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Distance Estimation with Social Distancing: A Mobile Augmented Reality Study

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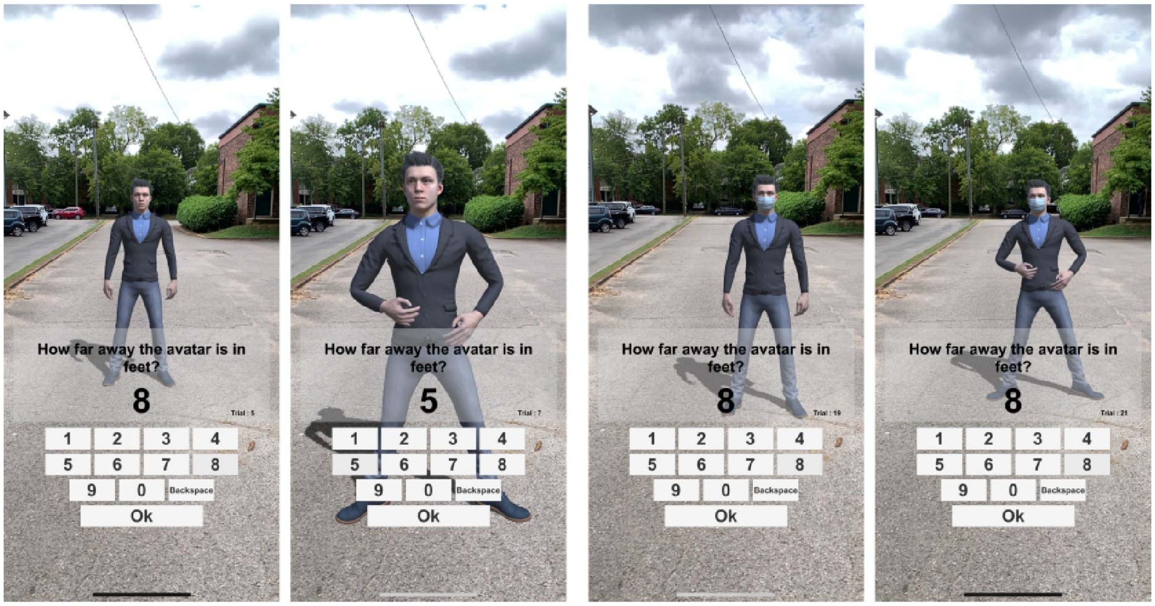

Figure 1: Left to right: Views of the unmasked static avatar around 8 feet (2.4 m) away, unmasked coughing avatar around 4 feet (1.2 m), masked static avatar around 8 feet (2.4 m), masked coughing avatar around 8 feet (2.4 m). Estimated distances are shown in the GUI in feet.

Abstract

Although Augmented Reality (AR) can be easily implemented with most smartphones and tablets today, the investigation of distance perception with these types of devices has been limited. In this paper, we question whether the distance of a virtual human, e.g., avatar, seen through a smartphone or tablet display is perceived accurately. We also investigate, due to the Covid-19 pandemic and increased sensitivity to distances to others, whether a coughing avatar that either does or does not have a mask on affects distance estimates compared to a static avatar. We performed an experiment in which all participants estimated the distances to avatars that were either static or coughing, with and without masks on. Avatars were placed at a range of distances that would be typical for interaction, i.e., action space. Data on judgments of distance to the varying avatars was collected in a distributed manner by deploying an app for smartphones. Results showed that participants were fairly accurate in estimating the distance to all avatars, regardless of coughing condition or mask condition. Such findings suggest that mobile AR applications can be used to obtain accurate estimations of distances to virtual others "in the wild," which is promising for using AR for simulations and training applications that require precise distance estimates.

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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

The increasing capabilities of recent smartphones and tablets for augmented reality (AR) has led to AR's adoption by many application developers to provide an easy-to-understand experience for customers. Using the camera on the device as a video see-through display, a user can experience such things as AR navigation and visualizing potential furniture in a room. AR thus allows people to experience virtual objects overlaid on the real world that can aid in training and decision making. It is therefore becoming important to understand how people perceive distances to virtual objects seen through these devices. For example, if users misperceive the distance to a virtual object while navigating, they could end up in the wrong location. Thus, if a systematic bias in distance perception exists between virtual objects and real objects presented at the same distances, then the use of AR applications on mobile devices that require accurate distance perception could be limited. Evidence exists that distance judgments in AR are distorted in head-mounted

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displays (HMDs) [4,14,17], so the question for this paper is whether biases are observed also in AR for mobile devices. Some work has been done to investigate distance perception in AR displayed through tablets and smartphones, but the results have been mixed [1,6,11,13,20]. For example, Swan et al. [20] found distance underestimation in tablet-based AR, whereas a recent study by Liu et al. [13] found accurate distance perception through a smartphone. Chakraborty et al. [1] also found accurate distance perception to virtual avatars with smartphones, which did not rely on motion of the virtual avatars.

