Chapter

Exploring the Effect of Size on Viewers' Perception of Augmented Reality Objects on Mobile Devices

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Abstract

Augmented reality (AR) has rapidly evolved and is increasingly being integrated into various industries, such as retail, education, and entertainment. One of the aims is to enhance the sense of reality by superimposing augmented digital objects onto the natural environment rather than replacing it. Therefore, integrating "realistically" digital AR objects with the physical environment becomes an essential factor for its success. Besides head-mounted displays, most AR applications run on mobile devices and take advantage of the widely distributed base of hardware, leading to user experience challenges due to scenery and augmentation distortion. While most current research on AR user experience addresses some aspects of user perception within optical see-through augmented reality, there is an existing gap in existing literature on the visual properties that affect user's perception of objects' size in AR experiences on mobile devices. To bridge this gap, this paper presents four experiments using an AR application that was developed on a mobile device and tested by two sets of participant groups. The experiments focused on four visual aspects of AR experiences that impact the perception of object size, including (1) background, (2) grouping of AR objects, (3) observing distance, and (4) observing perspective. The results show that grouping, the observing distance, and the observing perspective can affect the user's size perception of augmented objects, whereas the background on which the digital objects are superimposed has no such effect. This study advances knowledge on the effect of visual aspects on the perception of objects' size in mobile AR.

Keywords: human-centered computing, human-computer interaction (HCI), augmented reality, size perception, mobile device, user studies

1. Introduction

One of the essential qualities of augmented reality (AR) is its ability to enhance the sense of reality by superimposing augmented objects onto the natural environment, rather than replacing it [1]. In doing so, it is essential for the success of an AR application that its properties are represented correctly in their dimensions and scale, which is challenging to AR developers: While scenery and augmentations can become significantly distorted and partly abstracted, impacting a viewer's perception of virtual objects' size [2], the influencing factors are rooted not only in the technical equipment used but also in the perceptually correct enhancement [3].

Technological developments try to minimize such effects, for instance, by the introduction of wearable devices, such as head-mounted displays (HMDs) or smart glasses, by offering a rather stable technological framework presenting information directly in front of the user's eye. For example, a form of heads-up display is a retinal display that "paints" a picture directly on the sensitive part of the user's retina [4]. However, for everyday usage, HMDs show limitations due to their weight and narrow viewing angle compared to the human viewing angle [5]. Moreover, because each HMD device or smart glass has different design configurations and specifications in terms of its parts, users often perceive the same virtual object differently, depending on the AR device in use [3]. Meanwhile, mobile devices supporting AR, such as smartphones and tablets [6], are becoming more powerful and less expensive at a very rapid pace, leading to increasing popularity in real-world usage for AR applications: Alsop [7] outlined an estimated 1.7 billion mobile augmented reality (AR) users worldwide, a rise of 1.5 billion from the 200 million seen in 2015.

However, as most research has gained insight into the viewer's perception of an object's size in VR, depth perception, and exocentric distance in optical see-through AR and others, less is known about the user's size perception in AR applications on mobile devices. The four main variables that affect a user's size perception are the background, the object grouping, the observing distance, and the observing perspective [8], which are difficult to define, especially in a mobile setting. As boundaries between physical and digital increasingly blur due to the augmentation of digital information onto the physical world in human-computer interaction settings [9], it is necessary for a broad and successful AR adaptation to understand if and how a user's size perception in AR differs from reality.

This research hypothesizes that there is a particular size perception error when people view and observe AR digital objects through the mobile screen within a specific range, and the viewer's perception of the size of AR objects and actual objects is different. This error will change with the distance and the perspective of the AR objects on the screen. In order to test this hypothesis, we developed an AR mobile application that allows the user to generate simple 3D digital cubes and conducted four experiments based on four variables that impact size perception [8], as outlined above. We then examined the effect on viewer's size perception for augmented objects by (1) the AR background, (2) the grouping of AR objects, (3) the observing distance, and (4) the observing perspective. Next, we present the background and related work this research is based on, followed by the methodology applied to run the experiments and the results obtained. We conclude with an in-depth discussion and the conclusion of this work and give an outlook on future work.

2. Background

To explore the effect of visual factors on the viewer's perception of objects through AR technology, we need to understand the size of objects at the intersection between digital and physical environments. In the virtual reality environment, for instance, Thomas [2] has studied user perception of an object's size. The study showed participants' understanding and their perception of matching the size of two different-colored virtual objects. The study indicated that participants were able to perceive height and width very close to the target values. Murdoch [10] has studied brightness matching in optical see-through augmented reality. Bremers et al. [11] have discussed two user studies on depth perception, in particular on the perspective cue, and compared perception for different graphical representations of angles. The study indicated that graphical alterations of angles displayed on a screen resulted in more variation between individuals' angle size estimations. Peillard et al. [12] studied exocentric distance perception, i.e., the distance between two objects, neither of them being directly linked to the user, in optical see-through AR. The study suggested that two virtual objects are perceived closer to one another compared with two real objects. Fischer et al. [13] explored how different static visualization techniques influence users' ability to perform perception-based alignment in AR for breast reconstruction surgery, where surgeons must accurately identify the locations of several perforator blood vessels while planning the procedure. Diaz et al. [14] conducted two experiments using a perceptual matching task to understand how shading, cast shadows, aerial perspective, texture, dimensionality (i.e., 2D vs. 3D shapes), and billboarding affected participant perceptions of virtual object depth relative to real-world targets. This paper, unlike the studies mentioned above, addresses the use of mobile phones as a viewing tool and focuses on four visual aspects that affect the viewer's perception of a digital object's size.

