Estimating Distances in Action Space in Augmented Reality

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Augmented reality (**AR**) is important for training complex tasks, such as navigation, assembly, and medical procedures. The effectiveness of such training may depend on accurate spatial localization of AR objects in the environment. This article presents two experiments that test egocentric distance perception in augmented reality within and at the boundaries of action space (up to 35 m) in comparison with distance perception in a matched **real-world** (**RW**) environment. Using the Microsoft HoloLens, in Experiment 1, participants in two different RW settings judged egocentric distances (ranging from 10 to 35 m) to an AR avatar or a real person using a visual matching measure. Distances to augmented targets were underestimated compared to real targets in the two indoor, RW contexts. Experiment 2 aimed to generalize the results to an absolute distance measure using verbal reports in one of the indoor environments. Similar to Experiment 1, distances to augmented targets were underestimated compared to real targets. We discuss these findings with respect to the importance of methodologies that directly compare performance in real and mediated environments, as well as the inherent differences present in mediated environments that are "matched" to the real world.

CCS Concepts: • **Human-centered computing** → **Virtual reality**; **Empirical studies in HCI**; • **Applied computing** → *Psychology*;

Additional Key Words and Phrases: Augmented reality, distance perception, avatars

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1 INTRODUCTION

The use of **augmented reality** (**AR**) in different fields has continued to grow as AR devices become more accessible. AR is being applied to areas such as entertainment, medicine, education, and navigation [2, 31, 32]. Depth perception is important for all of these applications, but prior research suggests that distance estimation in AR differs from that of the real world [10, 14]. Most of the previous research has focused on the perception of egocentric distance (from an observer to a target) in AR in personal (within arm's reach) and near-action (2–10 meter) space (also referred to as medium-field distance), but few studies have investigated perception in AR at farther distances. Knowing how farther distances are perceived in AR is particularly important for training applications where users might engage with targets at far distances in AR and then need to apply their training to the real world (such as in the military). The perception of far distance may also be quite important for navigation. If far distances are perceived differently in AR compared to the real world, training will not effectively generalize to **real-world** (**RW**) situations.

Common AR devices are typically head-mounted or hand-held (e.g., a tablet). Within the head-mounted category, devices can use optical see-through displays or video overlay to present the AR objects. As their names imply, optical see-through devices allow the user to see the real world with AR objects projected onto it; video overlay devices capture the real world via cameras in real time and present that image to the user with AR objects overlaid. In the present study, we used the Microsoft HoloLens 1, an optical see-through device, to investigate the perception of distances portrayed from 10 to 35 m. Distance estimates for real and augmented targets were gathered in two indoor environments.

The study of the perception of distances to AR targets beyond near-action space can be difficult due to a number of factors, including limitations of the spatial mapping abilities of the AR devices, as well as limitations to the types of response measures that can be used to assess distance perception. For example, walking without vision to a previously viewed target is a commonly used measure of egocentric distance perception but is difficult to perform beyond about 15–20 m. Other measures that are more feasible for farther distances often rely on relative comparisons, such as matching or bisection tasks. Our goal was to test both relative and absolute measures of egocentric distance to both AR and RW targets, and to test whether multiple measures reveal similar conclusions about the accuracy of AR distance perception.

2 BACKGROUND

Human perception of egocentric distance has been studied for many decades in real and virtual environments and, more recently, AR environments which typically display a virtual target located within a RW context. A majority of this work has focused on distances that fall relatively close to the observer. Cutting and Vishton [9] provide a useful framework for considering space perception at different distances, defined by the viewer's potential for moving through space and the relative utility of visual cues to provide information about distance. Personal space extends out to about arm's reach, whereas action space is that which allows locomotion through the space and extends to about 30 m from the viewer. Vista space is defined as beyond 30 m where self-movement occurs over a much longer time scale. Cutting and Vishton's definitions of these three areas of space suggest that oculomotor cues such as accommodation and convergence, as well as binocular disparity, are effective for a limited range of distances close to the observer. In contrast, cues such as occlusion, relative size (including texture gradients), linear perspective, and height in the field provide more information for distance at farther ranges. Most of these cues are relative distance cues (specified as comparisons with other distances), but height in the field can provide absolute distance information when combined with an observer's eye height above the ground. At very far distances, there are fewer sources of information for distance, although cues such as occlusion, height in the field, and relative size can sometimes be used, along with aerial perspective.

In the current experiments, we examined the perception of distances ranging from 10 to 35 m, encompassing action space and slightly beyond, in contrast to most research which has focused on "near-action" space (up to

10 m). One challenge of studying this range of distances is determining the appropriate measure of what the viewer "sees." While there are numerous established behavioral measures used in the distance perception literature, the choice of measure should be influenced by the specific research question. Absolute measures of distance perception reveal perception of scale, meaning that the viewer must indicate perceived distance in an absolute metric, without a visual reference. In contrast, relative measures reveal perception of distance in comparison to other visually determined distances, so they reveal perception of an extent but at some fixed and unknown scale.