Given the mixed results, more work is necessary to understand distance perception in AR for mobile devices. The current experiment investigates perception of distance to virtual avatars that are placed at various distances (approximately 1–4 m) from users in what is known as *action* space [3]. We expect to replicate and extend the results of Liu et al. [13], which were found at distances of 10–40 m. However, Chakraborty et al. [1] also tested whether motion cues associated with a virtual avatar improved distance perception in action space, i.e., less than 10m. In their study, the avatar walked side-to-side to simulate motion parallax at various distances from the observer, but this animation did not change the accuracy of distance estimates, which were accurate without motion. In the present experiment, and due to the focus of distance perception between the self and others for Covid-19, we decided to implement a coughing animation for the virtual avatar as well as a manipulation of whether or not the virtual avatar was wearing a mask. To further reduce risks from Covid-19, we conducted the experiment on smartphones "in the wild." In other words, users downloaded the distance estimation app onto their smartphone and did the experiment in their own surroundings. Challenges associated with that practice are discussed, but this experiment also contributes to a growing body of work on whether or not such "in the wild" experiments are feasible and can produce reliable results remotely.

2 Background

Although a significant amount of work has been done on distance estimation in AR [4–12,14–21], there is no consensus on the accuracy of perceived distance using various AR platforms. There could be various reasons for the lack of a consensus, including (1) environmental contexts and available cues, (2) methodologies and designs employed, (3) distances considered, and (4) the AR devices themselves. Most of the previous work suggests that people underestimate distances in augmented reality. However, there is some work that showed overestimation of distances presented in AR ([14,18,19]). This overestimation tended to occur if the distances were particularly far from the observer, i.e., beyond action space or about 30m [3], and also when the distances were displayed in an outdoor setting rather than indoors [14]. For example, Swan et al. [18,19] found that people underestimated distances up to 23 m but overestimated those beyond 23 m when virtual objects were placed at distances ranging from 5 to 45 m in the experiment. Further, Livingston et al. [14] ran a distance estimation experiment in AR both indoors and outdoors. They found that people underestimated the distances in the indoor environment but overestimated the distances in the outdoor environment. However, other work has shown that distances estimated in personal (up to 2 m) to action spaces (2–30 m) using various optical see-through AR displays (such as the Microsoft HoloLens) are consistently underestimated [8,17,19].

Recent smartphones and tablets now have the capabilities to run AR applications. As a result, researchers have begun investigating the accuracy of perceived distance in these devices compared to the optical see-through head-mounted displays that have been used previously. Dey and colleagues investigated the influence of different AR visualization methods and sizes of tablet displays on egocentric distance perception [4–7]. Across their studies, they generally found underestimation of egocentric distances by participants, but the underestimation of distance was reduced with smaller devices (such as iPhones) and increased with larger devices (such as iPads). Interestingly, Liu et al. [13] and Chakraborty et al. [1] found that people estimate the egocentric distance of a life-sized human avatar accurately from 10–40 m.

Given the prior work on distance estimation using mobile AR devices is not extensive and has resulted in mixed findings, we decided to test perceived distance to a virtual avatar on mobile AR devices with distances tested in action spaces only. This differentiates the current study from that conducted by Liu et al. [13], which investigated farther distances. Further, we did not conduct the experiment in an environmentally controlled setting as in [13]. Instead, we deployed the experiment as an app for people to participate in their natural environments, or what we term "in the wild" here. Recent work suggests that more experiments may be conducted this way in the future given the ease of recruitment and the increase in generalizability of the findings given diverse settings. To make our experiment more applicable to current events, we also tested distance perception to virtual avatars that were coughing and/or masked. We did this because we wanted to test whether a more evocative motion cue than that used in [1] would affect distance estimation in mobile AR, but also because there is growing interest in understanding how behaviors such as coughing and masking may alter distance estimation to others. For example, work on embodied perception has shown that people perceive threatening objects as closer than non-threatening objects [2,22].