2.1 Size perception of digital objects in AR

Augmented reality (AR) offers various situations in which users can visualize and interact to improve their experience and performance in completing actual tasks in everyday spaces [15]. However, with the increased utility and availability of AR technology, its usability aspect has started to draw much more attention lately in the research community [16]. One of the more important breakthroughs for AR vision technology is the size perception in the AR interface. Ahn et al. [16] studied the correct size perception of the augmented object for three representative AR displays. Their focus was more on finding out how people's vision of AR objects differed between devices, such as optical see-through HMDs and mobile devices. Shin et al. [17] have stated that it is necessary to resolve visual differences between different AR devices to obtain mixing consistency. Their focus remains on finding a balance of size perception and colors of augmented objects between different devices so that the size of virtual objects and colors seen by everyone is balanced between different AR devices. Rolland et al. [18] have investigated more about depth perception and size perception in AR from HMD, and the experiments carried out are based on 2D pictures. Thus, the user's size perception of 3D objects is not clearly defined either. Ling et al. [19] have carried out two experiments to explore the effect of the perspective projection, on a wall, on the sense of presence and space perception. They found that the way the digital space is presented is critical for the level of experienced presence and that the field of view, viewing mode, center of projection, and display critically affect the presence and the perceived layout in the digital projection. Peillard et al. [12] stated that, when using an HMD, people tend to perceive virtual objects located on the side farther than the objects located in front of them. Diaz et al. [14] stated that by using a perceptual matching task, people perceive the position of an AR object closer than a real-world object. Swan et al. [20] found a significant difference in distance estimation between the virtual object and the real object. Eggleston et al. [21] suggested that there was a difference in the participants' size judgments between VR and physical environments. Experiments by Luo et al. [22] were consistent across the participant population, and results showed that scene complexity and stereo vision could have a significant impact on user performance in virtual environments to make precise judgments on the size of virtual objects. Stefanucci et al. [23] employed size-judgment tasks to measure the perceived size of virtual objects displayed on a large screen monitor. They determined that the size of an object in the virtual environment is underestimated compared to an object in the real world. This difference was smaller when viewed in stereo. Thomas [2] has researched to explore the user's ability to judge the size of an object relative to a second object of a different color in the virtual environment. Kelly et al. [24] found that egocentric distances in virtual environments are frequently underestimated by up to 50% of the actual distances. In summary, many researchers have studied the size perception of objects in VR and the difference in size perception by the viewer between different AR devices, but to our knowledge, no one has focused on the effect of different factors on user size perception of AR on mobile phones. We believe it is necessary to investigate the effect of viewer's size perception of AR displays on the mobile device in-depth for its further widespread applications.

2.2 Size perception of physical 3D objects

Judging the sizes of objects accurately is necessary for organisms and machines to operate successfully in the world [25]. People's size perception of AR objects is also based on their basic size perception of real objects. People trust their intuition and feel that their perception is correct, but there is a cognitive bias that occurs when people are processing and interpreting information in the world around them, and this may affect the decisions and judgments they make [26]. Long and unreliable delays are involved in processing visual information in the retina, and ineluctably, such delays result in spatial errors [27]. One of the important factors in perceptions by people is the size perception of objects. The perceived size of an object depends on factors including: 1. the actual size of the object, 2. the distance of the object from the eye, 3. size constancy: This phenomenon results in objects of known size tending to appear constant in size regardless of their distance, and 4. perspective of the observer [8]. Because size constancy results in objects of known size tending to appear constant in size regardless of their distance [8], it will not be studied in this research. Gepshtein and Banks [28] have carried out experiments to estimate the distance between two parallel surfaces to explore the combination of vision and haptics in size perception. Peschel and Orquin [29] have studied surface size effects on visual attention. Foley [30] found that visual angles correspond closely to physical angles. A 3D object seen from different views forms quite different retinal images, and many different objects can form identical retinal images [31]. We extend this research and build on the study of people's visual size perception of objects in AR and focus on four visual aspects, including: 1. the background, 2. object size, 3. observing distance, and 4. observing perspective.

3. Methodology

To understand the viewer's size perception of AR objects in handheld mobile devices and how the viewer's size perception in AR differs from reality, we conducted a series of four experiments. All four experiments were built on the theory of the classical psychophysical method [32] and were designed to examine the effect of four aspects that were found to impact size perception by the viewer [8] in AR:

- Experiment 1 investigated the effect of environment, whether the AR context influenced viewer's visual judgments of size, and how much of the size variation from AR objects could be correctly observed by the average participant.
- Experiment 2 investigated the effect of grouping, viewer's visual size judgments of multiple AR objects.
- Experiment 3 investigated the effect of distance and whether there is a difference in the perception of an object's size between the actual and digital AR objects. If so, whether this difference is related to the observing distance between the object and the viewer.
- Experiment 4 investigated the effect of perspective—whether the viewer's size perception and the difference between AR objects and actual physical objects were related to the viewing perspective and angle.

At the end of each experiment, and finally, the results of the experiments were analyzed.

To conduct the following experiments, a Unity-based AR system was developed, allowing users to place digital objects on a mobile phone interface into the existing physical environment, using AR core[1], AR-Foundation[2], and a placement indicator asset[3].