Verbal reports and action-based measures are commonly used absolute measures. Verbal reports entail stating how far away a target is using a predefined metric, such as feet or meters. Although convenient, verbal reports can vary widely across individuals and are confounded by participants' familiarity with the metric and other cognitive factors, such as a bias in scaling the stored metric appropriately [33, 47]. Studies using verbal reports to assess distance perception in both real and virtual environments generally find underestimation of distance [6, 26]. Blind walking is an example of an action-based measure, which involves directing an action that is based on perceived distance. Action-based measures such as blind walking are less variable and tend to be more accurate than verbal reports, partly because they do not rely on a stored metric that has to be scaled to the currently perceived distance [25, 26]. In contrast to absolute measures, relative measures rely on comparisons of two extents or objects in the environment. Common relative measures of distance perception are magnitude comparisons and visual matching techniques. Magnitude comparisons involve numerically comparing the distance or size of a standard to another viewed extent or object. Observers report on the magnitude of the comparison relative to the standard (e.g., the currently viewed extent is 40% larger than the standard). In visual matching techniques, distance perception is measured by adjusting an object until it is perceived to be at the same distance as a previously viewed target. Visual matching techniques tend to be less variable because they do not rely on numerical calculations, similar to action-based measures [25].

In **virtual reality** (**VR**), distances are typically underestimated regardless of the response measure used [6, 16, 17, 19, 37, 40, 47]. However, there tends to be less underestimation in newer VR devices [5, 7, 18]. These previous studies have generally focused on measures of absolute egocentric distance at less than 10 m. However, those investigating farther distances and relative measures also show underestimation when compared to perception of the real world. For example, Bodenheimer et al. [4] tested perception of targets at 15 m and 30 m in indoor and outdoor virtual environments using a bisection task where users bisected a distance in half in order to indicate their perception of the total distance. They showed nonlinear distance compression when compared to estimates made in the real world.

In AR, the results are more mixed with some studies finding underestimation of distance [13, 39, 42, 43], and others finding accurate performance [36] or overestimation [24]. These differences may be the result of differences in available AR cues, response measures, or AR devices. Some studies have even shown that the underestimation occurs in indoor environments but that outdoor distance estimates may result in overestimation when examined with mobile AR technology [24]. Several recent studies have manipulated the cues available for distance, including relative distance cues [21], shadows as information for ground contact [13, 39], and binocular vision [39]. For example, Rosales et al. [39] used blind walking to measure how distance perception in AR changes with targets presented on and off the ground and with binocular and monocular viewing of the targets at distances ranging from 4 to 8 m. They found underestimation of distance in all conditions. Distances to on-ground cubes were underestimated by 15%, while distances to off-ground cubes were underestimated by 7%. This result suggested that cues for ground contact may be especially important in AR and that when targets are presented off the ground in the absence of additional cues (such as shadows), they are perceived as intersecting the ground at a farther distance. Furthermore, reducing binocular information for distance exaggerated this effect.

Kuparinen et al. [20] studied distance perception up to 30 m using tablet-based AR. In both the real world and in AR, distances at 15 m were slightly overestimated. Distances at 30 m were underestimated and considerably less precise and accurate than the 15 m estimates. This suggests that a consistent bias in distance perception was not observed across space. In contrast, Swan et al. [44] used a perceptual matching task to investigate egocentric distance perception at distances ranging 5–45 m. Here, participants underestimated distances up to 23 m and overestimated distances past 23 m. However, this 23 m switch was not replicated in a follow-up study [24]. As stated previously, Livingston et al. [24] found that participants underestimated distances indoors but overestimated distances outdoors when targets were presented at 4–40 m. Wither and Höllerer [49] tested the effectiveness of different pictorial cues in helping users to annotate depth in an outdoor environment with AR. They found that giving users a top-down view was the preferred cue for aiding in annotation of relative and absolute far-field distances (ranging from 20 to 80 m), but that none of the cues they implemented significantly differed in accuracy of annotated distances.

3 RATIONALE

Taken together, the literature on egocentric distance estimation in AR for action space and beyond is mixed. Most of the prior work suggests that the amount of underestimation and variability in participants' estimates will increase with distance, across real and mediated environments. Further, distances are generally underestimated in mediated environments compared to real environments, although with some variation across different environmental contexts or devices. We decided to conduct an experiment to investigate how medium-field distances (ranging through action space to its boundary) are perceived in AR and the real world. We chose this range of distances because there is ample data from RW estimation to make predictions, but also because the Microsoft HoloLens 1 can reliably display targets at this range (without jitter or inconsistency in placement due to tracking issues). To replicate and extend prior work, we asked participants to estimate distances to AR and real targets, which allowed for a direct comparison of distance estimates for virtual targets in action space to estimates made to real targets in the same indoor environments. Such direct comparisons have been rare in prior work, but are especially important in gauging the direction and magnitude of any observed effects with distance estimation in AR. We also tested distance estimation in two different indoor environments: a hallway and a large open room (as in [45]). Including environment type as a factor allowed us to understand whether any potential biases that may occur with distance estimation in AR generalize across environments with different visual cues for depth.

