimuli are: Stimuli 0%: $P_s = 0.800$, Stimuli 1%: $P_s = 0.767$, Stimuli 2%: $P_s = 0.800$, Stimuli 3%: $P_s = 0.800$ (All of them are over than 75%). Although both subjects in the pilot study could give all ‘same’ answers in the interval 0%–3%, there is missing a common consent on the size perception results. This result could be due to the fatigue or uncertainty from users when they

explore the unknown environment. Overall, to investigate the more accurate PSE values and more clear discrimination gains, we determined the next user perception experiment with a narrowed range of stimuli (3%–7%). And this would be described precisely in the next module.

3.3 Experiment 2: 3–7 Range Increasing

In order to measure a more detailed ability of size discrimination, we conduct experiment 2 towards a narrower range for size discrimination. From the Experiment 1 results, we observe that the probability of size discrimination is relatively stable in 0–3 interval. Therefore, we choose 3%–7% as a new interval to start our Experiment 2.

Participants and Task. Eight participants, 4 females, all right-hand, were recruited for this experiment. The average age was 23.375 years old ($SD = 2.504$). The average score of AR experience is 2 ($SD = 0.926$).

The experiment task was similar to the task described in Sect. 3.2. In this experiment, we want to explore a more accurate threshold for the height-changed virtual objects that users can not identify through their eyes. Again, we also used the VIVE controller as a rotating handle to display the virtual object and applied it in the same VST(video-see-through)-HMD. And also present the same virtual object in the actual physical scene. Subjects were seated and kept the controller in the same analogue to the setup described in Sect. 3.2. The experiment process in Experiment 2 also keeps the 2AFC method to continue the experiment. Questions and answers are also setting in the same way with Sect. 3.2.

Procedure. The procedure of Experiment 2 was similar to Sect. 3.2. We still divided the experiment into two parts, training session and testing session. Each trial in both sessions also included four same order rounds as Sect. 3.2: observation period for reference, 5-s rest, height-changed stimuli watching period, answer and end-trial rest. In the training stage, compared with Sect. 3.2, we also told users that using cheating methods (e.g., always keep the controller in the same position or use a body part as a reference to measure height) to judge the height changes of objects is not allowed in our experiment. And this will cause the experiment to restart directly. Due to the tiny changes of virtual objects in the testing stage, we would ask participants whether to rest more times to avoid fatigue or being over-skilled. The remainder of the process remains the same as in Sect. 3.2.

Stimuli. This experiment provided nine different visual (from 3% to 7%) stimuli for height-changed objects to users. It allowed them to compare stimuli with the reference cube. The reference height was set as 10 cm, and the nine virtual cube heights augmented in 0.5% as step-level extends the increase from 3% up to

7%. In addition, we still implemented six repetitions for each of the nine stimuli. Therefore, each participant should discriminate in total $9 \text{ stimuli} \times 6 \text{ repetitions} = 54$ comparison trials. The order for stimuli was randomized, and the total duration of the experiment was approximately 50 min.