The system interface consists of 4 sets of control buttons (**Figure 1**): According to "Cognitive Augmented Reality Cubes" that have been implemented throughout cognitive AR research [33, 34], the user is able to place a neutral white 30x30x30 cm AR cube by clicking the button in the upper left corner (**Figure 1, A**). Selecting the AR cube is marked by a green bottom edge to distinguish selected from unselected AR cubes. At the lower right corner of the interface, the user can rotate (B), scale (C), or delete (D) AR cubes. Furthermore, the user can touch the screen to move and drag the cube to its desired position.

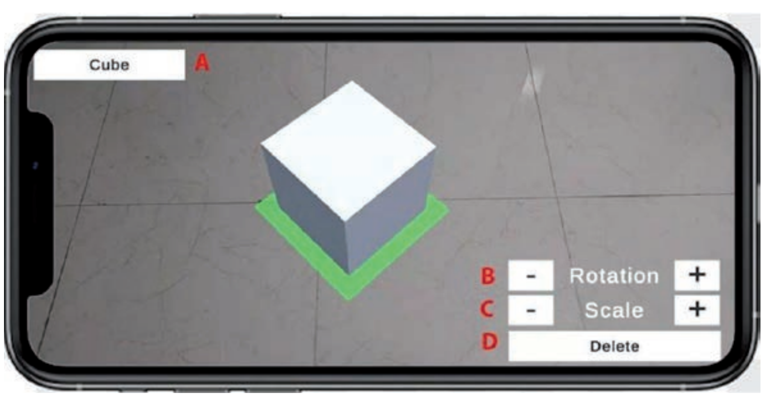

Figure 1.
AR application mobile interface: showing (A) cube placement button, (B) rotation button, (C) scale button, and (D) delete button.

[1] Download and install directly from Unity's Package Manager.
[2] Download and install directly from Unity's Package Manager.
[3] Download from Github: https://github.com/fariazz/ARFoundationPlacementIndicator.

4. Experiments

To test our hypothesis, we conducted four experiments on the effect of the background environment (4.1), the object grouping (4.2), viewing distance (4.3), and viewing perspective (4.4) on the viewer's perception of AR objects' size. A total of 15 participants (10 males, 5 females, mean age 28.6 years) were recruited from the researcher's personal network to conduct Experiments 1 and 2, and a total of 30 participants (19 males, 11 females, mean age 28.6 years) were recruited to conduct Experiments 3 and 4. The experimental setup consisted of a Xiaomi Redmi Note 8 T mobile phone and a defined observation point from which participants conducted the AR experiments. At the beginning of each experiment, each participant was given information about the background of the experiment and was then guided to the observation point, the start of the AR experience.

4.1 Environment

In the first step, we examined how the environment influenced viewer's visual judgments of the AR objects' size and how much of the change in the size of AR objects was correctly observed by the participants. The experiment followed the psychophysics theory of the "method of limits" that indicated the sensory threshold by gradually increasing or decreasing the magnitude of the stimulus presented in discrete steps, hence gradually increasing the size difference until the participants noticed the difference [35]. To do so, we defined an "AR group" and a "control group" for the experiment. In the AR group (**Figure 2**, left), two AR cubes were placed on the ground at a distance of 2 meters from the observation point [18] on the AR operator interface of the handheld device: the left AR cube with the original size of 30x30x30cm and the right AR cube with 105% size. In the control group (**Figure 2**, right), the background of the two AR cubes was replaced with black, and all the other conditions stayed the same as in the AR group (**Figure 2**).

The experiment started with the first stimulus, a 5% size difference, i.e., an AR cube of 100% size and an AR cube of 105% size. Each participant was given 30 seconds to intuitively determine if there was a size difference between the two AR cubes or not. If the participant noticed a size difference, the participant was asked which of the cubes felt larger. If the participant did not notice a size difference, no further questions were asked, and the participant proceeded directly to the control group. After a 30-second break, participants were shown the control group experience, including the exact same situation just on a solid black background. The participant was also given 30 seconds to answer the same question as in the AR group. If all the participants had judged the AR cube size difference correctly at a 5% difference, the

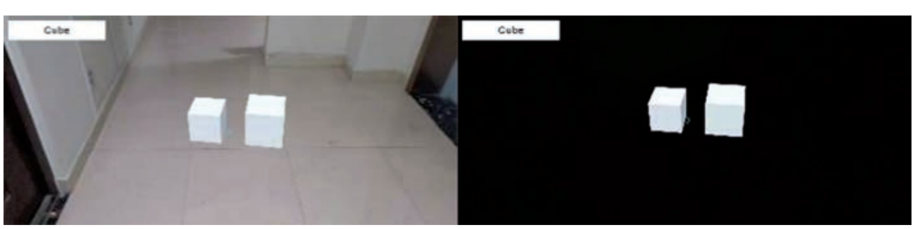

Figure 2.
Two AR cubes with a 10% size difference (2 meters away from observation point) - AR group (left), control group (right).

experiment would have ended. Otherwise, the experiment was repeated by increasing the cube size difference by 2.5% [2] each time until all the participants could correctly judge the two cube sizes. The whole experiment took about 2 minutes per participant.

4.2 Grouping

Next, we examined people's visual size judgments of multiple AR objects by employing the psychophysics measure "just-noticeable difference," which states the just-noticeable difference (JND) is not a fixed quantity but rather depends on how intense the stimuli are being measured [36]. We placed three AR cubes at 2-meter distances, starting with 5% size differences: one in original size, one with a 5% size decrease (95% of original size), and one with a 5% size increase (105% of original size), according to Weber's Law [37]. These three cubes were placed on the ground in parallel, and the order in which they were presented to participants was random (**Figure 3**).