In addition, we assessed distance perception using two different response methods. The use of two measures—one relative and one absolute—gives us more insight into how accurately observers are perceiving the target distances compared to just one measure alone, given that visual cues may not affect relative and absolute estimates in the same manner. In Experiment 1, we used a visual matching measure in order to try to increase estimation accuracy and reduce variability. Based on previous research in AR and VR, we predicted that distances portrayed in AR in an indoor setting would be underestimated compared to the veridical distance, but that this underestimation would not be extreme [24]. Further, this underestimation could be reduced in a hallway environment that contains more clutter and linear perspective cues [3, 22, 45]. In Experiment 2, we used verbal reports to assess absolute perception of distance. Verbal reports rely on a stored metric, so they may be more prone to bias, but they are also more feasible to use than blind walking, particularly with current AR head-worn devices, because they do not require moving over far distances. Prior research conducted within the range of distances studied here has demonstrated that verbal reports and blind walking may be driven by a single perceptual representation of location [33, 34]. However, differences between verbal reports and visually directed actions have also been demonstrated given different visual cues in virtual environments [19] and within reaching spaces [28–30]. These differences in accuracy and variability suggest that while verbal judgments are measures that rely on an absolute metric, they are not equivalent to actions directed at a target that necessarily rely on perception of absolute distance. We chose to use only the open environment from Experiment 1 for the absolute estimates in Experiment 2 to reduce the possibility that verbal reports would recruit cognitive strategies based on additional cues in the close hallway (such as using doorways as landmarks). Given that prior work in the real world has found underestimation of distance with verbal reports, we predicted that distances would be underestimated in both viewing conditions, but that underestimation would be greater in AR.

4 EXPERIMENT 1

In the current experiment, we explored the perception of egocentric distances in action space up to the boundary of vista space (10–35 m) in two different indoor environments. Our primary goal was to discern whether medium-field action space distances are perceived differently in AR than in the real world. Based on previous research, we hypothesized that distances would be underestimated to AR targets compared to RW targets, and that underestimation would increase as distance increased in both the real world and AR. In addition, we tested for an interaction between distance and viewing condition (AR vs. RW). It is possible that the amount of underestimation associated with increasing distance might differ depending on whether judgments were made in AR or the real world.

Our second goal was to test whether distance underestimation held across different environments (open area vs. hallway). Prior work clearly suggests that distance estimation indoors can differ from outdoors [46], possibly due to differences in visual cues present in indoor settings. We chose two indoor settings that differed in visual cues that were similar to those tested in Teghtsoonian and Teghtsoonian [45] (e.g., a long, narrow hallway that provided more linear perspective, and an open room that was less cluttered and bounded). As a result, we were able to test whether environmental setting had an effect on distance estimation as well. Finally, we tested for an interaction between environment setting and viewing condition, given it is possible that distance perception in the RW or AR could be biased differently depending on the visual cues present in the environment.

Our specific hypotheses were as follows:

- **H1.** Distances will be underestimated to AR targets as compared to real targets.
- **H2.** Farther distances to AR targets may be underestimated more than closer distances when compared to distance estimates made to real targets.
- **H3.** Distances to AR targets will be underestimated less in the hallway environment compared to the open environment due to an increase in perspective cues for depth.

4.1 Participants

Participants were recruited from the University of Utah and Vanderbilt University. Data were collected from 13 participants at the University of Utah and from 12 participants at Vanderbilt University, resulting in a total of 25 participants (12 female, $M_{\text{age}} = 23.30$, $SD_{\text{age}} = 5.76$). Participants had normal or corrected-to-normal vision and gave written consent for their participation in the study. They were compensated with $10 or course credit for their participation.

4.2 Stimuli and Design

Participants at the University of Utah completed the study in a large room in the campus library where there was at least 40 m of open space to the front of and to the left of the participant. Figure 1 shows an AR avatar placed in the room. The AR avatar was a male avatar with a height of 1.8 m. Because of challenges with creating realistic shadows in AR as well as an uncertainty in the effectiveness of drop shadows on distance perception in AR [13], we decided to implement the avatar without shadows as an initial investigation of targets at these distances. Participants at Vanderbilt University completed the study in an L-shaped hallway intersection where they were able to view the target in one hallway and adjust the experimenter in the hallway to their left. This hallway was over 50 m long and about 1.8 m wide. Care was taken to replicate procedures as exactly as possible across institutions. A detailed script was written and shared amongst experimenters at both locations and discussion of questions and procedures occurred prior to experimental trials being run.

Fig. 1. Presentation of the AR avatar in the large, open room (left, University of Utah) and hallway (right, Vanderbilt University).

AR targets were presented with the Microsoft HoloLens 1. The HoloLens weighs approximately 579 g and has a graphical field of view of 30° × 17°. The AR program was created using Unity (version 2017.4.3) on a Windows 10 laptop and run as a stand-alone application. The program presented a 1.8-m-tall virtual avatar on the ground at six different distances (10 m, 15 m, 20 m, 25 m, 30 m, and 35 m) from a virtual red line. Participants always viewed the avatar and made their distance judgments while standing at the red line.

Viewing condition was manipulated via a within-participants design such that each participant completed a block of both AR and RW trials. The order of the AR and RW condition blocks was counterbalanced across participants. Each block consisted of 13 trials. The first trial in each block was always 18 m (roughly the average of the distances shown so as not to bias the actual estimates) and was treated as a practice trial. The rest of the trials consisted of the six target distances, each presented twice. The target trials were randomized such that all six distances were presented in a random order before a second randomly ordered presentation of the distances. The same distance was never presented twice in a row. In addition, the starting point of the experimenter (near to the participant or far from the participant) that the participant adjusted for the visual matching estimates was counterbalanced across the six distances within each participant and for each viewing condition (AR and RW).