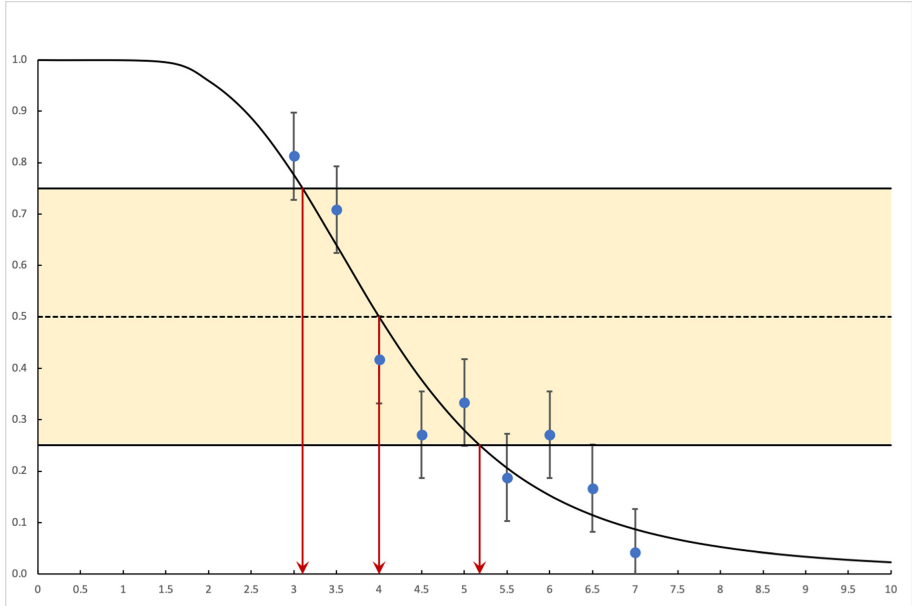


Fig. 4. The result of our Experiment 2. The size of referenced cuboid is 10cm and the stimuli with augmented size is from 10.3–10.7 cm with 0.05 cm as the interval. The error bars show the standard deviation. The dashed line shows the equivalent probability (50%) for the perceived stimuli reacted by the participants as ‘same’ or ‘not same’, compared to the reference. The yellow shady shows the range of 25%–75% discrimination gain for size discrimination by the participants. (Color figure online)

Results and Analysis. Figure 4 illustrates the results of our Experiment 2. The psychometric function reveals the specific discrimination boundaries of virtual object size increment. Similar to the analysis of the previous results, the x-axis shows the increasing percentage of virtual cube height and started from 3%. The y-axis shows the probability that subjects perceive the virtual cube as the same as the reference. The solid line shows the fitted sigmoid function that could match the data. We determined a value from the sigmoid function for the point of subjective equality (PSE). The probability of perceived the stimuli as same as the reference P'_s , is 0.36 (SD = 0.254), and the PSE value is 4.00. The detection thresholds were at gains of 3.10 and 5.18 for responses in which subjects judged the virtual objects rendered with height-increased has a high probability of similarity compare with reference. The detection thresholds were at gains of 3.10 and 5.18 for responses. Subjects judged the virtual objects

rendered with the larger height as same as a reference. These results show that gain differences within this range cannot be reliably estimated when the height increases between 3.10%–5.18%. Moreover, subjects were able to discriminate against size discrimination reliably and efficiently when the size exceeded 5.18%.

4 Discussion

Our exploratory study yielded two key findings. (1) confirmed an indistinguishable dimensional change on virtual objects in augmented reality. (2) explored the precise threshold of size discrimination that is confusing for humans' visual perception. The following two paragraphs discuss our hypothesis based on these results.

We observed that, from the pilot study, there was a phenomenon that even though the height of the virtual objects increased in a tiny percentage, the subjects still perceived it as a standard stimulus. Pelli et al. measured contrast sensitivity on human eyes [16], and they concluded that for an extensive range of targets and conditions, the threshold was 1%. Our experiments show that this sensitivity is still present on virtual objects through AR. However, we observed that at least 3% addition on the object's height could be noticeable for users, which is three times larger than the threshold observed by the naked eye. The possible reason is the influence of the AR device, such as the rendering performance or latency. Additionally, the AR scenario (e.g., button manipulation or object lifting) and the properties of virtual objects (e.g., shape or colour) might also affect the human perception performance. Therefore, we will extend our work to explore the potential influence of these factors in the future.

Our experimental results show that users could identify these two different objects with height increasing over 5.18% and consider two objects identical with a size change of less than 3.10%. Comparing to the previous studies about size perception/discrimination on virtual objects in VR [22], our results demonstrate a little different threshold for size discrimination. One possible reason is that we adopted different experimental methods. Thomas's work conducted an experiment [22] that allowed users to adjust the height of a virtual object by a game controller with the visible reference object. At the same time, we adopted a similar method from [19], allowing users to determine the size discrimination indirectly. Based on the effectiveness of the 2AFC method in other areas, such as image classification [1], we adopted this in our experiment. Additionally, in the process of our experiments, we have also noticed that users might become tired and over-skilled, thus we will also consider choosing other experimental designs which could avoid those phenomenons and also support accurate measurement of thresholds.

Last but not least, our work could also inspire the future follow-ups in the object perception in AR/VR, such as size-weight illusion [8,20], resize grasping in VR [5,9]. In our future work, we will further investigate the relationships between size and other physical cues (e.g., weight, shape). And we also want to integrate other modalities (e.g., audio, haptic) to explore the multi-modal effects

on object perception. Furthermore, we will also explore the detection thresholds corresponding to the size-reduction objects, which replies to diminished reality.

5 Conclusion

In this paper, we performed one pilot study and two user perception experiments to explore and evaluate the humans' ability of size discrimination. The experimental results show that the users could not perform considerably on size discrimination when the object size increases below 5.18%. Our work could potentially benefit those AR designers or developers to help design and evaluate the virtual content with interacting virtual objects, such as picking up or touching the objects. In addition, the probability range of 25%–75% for the size increasing discrimination is 3.10%–5.18%, which denotes above 5.18% increasing has over 75% [19] probability that the participants can reliably determine the changeable height.

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