First, the participant was asked at the observation point if a size difference exists between these three AR cubes. When the participants noticed a difference, they were asked to select three objects from large, medium, and small. When the participant did not notice a difference, the experiment ended for that participant.

Suppose that at 2 meters, everyone was able to arrange the objects in the correct size; the experiment was no longer conducted by enlarging the object gap but by increasing the distance to 4 meters instead, to test the effect of distance on the group. In these cases, whenever someone could not identify the size difference between three AR cubes, the 5% difference in size was increased to 7.5%, and the experiment was repeated at 2 meters. Size differences increased by 2.5% each time until all participants aligned the three objects correctly. The 4-meter experiment was then conducted for verification. The whole experiment took about 2 minutes per person.

4.3 Viewing distance

Next, we examined whether there was a difference in viewer's size perception between a physical object and an AR object and whether it was related to the distance of observation. In this experiment, five AR cubes were visualized that looked the same as the actual, physical cube, only differing in size. The selection of AR cube

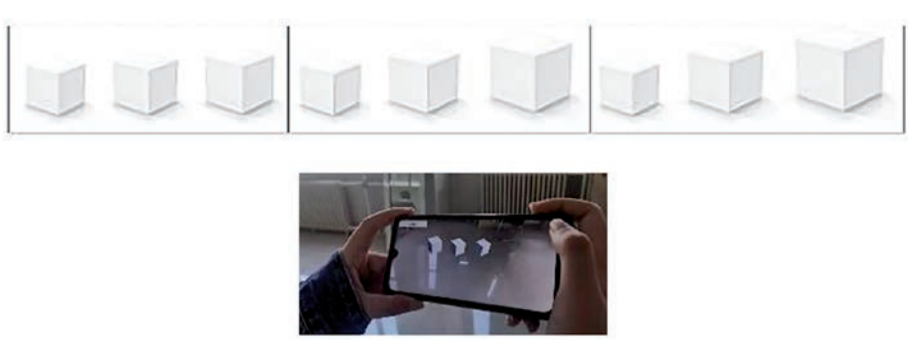

Figure 3.
AR Cubes with 5, 7.5, and 10% size intervals (above, from left to right) and as shown on the mobile interface during the AR experience (below).

quantities was based on one of the principal paradigms to explore the capacity of spatial attention, which has been the multiple objects tracking task. Subjects can track a subset of up to five objects [38]. The interval of the cube's size change was set at 10% according to Experiments 1 and 2, resulting in five AR cubes with 80% size, 90% size, 100% size, 110% size, and 120% size. They were arranged side by side and equally spaced on the interface of the mobile phone, placed on the ground at the same angle as the physical cubes (**Figure 4**).

Figure 4.
Real cube and AR cube with the same size (left) and AR cubes with four different sizes, the interval of variation is 10% (right).

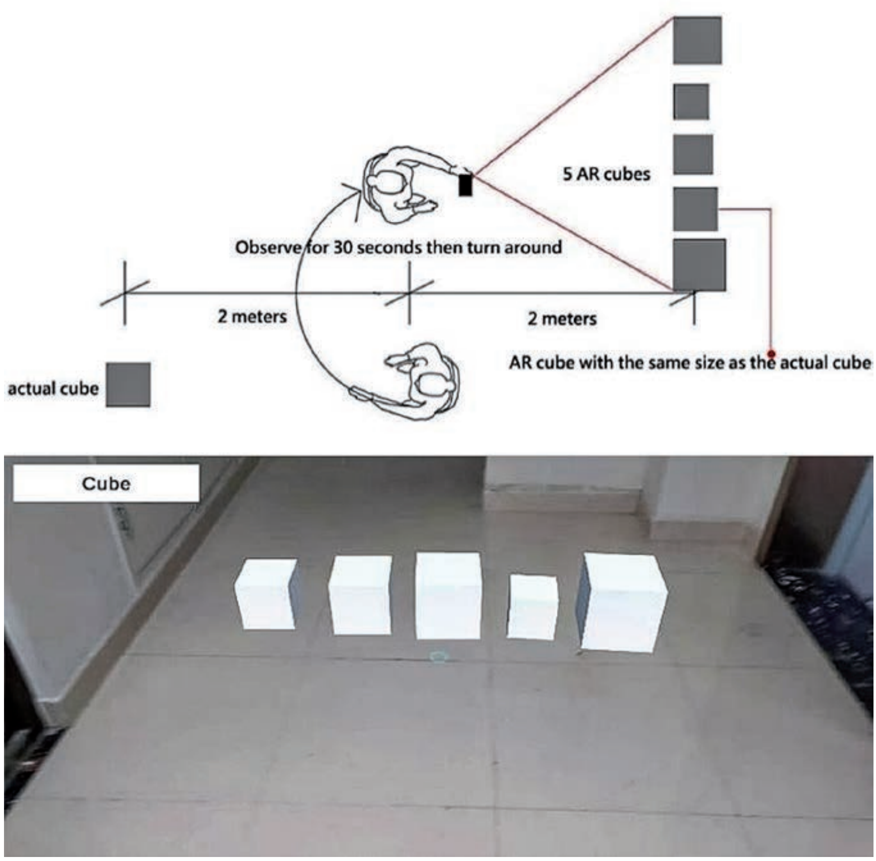

Figure 5.
Experimental procedure (above), and during AR experience (below).