4.3 Procedure

Upon arrival, participants granted consent and completed a random-dot stereogram test to ensure they had stereo vision. Participants made distance judgments using a visual matching measure. In the AR trials, the participant instructed an experimenter standing to their left to move closer or farther away until they felt that the experimenter was the same distance from them as the avatar was from them (see Figure 2). Once the participant indicated that the experimenter was at the right distance, they would say "ready." This vocal command made the avatar disappear. The experimenter measured and recorded the distance between themselves and the participant in meters using a laser distance meter. The participant would then say "next," which would advance the trial and make the next avatar appear. Participants were given as much time as needed to view the avatar and adjust the experimenter. The RW trials were the same as the AR trials, except that instead of an AR avatar, the participant viewed an experimenter in the real world at the different distances. During the RW trials the participant still

Fig. 2. Depiction of the visual matching task for the RW viewing condition in the large, open room. Participant (A) viewed the real target experimenter (B) and adjusted another experimenter (C) to match the distance between themselves and the target experimenter.

wore the HoloLens, but it was turned off. After completion of both viewing condition blocks, the experimenter collected responses to a short set of debriefing questions.

5 RESULTS—EXPERIMENT 1

Participants' distance judgments were recorded in meters. Distance ratios were calculated by dividing the estimated distance by the actual distance at which the target was presented for each trial. Thus, a ratio equal to 1 indicates that participants accurately perceived the distance to the target, while a ratio greater than one indicates overestimation of distance to the target, and a ratio less than 1 indicates that the distance to the target was underestimated. Data are available at https://osf.io/rjwqn/.

Prior to performing the analyses, we averaged together the ratios for the two trials at each distance for each viewing condition block. A 2 (viewing condition: AR, RW) $\times$ 6 (distance) $\times$ 2 (viewing location: hallway or open room) $\times$ 2 (order: AR first or RW first) repeated-measures **analysis of variance** (**ANOVA**) with ratios as the dependent variable was run. Viewing condition and target distance were within-participants factors, while viewing location and order were between-participants factors. For all of the following analyses, Greenhouse-Geisser corrected results (and adjusted degrees of freedom) are reported when the assumption of sphericity was violated.

There was a main effect of viewing condition ($F(1, 21) = 48.04$, $p < 0.001$, $\eta_p^2 = 0.70$); visually matched estimates were underestimated more (i.e., had lower ratios) in the AR viewing condition ($M = 0.80$, $SD = 0.15$) compared to the RW condition ($M = 0.97$, $SD = 0.12$) (see Figure 3, left). There was also a main effect of distance ($F(1, 21) = 6.13$, $p < 0.001$, $\eta_p^2 = 0.23$) such that ratios decreased as distance increased, suggesting greater underestimation at farther distances. Planned repeated contrasts on distance indicated that ratios significantly decreased from 25 m to 30 m ($F(1, 21) = 6.87$, $p < 0.05$, $\eta_p^2 = 0.25$). There was a main effect of location ($F(1, 21) = 4.60$, $p < 0.05$, $\eta_p^2 = 0.18$) in that distance estimates were underestimated more in the large room ($M = 0.85$, $SD = 0.15$) compared to the hallway ($M = 0.93$, $SD = 0.16$) (see Figure 3, right). Additionally, there was a significant interaction between distance and location ($F(1, 21) = 2.75$, $p < 0.05$, $\eta_p^2 = 0.12$), which suggests that the pattern of increasing underestimation with distance differed for the two locations. To further examine this interaction, we conducted a one-way repeated-measures ANOVA with distance as a within-participants variable for each location separately. Ratios significantly decreased with distance in the large room ($F(2.27, 27.18) = 6.65$,

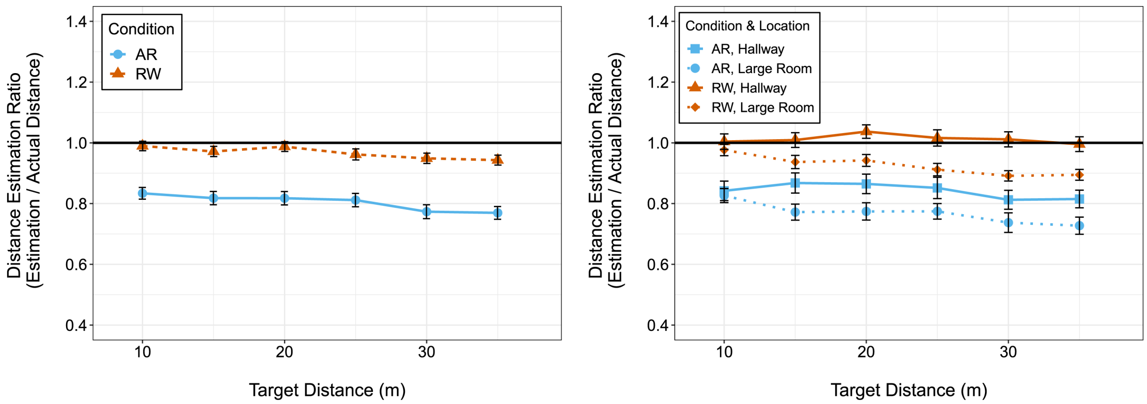

Fig. 3. Experiment 1 (matching) ratio results. In both graphs, the horizontal solid black line at 1.0 indicates perfect accuracy. Error bars indicate one standard error above and below the mean ratio. The graph on the left displays the main effect of viewing condition; distances were underestimated more in AR (solid blue line with circle points) compared to the RW (dotted orange line with triangle points). The graph on the right depicts the mean ratios by location and viewing condition. In both viewing conditions, distances were underestimated more in the large room (dotted lines) compared to the hallway (solid lines). Underestimation also increased with increasing distance in the large room.