Our hypotheses were as follows:

- **[H1]** Given recent work on distance estimation in mobile AR devices, participants will be able to accurately perceive the distance to virtual avatars displayed in action space.
- **[H2]** A coughing, unmasked avatar will cause an emotional reaction in subjects that will cause them to perceive the avatar as closer to them than it actually is, given that they will want to ensure a safe distance away from an unhealthy avatar.

3 Experiment

3.1 Stimuli and Design

In this experiment, we used both a male avatar (Josh) and a female avatar (Kate) from Mixamo. Participants were given a gender-matched avatar for their distance estimation in order to control for any potential effects of non-gender matching. For the coughing animation, we chose the "Laying Mild Cough" animation provided by Mixamo for both avatars, which had to be rotated by ninety degrees on the positive x-axis in the Unity Game Engine to simulate realistic coughing while the avatars were standing (Figure 1). Inspired by the prescribed social distancing of the COVID-19 pandemic, we also tested whether masks affected distance estimation. The addition of the mask manipulation resulted in a 2 (coughing vs. static) x 2 (masked vs. unmasked) experimental design. We purchased the Disposable mask asset from the Unity Asset Store in order to mask the virtual avatars. Four different virtual avatars were built for each gender, including a unmasked static avatar, unmasked coughing avatar, masked static avatar, and masked coughing avatar. To make the coughing animation more realistic, we implemented coughing sounds for both the male and the female avatars. The male coughing sound was downloaded from *https://www.fesliyanstudios.com/* and a female coughing audio clip from *https://www.freesoundeffects.com/*. We added shadows to the avatar using a Unity asset called *Simple AR-VR Invisible Light and Shadow Receivers*, so that the participants got visual cues suggesting the avatars were standing on the ground plane. We did not directly ask participants whether they felt that the avatar was on the ground or not during our experiment. However, our anecdotal experience in pilot testing was that the shadows were helpful for portraying ground contact of the avatars. We used Unity's default Skybox lighting in our app. We used the amount

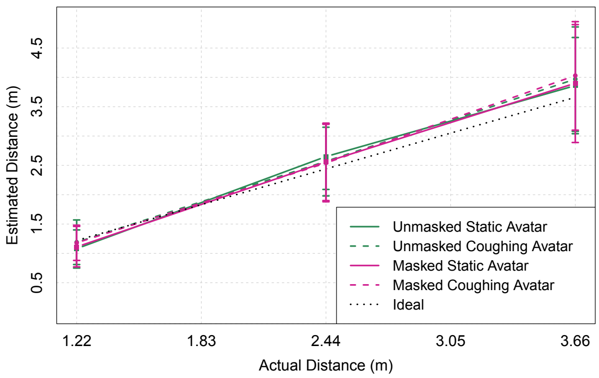

Figure 2: Mean distance estimates as a function of distance for the four different avatar conditions, collapsed across environment. The black dotted line indicates veridical estimation. Error bars indicate one standard error of the mean.

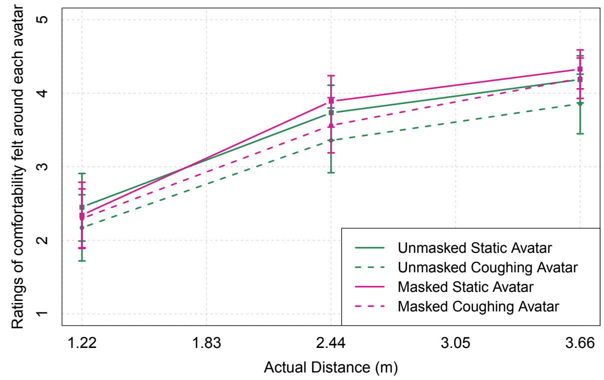

Figure 3: Ratings of comfort felt around each of the avatar conditions at each distance.

of real light detected by the phone camera to gauge intensity and to change the direction of the shadow of the avatar during the run time of the app. Due to Unity's default Skybox lighting settings, the avatar should be easily visible in most real-world indoor or outdoor lighting conditions. Also, if participants ran the app indoors, ambient and positional lighting was detected in the room, and the shadow of the avatar was projected accordingly. For publishing the app, we used the Google Play Console for android devices and the Apple App Store Connect from the Apple Developer portal for the iOS devices. Once approved by Google and Apple, we were able to share the apps among participants.

3.2 Participants

We recruited 38 participants from the USA and India. An online consent form was included with the app so that when the participant ran the app, they first read the consent form and gave their consent to participate in the experiment.The data of 6 participants were faulty for one random trial because of a misplacement of the avatar in that trial due to a bug not discovered during testing. Data from these 6 participants was discarded. There were 14 female and 18 males among the remaining 32 participants, with ages ranging from 19 to 69 years.