This experimental setup consisted of two distances as control groups to detect the effect of different distances on human size judgments of AR objects [39]. Each participant was asked to look at the physical cube from the observation point for 30 seconds. Then, the participants were asked to turn around, hence not being able to see the physical cube. After a 30-second break in between, the five AR cubes were then shown to participants in the AR application at a 2-meter distance from the observation point on the screen, one of which was the same size as the actual cube. The order of the five AR cubes was randomly displayed. Each participant was then asked to choose an AR cube of the same size as the physical cube shown. When all participants have completed the experiment at 2 meters, they move on to the next experiment at 4 meters, following similar conditions. The whole experiment took about 3 minutes per participant (**Figure 5**).

4.4 Viewing perspective

Finally, we examined how participants' different observing perspectives would affect viewer's size judgments of AR objects. In this experiment, five AR cubes were visualized to look the same as the physical cube, only with a different size. Similar to Experiment 4.3, the interval of the cube's size change was set at 10% according to Experiments 1 and 2, resulting in five AR cubes with 80% size, 90% size, 100% size, 110% size, and 120% size. Cubes were arranged side by side and equally spaced on the interface of the mobile phone, placed on the ground at the same angle as the physical cube (**Figures 6** and 7).

Taking [40] as a reference, we set up two angle experiments, one of which was done with a 90-degree angle. The other experimental setting was at an angle of 45 degrees [16]. Participants were first asked to stand at the observation point and to observe the actual cube at 45° to the left, 2 meters away from the observation point. Then, they took a 30-second break, after which they were asked to turn around and pick out the AR cube on their phone screen that matched the size of the actual cube they observed. Next, the same experiment was conducted 2 meters from the observation point, 45° to the right. This was followed by the same experiment with 2 meters from the observation point, 90° to the left, and 2 meters from the observation point, 90° to the right. All conditions were the same for each experiment, except for the angle of observation. This whole experiment took about 3 minutes per participant.

Figure 6.
AR cubes at 45° (left) 2 meters away from observation point.

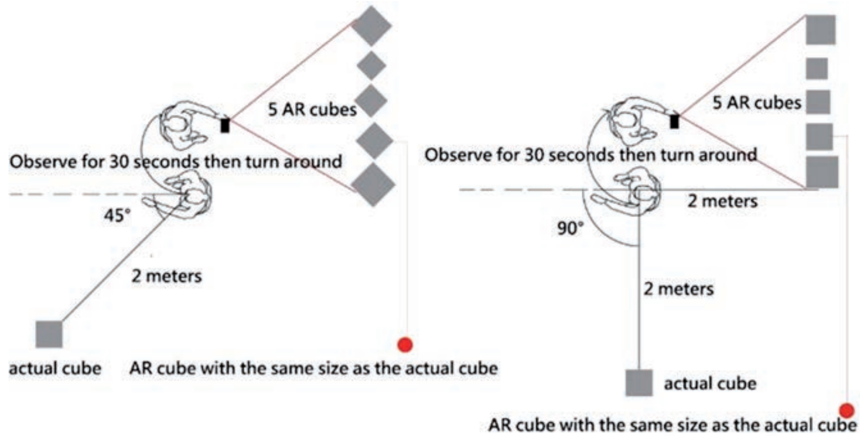

Figure 7.
The steps of the experiment at the 45° and 90° directions.

5. Results

5.1 Environment

The collected data were analyzed using a one-way ANOVA. When the size difference between two objects was 5%, the majority of participants (80%) were not able to accurately judge the size difference between AR cubes with the natural environment background, and almost half of the participants (46.7%) were not able to accurately judge the size difference when the background was black. Nevertheless, when the size difference between objects increased to 7.5 and 10%, the same number of participants could not identify the size difference between AR cubes on a physical or black background (26.7% at 7.5% increase and 7% at 10% increase), as shown in **Figure 8**.

These findings indicated that the size differences between AR objects could affect people's size judgment ($p < 0.05$); however, no significant effect between AR

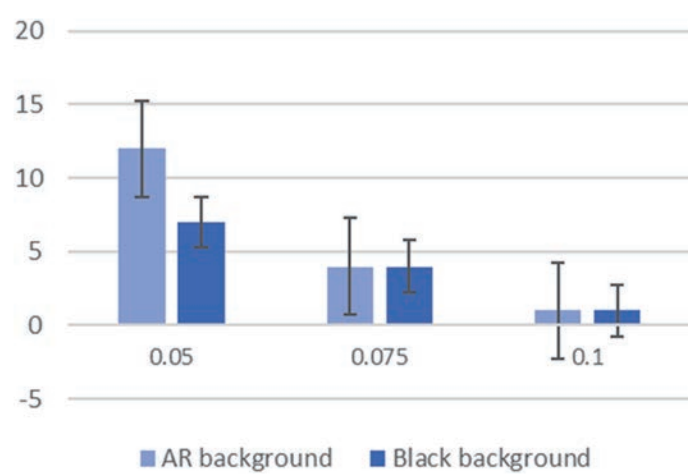

Figure 8.
Number of participants who cannot correctly determine the sizes of two cubes.

background and black background was found (p = 0.677). This outcome suggests that a realistic background does not affect people's misjudgment of the size of AR objects; hence, the effect of the background behind the AR objects can be ignored in the subsequent experiments.