$p < 0.01$, $\eta_p^2 = 0.36$). Planned repeated contrasts indicated that ratios significantly decreased from 10 m to 15 m ($F(1, 12) = 15.85$, $p < 0.01$, $\eta_p^2 = 0.57$) and from 25 m to 30 m ($F(1, 12) = 9.10$, $p < 0.05$, $\eta_p^2 = 0.43$). In contrast, ratios did not differ across distances in the hallway. All other effects were non-significant (*ps* > 0.05).

We also analyzed the variability of distance estimations. Within-participants variability was computed as the standard deviation of the mean of the two estimates (in meters) at each distance for each viewing condition. A 2 (viewing condition: AR, RW) × 6 (target distance) × 2 (viewing location: hallway or open room) × 2 (order: AR first or RW first) repeated-measures ANOVA was run with the standard deviations as the dependent variable. Viewing location and order were between-participants factors, while viewing condition and distance were within-participants factors. As expected, there was a main effect of distance ($F(3.49, 73.26) = 6.72$, $p < 0.001$, $\eta_p^2 = 0.24$). As distance increased, variability in visually matched estimates increased. There was also a main effect of condition order ($F(1, 21) = 6.62$, $p < 0.05$, $\eta_p^2 = 0.24$). Participants who experienced the AR condition first had lower variability overall ($M_{\text{SD}} = 1.13$) compared to participants who experienced the RW condition first ($M_{\text{SD}} = 1.57$). All other effects were non-significant (*ps* > 0.05).

At the end of the experiment, participants were asked about their perception of the AR avatar and whether they perceived it as on the ground or off the ground. Although the avatar was always presented on the ground, 22 of the 25 participants (88%) perceived the avatar as off the ground at some point during the experiment. This could have implications for our results considering that distance estimation can differ based on whether the target object is presented on or off the ground [39].

6 DISCUSSION—EXPERIMENT 1

In Experiment 1, distances were underestimated in AR compared to the real world in both a large, open room and a hallway, but there was more overall underestimation in the large room. This finding contributes more evidence to the argument that distances are underestimated in AR relative to matched RW contexts. Moreover, distances were perceived accurately in the real world ($M_{\text{Ratio}} = 0.97$), concordant with previous work finding accurate distance estimation when using a perceptual matching task [25]. Additionally, there was more underestimation at farther distances, but only for the large room. The visual cues present in the hallway, such as the doorways and the linear perspective indicated by the walls, may have provided stronger cues for distance perception than those in the open room, thereby contributing to the greater accuracy in the hallway. Finally, we found that variability increased with distance, consistent with prior research [8, 40]. Surprisingly, variability also differed between condition order; there was more variability when the RW condition was viewed first compared to when the AR condition was experienced first.

One limitation to the current experiment is the relatively small sample size. Although we ran 25 participants in total, this sample was split across two different environments in a between-participants design. Thus, in Experiment 2, we chose to use a single environment to allow for a larger sample size within-participants, as well as to generalize these findings to a different response measure.

7 EXPERIMENT 2

Our goal in Experiment 2 was to further test predicted differences between perception to augmented and real targets with verbal reports as an absolute measure of distance perception. It is important to examine whether the pattern of results from the relative measure of distance perception assessed in Experiment 1 generalizes to absolute measures. Absolute distance is specified by different visual cues (e.g., eye height-scaled perspective cues), and absolute measures of distance perception reflect perception of scale without a visual comparison. Experiment 1 revealed that perception of distance to an AR target is underestimated more than to a real target when visually comparing to another extent, but it did not tell us whether AR distances are perceived in absolute scale differently than real targets. Assessing distance perception with both types of measures allows for better generalizability of any resulting claims about AR distance perception as it compares to the real world. Finally, understanding how verbal reports capture distance perception in action space is particularly relevant because they are typically more feasible to use at farther distances compared to matching tasks.

In Experiment 1, distances to targets were underestimated when they were presented in AR compared to the real world, in line with prior work that also found distance compression in AR. We predicted that we would find this same effect in Experiment 2, as previous studies using verbal reports to estimate distances in AR have also displayed underestimated distance perception. Further, based on prior AR work showing inconsistent scaling across space [20, 23], we predicted greater underestimation to AR targets with increasing distance.

We had two specific hypotheses:

- **H1.** Verbal reports of distance to AR targets will be underestimated more than verbal reports of distance to real targets.
- **H2.** As distance increases, there will be a greater increase in the amount of underestimation to AR targets than real targets.

7.1 Participants

Thirty-three participants were recruited from the University of Utah Department of Psychology participant pool. One participant was removed who failed to pass the stereogram test, leaving 32 participants for analysis (20 Female, $M_{\text{age}} = 21.75$, $SD_{\text{age}} = 5.23$). Participants had normal or corrected-to-normal vision and provided informed consent. They received either course credit or $5 for their participation.

7.2 Stimuli and Design

The same HoloLens 1, large library room, and avatar target were used as in Experiment 1. Participants experienced two viewing conditions: an AR condition and a RW condition. The order that the conditions were presented was counterbalanced across participants. Participants also experienced two viewing directions: North and East. The change in viewing direction was implemented to reduce the reliance on references or cues to distance in either viewing direction in order to ensure the results were not the consequence of environmental factors present in a single direction that biased estimates. The order of viewing directions was counterbalanced across viewing conditions.