3.3 Procedure

After obtaining consent from the participants, the app gathered demographic information including the name, age, and gender of the participants. Participants were then asked to find an indoor or outdoor space that extended at least 15 feet (approximately 4.5 m) without obstructions. Once participants were in the space, the app asked participants whether they would like to estimate distance in feet, yards, or meters. After choosing their preferred units, participants were asked to point the mobile phone down so that it could detect the ground or floor. Once that was detected, the app asked the participants to move the phone upwards slowly to point towards the farthest distance in front of the person and then tap anywhere on the detected ground/floor to instantiate the gender-matched avatar at 2 feet away (0.6 m) from the device. If the position of the avatar was not right for the space for some reason, participants were given the option to replace the avatar in a new location by repeating the previous scanning. After placing the avatar at a suitable place, the app showed participants a white square plane approximately one foot (0.3 m) long on the ground that participants were told could serve as a reference to help them to estimate distances. The length of the sides of the reference square was shown to the participants in the units they chose to conduct the experiment in. After completing this setup phase, participants were asked not to move from where they were standing, and the experiment started thereafter.

The experiment was within-participants and there were 24 total trials, where each of the 4 types of avatars were randomly instantiated at 4 feet (1.22 m), 8 feet (2.44 m), and 12 feet (3.66 m) away from the device. At each location, the avatar placement was jittered between ± 1 foot from the device as well as either 0 to 1 foot (0.3 m) to the left or right side of its instantiation point randomly, so that the participant could not use consistent references in the real environment to estimate the distance to the avatars. During each trial, participants were given a GUI where they were able to enter the value of the estimated egocentric distance of the avatar and hit the "Ok" button to go to the next trial. After each trial, participants were asked to rate whether they felt comfortable around the avatar with the given animation condition at the given distance based on a five-point Likert scale where 1 represents strongly disagree and 5 represents strongly agree. At the end of 12 trials, the participants were asked to walk eight to ten steps forward, turn around and face the other direction, and then perform the next twelve trials. We implemented this walking to reduce participants' abilities to use elements in the environment as references for distance estimation across all trials. Participants were not asked to re-scan the ground/floor after walking and turning given time limitations, but also because we had calculated the height of the ground/floor from the phone at the beginning of the experiment and that height was used throughout. As a result, we could stop the continuous floor detection SLAM algorithm of the respective mobile AR devices immediately after getting the floor height from the device, which also reduced battery drainage. At the end of 24 trials, the participants were asked to rate how comfortable they felt around the animated avatars displayed during the experiment based on the same five-point Likert scale mentioned above (1 being not comfortable and 5 being very). All of the recorded data was then sent by the app to the experimenter via email and the app showed the participants a confirmation of receipt. Participants were asked to uninstall the app from their device after completion of the experiment.

4 Results

We ran a 2 (mask or no mask) x 2 (cough or static) x 3 (distance) repeated-measures ANOVA on the mean distance estimations. There was a significant main effect of distance, $F(2,62) = 55.14, p < .001, \eta_p^2 = .64$ showing that estimates increased with actual distance.

Estimates were quite accurate with slight overestimation at the 8 and 12 feet distances (*Ms* = 3.74 feet, 8.46 feet, 12.93 feet for 4 feet, 8 feet, 12 feet, respectively). There were no effects of the mask $F(1,31) = 0.00, p = .99, \eta_p^2 = .00$ or coughing animation $F(1,31) = 1.41, p = .24, \eta_p^2 = .04$. The results are shown in Figure 2.

We also analyzed the ratings of how comfortable participants felt around the avatar for each trial in each animation condition, using a 4 (condition) x 3 (distance) x 2 (trials) repeated measures ANOVA. We found a significant effect of animation condition, $F(3,93) = 5.11, p < .003, \eta_p^2 = .14$. Planned contrasts comparing each condition to the masked static avatar as a control showed that this effect was driven by lower ratings (feeling less comfortable) for the unmasked coughing avatar ($M = 3.13$) compared to the control ($M = 3.52$), $F(1,31) = 6.85, p < .02, \eta_p^2 = .18$. There were no differences between the other conditions ($Ms = 3.46$ and 3.35 for unmasked static and masked coughing avatars, respectively) and the control ($ps > .07$). We also found an effect of distance, $F(2,62) = 93.21, p < .001, \eta_p^2 = .75$, where ratings of comfort increased as distance increased for all animation conditions. The mean ratings for each condition and distance are shown in Figure 3.