5.2 Grouping

Our findings from Experiment 2 indicated that when there were three AR cubes grouped, all participants (100%) were able to tell that there was a size difference between these three AR cubes compared to the situation when there are only two AR cubes: results showed that at a difference of only 5% in the size of each cube, all people were able to identify the largest cube, but only about a third (31%) of the participants could fully distinguish the size difference between the three AR cubes. When the size difference between three AR cubes increased to 7.5%, the proportion of the participants who could distinguish the size difference increased to 86.7%. When the size difference between the cubes increased to 10%, all participants (100%) could identify the largest and smallest cubes correctly (**Figure 9**). Then the experiment was repeated at 4 meters [39], which also proved that all participants (100%) could identify the largest and smallest cubes correctly.

These results revealed that on mobile devices, people are able to identify the largest AR objects, but there was a certain amount of error (69% at a 5% size difference and 13.3% at a 7.5% size difference) in determining which one is the smallest. Furthermore, even when the size difference between AR objects is small, such as 5%, one can still distinguish the largest of them. However, it is easy for people to confuse the smallest and middle-sized objects, which decreases as the difference in the size of the objects increases. Besides, when the size difference between AR objects is large enough, such as 10%, people were able to recognize the difference in size between all AR objects 100% of the time. The result from this experiment is an essential prerequisite for subsequent experiments.

5.3 Viewing distance

The data collected from Experiment 3 were analyzed by ANOVA. At 2 meters, a third (33.3%) of the participants chose the correct AR cube that was the same size as the physical cube. A minority of the participants (10%) chose an 80% decreased-size

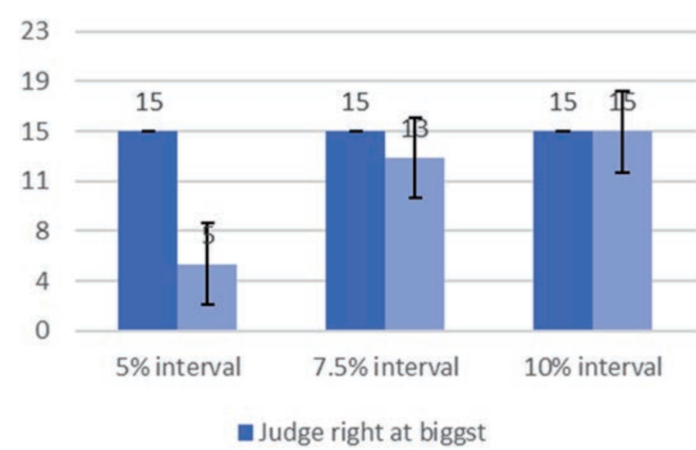

Figure 9.
Number of participants who have made the right choice.

AR cube, 16.7% of the participants chose the 90% decreased-size AR cube, 23.3% of the participants chose a 110% increased size AR cube, and 16.7% of the participants chose the 120% increased size AR cube. At a 2-meter distance, 40% of participants underestimated the size of the AR cubes, and 26.7% of participants overestimated the size of the AR cubes. At 4 meters distance, almost half of the participants (46.7%) made the correct choice, 3% of participants chose the 80% decreased-size AR cube, and 20% of participants chose the 90% decreased-size AR cube; over a quarter (26.7%) of participants chose the 110% increased size AR cube, and 3% chose the 120% increased size AR cube. At a 4-meter distance, almost a quarter (23%) of participants overestimated the size of the object, and almost a third (30%) underestimated the size of the object. The distance from the observing point was found to significantly influence the participant's judgment of the object's size ($p < 0.05$) (**Figure 10**).

These results suggest that the probability of people judging AR digital objects to be the same size as physical objects increases, and the probability of underestimating the size of objects decreases when observing distance increases. The margin of error that people choose tends to be more than a 10% difference in size.

5.4 Viewing perspective

According to our findings, the comparison between the angle on the left and the angle on the right shows that there is not much difference in people's choices (**Figure 11**) (The correct size was selected by 20% of participants at 45 degrees from either the left or the right, by 40% of participants at 90 degrees from the left, and by 37% of participants at 90 degrees from the right). Whether at 45° or 90°, participants made similar choices when looking at the left or right side. However, when comparing the 45° and 90° angles, it becomes clear that the angle of observation dramatically influences the final choice made by the participants. For instance, at 45°, a total of 5% of the left- and right-hand observations resulted in a choice of an 80% decreased-size AR cube, 22% in a 90% decreased-size AR cube, 20% in the original (100%) size AR cube, 45% in a 110% increased size AR cube, and 8% in a 120% increased size AR

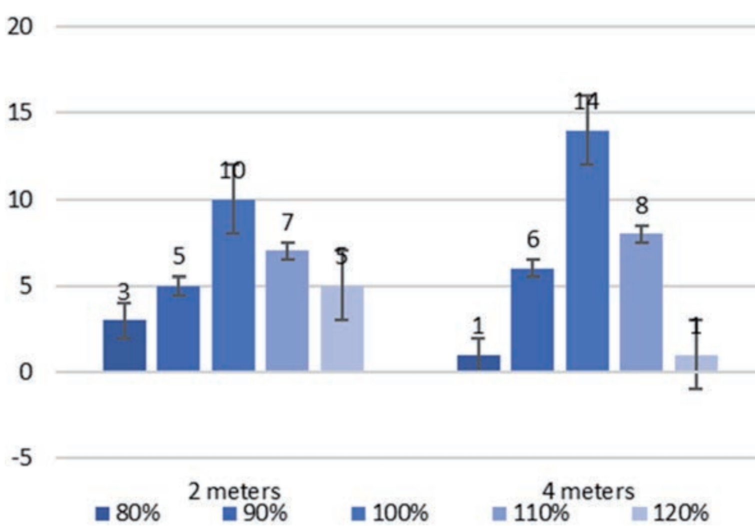

Figure 10.
All types of choices that participants made.