The AR and RW conditions presented participants with 10 distances. Six of these distances were shared among both conditions (10 m, 15 m, 20 m, 25 m, 30 m, and 35 m) and four were not. The four unshared distances served as distractors (so that participants did not see the same set of distances for each direction and condition) and were subsequently not analyzed (distractor distances: 13 m, 18 m, 27 m, and 32 m in AR; 16 m, 21 m, 24 m, and 29 m in RW). Additionally, there was one practice trial for each viewing condition. This practice trial took place at the beginning of the AR and RW trials and was always 17 m in the AR condition and 19 m in the RW condition. The 10 distances were presented twice in a random order, and no distance was ever presented twice in a row.

7.3 Procedure

After granting consent, participants took a random-dot stereogram test to ensure they had stereo vision. Participants were then presented with a yardstick and shown what 1 foot, 2 feet, and 3 feet looked like. Participants were also told that 3 feet is slightly less than a meter. After receiving the distance references, participants were read the instructions and donned the HoloLens.

In the RW trials, participants estimated the distance from themselves to another experimenter by verbally reporting the extent in feet or meters (whichever unit they preferred). Before each trial, participants were asked to turn around and face the other way while the experimenter walked to the appropriate position. The HoloLens remained powered off throughout this condition, but the participants were wearing it and viewing the RW distances through the inactive lenses.

In the AR trials, participants verbally reported the distance from themselves to an AR avatar in their preferred unit of measurement (feet or meters). They were specifically instructed to base their estimates on where they perceived the AR avatar's feet to touch the ground. In these trials, participants would make an estimate and then they would say "ready" to make the avatar disappear and then "next" to start the next trial. When all trials were completed, participants were asked a few debriefing questions.

8 RESULTS—EXPERIMENT 2

The data was analyzed in the same way as Experiment 1. Participants' verbal reports of distance were recorded in meters, and distance ratios were calculated by dividing the estimated distance to the target by the actual distance to the target. A ratio of 1 indicates perfect accuracy, while a ratio greater than 1 indicates overestimation of distance, and a ratio under 1 indicates underestimation. Data are available at https://osf.io/rjwqn/.

Prior to performing the analyses, we averaged together the ratios for the two trials at each distance for each viewing condition. A 2 (viewing condition: AR, RW) × 6 (distance) × 2 (order: AR first or RW first) repeated-measures ANOVA with ratios as the dependent variable was run. Viewing condition and target distance were within-participants factors, while order was a between-participants factor. Greenhouse-Geisser corrected results are reported when theANOVA assumption of sphericity was violated. There was a main effect of viewing condition ($F(1, 30) = 35.17$, $p < 0.001$, $\eta_p^2 = 0.54$). Distances were underestimated more in the AR viewing condition ($M = 0.64$, $SD = 0.37$) compared to the RW viewing condition ($M = 0.90$, $SD = 0.42$) (see Figure 4, left). The interaction between condition and distance was significant ($F(2.78, 83.51) = 8.94$, $p < 0.001$, $\eta_p^2 = 0.23$). To further examine this interaction, we conducted a one-way repeated-measures ANOVA with distance as a within-participants variable for each condition separately. As shown in Figure 4 (left figure), ratios significantly increased with distance in the RW viewing condition ($F(1.89, 58.64) = 5.09$, $p < 0.05$, $\eta_p^2 = 0.14$). Planned repeated contrasts indicated that ratios significantly increased from 10 m to 15 m ($F(1, 31) = 4.46$, $p < 0.05$, $\eta_p^2 = 0.13$) and from 15 m to 20 m ($F(1, 31) = 8.24$, $p < 0.01$, $\eta_p^2 = 0.21$), but did not increase beyond 20 m. In contrast, ratios did not differ across distances in the AR viewing condition. There was also a significant interaction between target distance and viewing condition order ($F(1.67, 49.96) = 4.63$, $p < 0.05$, $\eta_p^2 = 0.13$). To further examine this

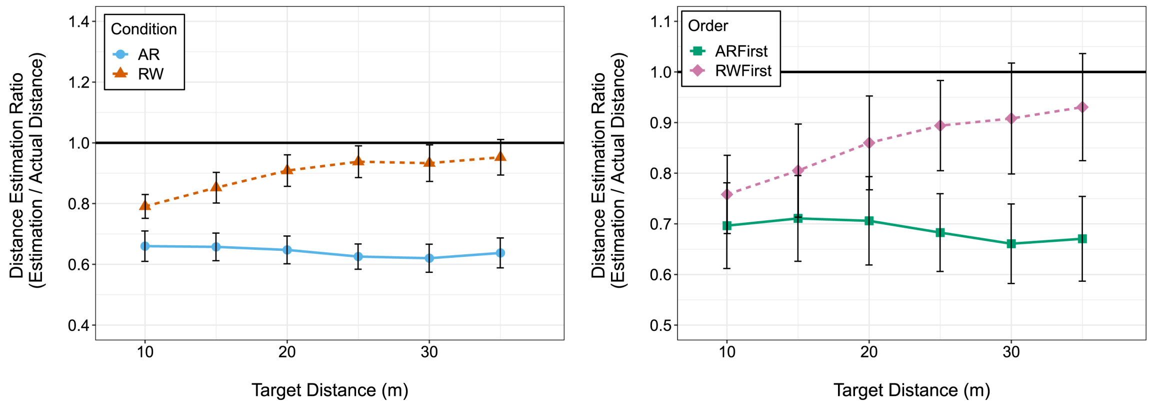

Fig. 4. Experiment 2 (verbal estimation) ratio results. In both graphs, the horizontal solid black line at 1.0 indicates perfect accuracy. Error bars indicate one standard error above and below the mean ratio. The graph on the left displays the viewing condition × distance effects. Distances were underestimated more in AR (solid blue line with circle points) compared to the RW (dotted orange line with triangle points). Condition interacted with distance, such that ratios increased with distance in the RW, but they did not change with distance in AR. The graph on the right displays the order × distance effect. When the RW condition was performed first (dotted purple line with diamond points), ratios tended to increase with distance, whereas ratios did not change with distance when the AR condition was performed first (solid green line with square points).