5 Discussion

The results from our experiment extend and replicate the findings of Liu et al. [13], who found that participants accurately estimated distances (ranging from 10-45m) to a virtual avatar using a mobile AR display. Their study compared the estimates made to a virtual avatar displayed through the smartphone in a laboratory setting to distance estimates made to a real person standing in the same locations and viewed through the same mobile AR display. Our current experiment also found fairly accurate estimation of distance to virtual avatars of different types at a range of distances closer than those tested by Liu et al. Extending their findings, we showed that accurate average distance estimation could occur even when the experiment was run "in the wild" or in the natural settings of the participants rather than a laboratory. Such a finding is important for considering running remote applications that require accurate distance perception in the future.

The general accuracy in estimation of distance observed in our data and that of Liu et al. (both data sets collected from mobile AR) is in contrast to several studies for which distances were underestimated when presented through head-mounted, optical see-through AR devices. An open question is why the accuracy of distance estimation may change based on the technology displaying the virtual targets. As noted by Swan et al. [20], it is possible that there are perceptual distortions that result from a viewpoint in the real world that is offset from the viewpoint of the device. This conflict in the center of projection would predict distortions that would expand the perceived environment, possibly counteracting the distance underestimation that is typically seen in the real world with increasing distance and in optical see-through devices such as the Microsoft HoloLens. More investigation of the differences in optics for these technologies could be fruitful in disentangling the mixed results observed across studies regarding the accuracy of distance perception in AR.

Contrary to our hypothesis, the added coughing animation of the avatar and the masking of the avatar did not affect participants' estimates of the distance to the virtual avatar. Because people were relatively accurate at distance estimation, it may have been difficult to manipulate the perceived distance to the avatars. Also, the manipulations of coughing and masking were run within-participants, in order to increase sample size more efficiently. This ability to see the manipulations across trials may have affected observers' estimates if they discerned our hypotheses. Findings from a previous study that displayed animated avatars (avatar walking back and forth at a distance) also did not show effects on accuracy of distance perception [1]. In the current experiment, we attempted to make the manipulation stronger by evoking fear or caution given the COVID-19 pandemic. It is possible (and some participants reported anecdotally) that participants did not even encode the status of the virtual avatar, but rather just focused on their feet and estimating ground distance to them. If that were the case, then the manipulation would have been ineffective. We tried to counteract that possibility by employing the coughing sound and by asking participants to rate their perceived safety around the avatar, but it is possible that the manipulation was just not strong enough in this experimental design to evoke an effect on distance perception. We did find that there was a difference in subjective ratings relating to less comfort around the potentially most harmful avatar (coughing without a mask) compared to the masked static avatar. Variability in environments in which the experiment was performed may have contributed to difficulty in observing a more subtle effect for masking or coughing. We plan to revisit these manipulations in a laboratory setting with more control because we believe there is value in understanding the perception of distance to others that are exhibiting health symptoms and precautions given current events.

Overall, an important contribution of the current work is that it shows that running mobile AR experiments for distance perception across distributed users who are outside of a laboratory setting is feasible and reliable. Of course, there are technical and procedural challenges to running such studies. Technically, the experimental apps must be significantly more robust than typical laboratory applications. Obtaining consent and properly gathering data are technical challenges that can be overcome, as demonstrated here. Understanding what users are doing during the experiment and why they are doing it becomes more problematic, as well as understanding if users are properly following the directions or noticing manipulations. A larger sample size is likely needed to reduce the variance of environmental factors as well as variability across participants. However, the current work provides a foundation for future work to build on with regard to running a distributed AR experiment with mobile devices to examine distance perception to virtual others.

6 Conclusions

Our study investigated egocentric distance estimation to a virtual avatar that was presented at varying distances in action space. The virtual avatar was coughing on some trials and masked or not on those trials. The experiment was fully deployed remotely on mobile AR devices. We hypothesized that distances to the avatar would be fairly accurate given previous findings with similar distances and on similar devices. However, we thought that the distance to a coughing, unmasked virtual avatar would lead to underestimation of distance – especially for the closest distance tested, which was less than the prescribed 6 ft (2 m) for Covid-19 prevention. We found that people were generally accurate in estimating the distances to the avatar regardless of coughing or mask condition. There are many reasons why the manipulations may not have affected distance perception, but the take-home message of this experiment is that the feasibility of collecting data on distance estimation in mobile AR applications is good. Future work could consider replicating this experiment in a laboratory with more instruction to observe the Covid-19 related manipulations, but overall, the results are promising for use of mobile AR to assess distance perception in action space.

Acknowledgments

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