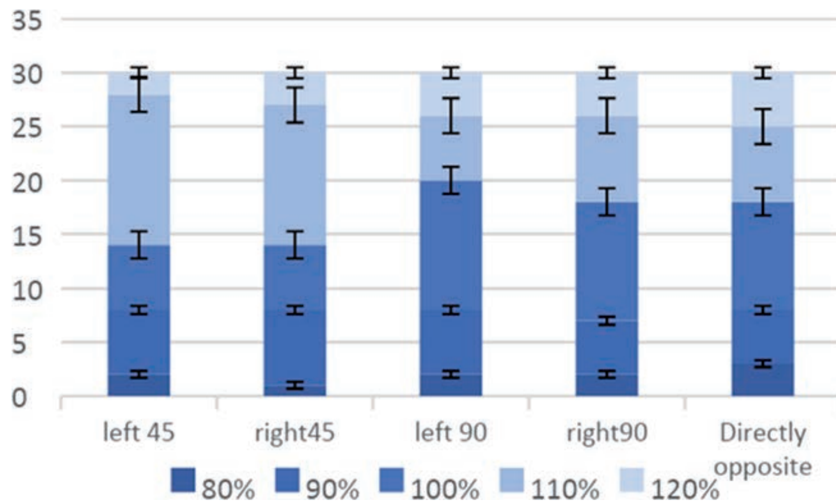

Figure 11.
Comparison of participants made decisions from different perspectives.

cube. This means that a total of 53% of people underestimated the size of the AR cubes, and 27% overestimated the size of the AR cubes after viewing the actual cube at 45°. When viewed at 90°, left-sided and right-sided viewing resulted in a total of 6% of participants selecting an 80% decreased-size AR cube. Eighteen percent of participants selected a 90% decreased-size AR cube. Thirty-eight percent of participants selected the original (100%) size AR cube, 24% of participants selected a 110% increased size AR cube, and 14% of participants selected a 120% increased size AR cube. This means that a total of 38% underestimated the size of the AR cubes, and 24% overestimated the size of the AR cubes after viewing the actual cube at 45° (**Figure 11**).

These results indicate that more participants made correct judgments (18%) at 90° from the observing point than at 45° from the observing point. However, regardless of whether people were viewing at 45° or 90° from the observing point, a much larger proportion of participants underestimated the size of AR objects if they misestimated the size. Hence, the angle at which an object is viewed does affect one's judgment of the size of AR objects ($p < 0.05$).

6. Discussion

This paper evaluated people's size perception of AR objects and how they differ from the size perception of natural objects. Addressing this problem requires both the development of effective evaluation methods and an understanding of what visual information might contribute to differences between virtual displays and the natural world [23]. Accordingly, a methodology was developed to explore the effect of different factors on people's perception of size through four experiments. The results from the experiments will be discussed below.

6.1 Background and the size of AR objects

Results from Experiment 1 showed that a real environment that is overlaid by digital objects has barely any impact on people's size perception of augmented objects.

Consequently, the location might make a difference to the AR context, but wherever people start using AR applications, it will not affect their perception of the size of the AR object. In addition, the difference in size between multiple AR objects does affect people's visual size judgment of the AR objects. When there are only two same basic AR geometries on the mobile device's screen, most subjects will make the wrong size comparison when the size difference between these two AR geometries is within a small interval. Furthermore, an increasing number of subjects will be able to correctly discriminate the gap between the sizes of the disparate objects. When the size difference between the two AR objects reaches a certain level, such as 10% in this experiment, essentially all subjects can judge it correctly, meaning that a 10% difference in volume size can be used as a threshold for discriminating two AR objects' size differences. In addition, when there are only two AR objects to compare, whatever the objective result may end up being, people subjectively feel that it is a straightforward matter to judge the object's size.

Nevertheless, when the number of objects increases, even if only one object is added, people subjectively believe that it becomes more difficult to judge the difference in size between more objects. This may conclude that even if the difference in size does not change, simply increasing the number of AR objects can make it more difficult to judge people from a subjective point of view. For example, when the size of three AR objects is being judged. Regardless of the difference in size between the objects, participants will be able to tell that the three objects are not the same size, unlike when two objects are judged; some participants think two AR cubes were the same size. This indicates that when there are more references to the same kind of AR object, people are more likely to notice differences in size. Almost all people can tell which is the largest object at any size difference between the AR cubes, but when the difference between the three objects is not large enough, it is easier to misjudge the size of the smallest and middle volumes. That is, with a constant size difference, as more AT objects were compared, people were often able to judge the largest object correctly. However, a greater number of objects did not help people to identify the relatively small object. Therefore, when many of the same AR objects are present simultaneously, the ability of the user to recognize the size of the relatively smaller AR objects is weaker.

Besides, results from Experiment 3 showed that there was a difference in the perception of the AR object's size on mobile devices compared to physical objects. In most cases, people tend to underestimate the size of AR objects that are the same size as physical objects (the same shape). At the same time, a relatively small number of people tended to overestimate the size of an AR object of the same volume as an actual object (the same shape). Some people will underestimate the size of AR objects, and some people will overestimate the size of AR objects within a specific range of size differences, and the needs of each group of people should not be ignored. Moreover, in both experiments, regardless of the number of objects being compared, 10% was a basic threshold at which all people were able to identify differences in object size correctly. It is also to provide a little help for people to build AR applications in the future: what is the smallest interval of size difference from AR objects that people will not distinguish wrongly?