interaction, we conducted a one-way repeated-measures ANOVA with distance as a within-participants variable for each order separately. Ratios marginally increased with distance when the RW condition was experienced first ($F(1.40, 19.61) = 3.51$, $p = 0.06$, $\eta_p^2 = 0.20$), driven by a significant increase in ratios between 15 m and 20 m ($F(1, 14) = 7.75$, $p < 0.05$, $\eta_p^2 = 0.36$). In contrast, ratios did not change with distance when AR was experienced first (see Figure 4, right). All other effects were non-significant ($ps > 0.05$).

A 2 (viewing condition: AR, RW) × 6 (distance) × 2 (order: AR first or RW first) repeated-measures ANOVA was used to analyze within-participants variability in the verbal estimates. Variability was calculated as the standard deviation of the mean estimates (in meters) for each distance in each viewing condition for each participant. One participant was excluded from the analysis because they only had one trial at the 35 m distance in the RW condition, and, as a result, a standard deviation could not be calculated. This left 31 participants for the variability analysis. There was a main effect of distance ($F(2.32, 67.34) = 4.79$, $p < 0.01$, $\eta_p^2 = 0.14$) such that variability in verbal reports increased with distance. There was a main effect of viewing condition ($F(1, 30) = 6.70$, $p < 0.05$, $\eta_p^2 = 0.19$) in that there was greater variability in the RW condition ($M_{SD} = 2.12$) compared to the AR condition ($M_{SD} = 1.45$). Order was marginally significant ($F(1, 30) = 4.06$, $p = 0.053$, $\eta_p^2 = 0.12$). All other effects were non-significant ($ps > 0.05$).

Similarly to Experiment 1, upon completion of the experiment trials, participants were asked about their perception of the AR avatar and its relation to the ground. Although the avatar was always presented on the ground, 30 of the 32 participants (94%) perceived the avatar as off the ground at some point during the experiment. It is possible that perceiving the avatar as being off the ground influenced participants' perception of distance to the avatar [39].

9 DISCUSSION—EXPERIMENT 2

Experiment 2 examined whether the findings from Experiment 1, which used a relative visual matching measure, would generalize to an absolute measure of distance perception. The absolute measure used in this experiment allowed us to better understand whether the underestimation of distance observed in Experiment 1 may have been due to the misperception of relative extents or to the perception of the absolute distance to the target itself.

When verbal reports (an absolute measure) were used to assess distance perception in this experiment, there was greater underestimation to targets presented in AR compared to real targets, replicating the results of Experiment 1. However, in this experiment, there was an interaction between distance and viewing condition. Ratios increased (became closer to 1.0) with increasing distance in the RW condition, but ratios in the AR condition did not change with distance. It appears that this effect may have been driven by viewing the RW trials first. When participants viewed the RW targets before the AR targets, their estimations were greater at the farther distances. One possible reason why condition order influenced distance perception in Experiment 2 but not in Experiment 1 is that verbal reports are more susceptible to contextual influences such as anchoring effects, where participants base their estimations on responses from preceding trials, than visual matching responses. We expand on this possibility in the general discussion.

Lastly, as in Experiment 1, variability increased with distance. In Experiment 1, variability was significantly higher when the RW condition was viewed first. A similar pattern was observed in Experiment 2, but the difference between orders failed to reach significance. Unlike Experiment 1, though, variability differed between viewing conditions, with the RW estimates showing greater variability than the AR estimates. A possible explanation for lower variability in AR compared to the real world could be that, overall, AR distance estimates were lower, so variability around these estimations would be expected to be lower as well. It could also be that observers relied on strategies or heuristics more consistently for AR targets because their locations were not specified as effectively by visual cues (e.g., lack of shadows).

10 GENERAL DISCUSSION

The goal of the current set of experiments was to investigate how distances to AR targets in action space (up to the boundary of vista space) are perceived when directly compared to the perception of the same distances to real targets in the same environments. In Experiment 1, we assessed the fidelity of perceived distance in AR using a visual matching task, which is a relative measure of distance perception, in two indoor environments. In Experiment 2, we investigated distance perception using an absolute measure of perception: verbal reports of distance. Across both experiments, distances to AR targets were underestimated compared to estimates made to real targets. This underestimation occurred across both of the indoor settings in Experiment 1, which is consistent with prior work in AR [24]. Moreover, variability in distance estimates increased with distance for visually matched estimates and verbal reports.

Specific to Experiment 1, we predicted that there would be less underestimation in the hallway environment compared to the open environment due to an increase in clutter and perspective cues for distance. Consistent with this prediction, we found that distance estimates were underestimated more in the large, open room than in the hallway, regardless of viewing condition. The hallway had stronger linear perspective cues, which has been shown to increase accuracy of distance estimates in AR in prior work [24]. However, it is possible that this difference in underestimation across environments could have been influenced by non-environmental factors such as differences in experimenters or participant sample, given that the two environments were tested at different universities. However, a strength of this design is that we were able to replicate the overall pattern of distance underestimation to AR targets relative to matched real-world targets across two distinct settings.

Experiment 2 assessed the perception of absolute distance to AR targets and real targets in the large, open room. Asking participants to estimate distance using verbal reports allowed us to investigate whether absolute distances (which require a metric-scaled response and may be specified by different visual cues) are similarly underestimated in AR compared to the real world. In Experiment 2, we replicated the finding in Experiment 1 that distances to AR targets were underestimated compared to real targets seen in the same environment.

In addition, there was an interaction between condition order and distance in Experiment 2 but not in Experiment 1. When the AR viewing condition preceded the RW condition, verbal reports of distance were underestimated consistently across distances. In contrast, when the RW viewing condition preceded the AR condition, distance ratios tended to be higher and increase with distance. Order effects have consistently been found when comparing distance estimates to targets presented in VR and the real world. Similar to our findings in Experiment 2, research in VR indicates that when the VR condition is experienced first, distance judgments to real targets are less accurate than when the RW condition is experienced first [35, 50, 51]. A possible reason why order effects were observed in Experiment 2 but not in Experiment 1 may be due to differences in the response method. When estimating distance using verbal reports, participants might be more likely to use the initial numbers they provide as a way to anchor later responses. In fact, at the end of the experiment when participants were asked about strategies that they used to make their verbal estimations, many reported basing their responses on estimates they provided in previous trials. Similar findings of anchoring responses to the range of distances presented have been found for verbal estimations in both farther space [45, 46] and reaching space [29]. In the current experiments, the underestimation of distance to AR targets when performed first may have reduced the distance estimates for real targets (or the reverse—the higher estimations to real targets when performed first may have increased the distance estimates to AR targets). It is unknown why the estimates to real targets increased with farther distances when performed first, but we speculate that distances beyond 20 m might have been more difficult to judge and cognitive strategies such as relying on the visual meter stick as a reference could have been used. Future work should examine action-based measures of absolute distance as these are less likely to be susceptible to cognitive or relative influences.

10.1 Limitations and Future Directions

There may be several reasons for the observed underestimation to virtual targets in the two experiments presented here. First, with AR targets embedded in RW spaces, the phenomenological experience is often that the AR target appears to be floating off the ground. This lack of perceived grounding of the target could have contributed to the underestimation of distance to the AR avatars relative to the RW comparison (a real person). Providing additional cues for ground contact such as shadows could potentially improve accuracy in follow-up experiments. The HoloLens poses challenges to the accurate presentation of shadows. However, recent work by AR researchers has led to the development of more feasible ways to implement shadows in AR [1, 13, 15], so future studies should investigate how using AR shadows might influence distance perception in action space.

It is also important to recognize that the HoloLens has a severely restricted field of view ($30° \times 17°$) in which the graphical targets are presented. Reduced field of view has been shown to be related to distance underestimation in VR environments in some studies [5] and may also have an impact in AR, particularly at close distances [36]. It is likely less of a concern in the current paradigm where farther distances allowed the target to fit within the display's field of view, but future studies should explore the effects of increasing the field of view as AR devices advance in this area. An additional limitation of the current work is that it only tested distance estimation to avatars or people, which are familiar in size. It is possible that the magnitude of underestimation observed here could change if the target was an unfamiliar or less familiar object.

Future studies should move beyond action space to investigate the perception of vista space distances in both indoor and outdoor RW and augmented or mixed reality environments to be able to test whether the currently observed underestimation in AR holds at farther distances and in different types of environments (e.g., outdoor settings). The feasibility of performing such experiments can be difficult due to limitations of technology (e.g., the HoloLens does not work well outdoors) and of laboratory testing spaces (e.g., the need for extremely large rooms or hallways indoors). But, tablet-based AR could be employed to test outdoor environments [11, 12, 23].

While we generally found consistent results supporting more underestimation to AR targets as compared to real targets across two very different measures of distance perception, there are a number of open questions relating to how perception of AR distances may be task-specific or calibrated similarly or differently than the real world (see [48] for a recent analysis of the role of different optical variables used for different distance perception tasks). As AR technologies improve for tracking action in larger spaces, other measures of absolute distance could be employed, such as walking without vision to previously viewed targets. Further, walking could also allow for calibration of distance perception over trials given visual feedback. Such calibration could potentially counteract the observed underestimation of distance observed in AR in the present studies, as has been found with similar VR distance estimation studies [27, 38, 41]. More systematic investigations of distance estimation in AR compared to the real world across environments, technologies used to display the virtual targets, and measures of perception are needed. The current study provides a foundation and methodology with which to consider conducting this future work.

10.2 Conclusions

Taken together, the two experiments presented here clearly show that perceived distance to virtual targets in real environments—as assessed with both relative and absolute measures of distance perception—are underestimated when directly compared to distance estimates to real targets in the exact same viewing environment. These results strongly suggest that perceived distance in action space and slightly beyond is different in AR than in the real world. The findings contribute to a growing body of work on perceived distance in AR, but also provide a much needed comparison to distances perceived to real targets in the same environment. General underestimation of perceived distance to virtual targets has implications for training protocols in many fields, such as military training or navigation applications. Future research should investigate how providing additional visual cues in AR might improve distance perception so that it more closely matches perception in the real world.

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