6.2 Distance from observing

The distance of the AR object to the person is the distance from the location where the AR object is located to the human eye, not the distance from the human eye to the phone screen. Experiment 3 indicated that the distance of an AR object to the human eye does affect one's judgment of its size. Only 33% of participants made the right choice at 2 meters, while when the distance increased to 4 meters, the correct rate increased to 46%, a 13% increase in correctness. At 2 meters, the proportion of people who made a choice at 80% size and 120% size is 27%, while at 4 meters, this error rate was only 6%, a rate reduction of 19%. With the choice at 90% and 110%, the proportion was 40% at 2 meters and 47% at 4 meters. Therefore, it can be concluded that if the distance at which people look at AR objects is increased, it can improve people's ability to identify the size of AR objects that are the same as real objects. Furthermore, when the distance is increased, the size difference interval at which people's judgment errors are made gradually decreases, gradually moving closer to being within the 10% size interval. Similarly, from Experiments 1 and 2, a 10% size difference of objects is the threshold of observation. The closer the AR object is to the screen, the greater the error in judging the object's size, and there will also be more people choosing objects with larger size errors.

6.3 Perspective from observing

Experiment 4 showed that the angle of observation does influence people's visual size judgment of AR objects. However, the left side and the right side do not influence people to make different judgments. When combined with the findings from Experiment 3 at 2 meters, it is clear that sideways orientation does not have a significant effect on one's observations because the proportions of the various choices for the two sides at 90° are very close to the selection of those observed head-on in Experiment 3.

When observing at 45°, only 20% of participants made the right choice. In comparison, when the viewing angle was adjusted to 90°, the ratio of participants who made the right choice was approximately 38%, an 18% increase in the correct rate. Besides, at 45°, approximately 43% would underestimate the size of the AR object. When people viewed objects at an off-diagonal angle, more people misjudged the size of the object, and those who misjudged tended to underestimate the size of the AR object. At the entire 90° observation range, from frontal to lateral, the correctness of one's judgment of the size of the AR object decreases as one's point of observation deviates from the forward 90° and begins to shift to the lateral direction. Participants have the lowest probability of making the correct choice when viewing from the observation point at 45°. When people misjudge the size of an AR object, this error tends to be more within the 10% size range.

6.4 Limitations

Having gained insights into how people's size perception of AR objects can differ due to the discussed variables, we are aware that this work is limited by several factors. Firstly, using one type of mobile device that has been used for all experiments, the experiment and its AR representation are bound to the device's technical specifications and screen size properties. While experiment measurements were not taken on other models of mobile devices (such as a tablet), this leaves question marks on the effect of screen size and the device's performance. Secondly, the interface design and its user interaction (UX) have not been further evaluated in this work, while having the potential to impact the AR experience for the viewer, which might affect their decision-making. Furthermore, while aiming to include a high diversity of people demographics from various social backgrounds, the situation this work was conducted in—during a global pandemic affecting especially the recruitment process—led to a limitation in recruitment, as most of the participants share similar work backgrounds that might affect the outcome.

7. Conclusion and future work

With many of us now at home during a global pandemic, AR is a tool that can help us transform our immediate surroundings into learning, work, and entertainment spaces [41]. The development of AR is still in its early stages, and there is still more potential for the future, which can bring reality and virtual environments closer together.

This multifaceted research intends to bridge the existing gap with its focus on the visual factors that impact the perception of the size of AR objects on mobile devices. Thus, experimental studies have been conducted on many aspects that affect people's visual size perception in AR, such as AR background, groups of AR objects, observing distance, and observing perspective. First of all, the natural environment behind the AR object does not interfere with the people's size judgment of the AR object itself. Secondly, there is a specific error in people's size perception of the AR objects on mobile device screens. When the size difference interval between AR objects is within 10%, some people will misjudge the size of AR objects. In terms of the extension to AR applications, such as AR games or AR furniture arrangement, if the same AR objects appear in the AR apps, the size difference between them is within 10%, which may cause people not to recognize the difference between them. Thirdly, people's perception of AR objects is not the same as physical objects in real life. Regardless of the conditions, most people tend to underestimate the size of AR objects. However, a certain number of people will overestimate the size of AR objects. People's perception of AR objects bias tends to occur in the 10% range. A 10% size difference from AR objects is a clear cut-off point where people can clearly distinguish volume size between AR objects. Nevertheless, when many objects are present simultaneously, it is subjectively more challenging to distinguish between them in terms of size. At the same time, people's size judgment of AR objects is also related to observing distance and angle. When the observation conditions are the same and only the observation distances differ, one has a greater probability of being able to judge the true size of an AR object when the observation distance is greater. When the observation conditions are the same and only the angle of observation differs, one is more likely to misjudge the size of an AR object when the angle is 45° to the point of observation. The conclusions of these experiments lead to recommendations for the design of future AR experiences and the application interface design. For instance, before people start with the AR experience officially, people are given a simple AR object size test to get a bias in people's size perception of AR objects. Depending on their tendency to judge, some adjustments are made to the overlay of the AR interface with natural objects to achieve a better visual effect.

This research has studied the difference between static AR objects and actual objects. However, in real-life environments, when people use AR applications with their phones or pads, in most cases, AR applications present dynamic images, and AR objects have more than simple geometric shapes. Lastly, the study of user's size perception for dynamic AR objects and complex forms of AR objects would be worthy of future investigations.

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