Evaluating Transitive Perceptual Effects Between Virtual Entities in Outdoor Augmented Reality

Juanita Benjamin[*] University of Central Florida
Austin Erickson[†] University of Central Florida
Matthew Gottsacker[‡] University of Central Florida
Gerd Bruder[§] University of Central Florida
Greg Welch[¶] University of Central Florida

Abstract

Augmented reality (AR) head-mounted displays (HMDs) provide users with a view in which digital content is blended spatially with the outside world. However, one critical issue faced with such display technologies is *misperception*, i.e., perceptions of computer-generated content that differs from our human perception of other real-world objects or entities. Misperception can lead to mistrust in these systems and negative impacts in a variety of application fields. Although there is a considerable amount of research investigating either size, distance, or speed misperception in AR, far less is known about the relationships between these aspects.

In this paper, we present an outdoor AR experiment (N=20) using a HoloLens 2 HMD. Participants estimated size, distance, and speed of *Familiar* and *Unfamiliar* outdoor animals at three distances (30, 60, 90 meters). To investigate whether providing information about one aspect may influence another, we divided our experiment into three phases. In *Phase I*, participants estimated the three aspects without any provided information. In *Phase II*, participants were given accurate *size* information, then asked to estimate distance and speed. In *Phase III*, participants were given accurate *distance* and *size* information, then asked to estimate speed.

Our results show that estimates of speed in particular of the Unfamiliar animals benefited from provided size information, while speed estimates of all animals benefited from provided distance information. We found no support for the assumption that distance estimates benefited from provided size information.

Index Terms: Human-centered computing—Human computer interaction—Human computer interaction (HCI) Interaction paradigms—Mixed / augmented reality;

1 Introduction

Augmented Reality (AR) is becoming increasingly popular, and widely available, and people are using this technology more frequently and for longer periods of time. AR displays are employed for a wide range of different application fields, including education, museums, entertainment, and training [24, 38, 45, 65]. We are further starting to see more consumer-oriented AR head-mounted displays (HMD) become available, such as the Microsoft HoloLens 2 and Magic Leap 2. One main issue associated with AR is the misperception of content presented on the display. The misinterpretation of content displayed on the display is a primary problem related to augmented reality. Perceptions of AR content that differ from users' perceptions of real-world objects or entities are referred to as misperceptions. For example, research by Kruijff et al [26]. highlighted factors like head-mounted display registration errors that can lead to visual misperception, influencing perception of the surrounding environment and three-dimensional objects. While a body of research has studied misperception in AR [26], and much progress has been made to understand human perception with AR displays, misperception still remains an issue with current HMDs. In particular, while distance perception is a widely-researched topic [9, 60, 64], and many studies in AR and virtual reality (VR) have shown that distance estimates of virtual content in public space [18] tend to be underestimated [51], this issue still remains present today. For the seamless integration of virtual content into the real world and the creation of convincing AR experiences, these issues with human perception must be resolved.

While a simulated AR object's state, including its size, distance, and speed may be geometrically correct based on trigonometry, human perception of these object properties may deviate from the simulation as it is instead based on a range of visual cues [43] and complex cue integration processes [11]. For instance, perceptions of size and distance are related, as known size information and visual size constancy assumptions [61] can be used to approximate distance, and vice versa. Additionally, speed perception is dependent on estimates of an object's size and position over time. For example, if an object is at a great distance and begins moving closer, its retinal size increases as its distance decreases. Incorrectly estimating the size of an object could potentially have effects on the perceived distance of the object, particularly at long distances where binocular depth cues are less helpful. Similarly, incorrectly estimating either the size or distance of an object could potentially affect the perceived speed of the object. So far, there have been few research studies that looked into how users perceive size, distance, and speed in VR/AR [6]. Moreover, it is not well-understood in how far misperception in one factor transfers over to another, and how providing AR users some of the information, e.g., by measuring the size or distance of an object, may affect their perception of other object properties.

In this paper, we present a human-subject study where we investigated how participants perceive the size, distance, and speed of AR entities in an outdoor environment at three different distances (30, 60, and 90 meters) and three different levels of provided information. For the stimuli, we chose two types of AR entities that are capable of locomotion: modern-day outdoor animals (Giraffe, Elephant, and Rhino), and dinosaurs (T-Rex, Velociraptor, Stegosaurus), which have higher and lower (respectively) familiarity for most people. These animals were chosen because the study is being conducted outside, and we want the stimuli to represent the setting. Additionally, we wanted two categories (1) unfamiliar entities that are not currently existing, with which the participants have no familiarity with, to be compared with (2) familiar entities that participants would have more familiarity with. Furthermore, since one of the factors is speed, it is more suitable to use stimuli that can express speed through a given gait rather than generic models like cubes.

- Phase I: Without any additional information, participants were

[*]e-mail: juanita.benjamin@ucf.edu
[†]e-mail: erickson656@hotmail.com
[‡]e-mail: matthew.gottsacker@ucf.edu
[§]e-mail: bruder@ucf.edu
[¶]e-mail: welch@ucf.edu

asked to estimate an AR animal's **size**, **distance**, and **speed**.

- Phase II: Participants were given accurate information about an AR animals' sizes, then were asked to estimate the AR animal's **distance** and **speed**.
- Phase III: Participants were given accurate information about an AR animal's size and distance, then were asked to estimate the AR animals' **speed**.

We decided on this experimental design to put an emphasis on speed estimates in this study, which received less attention from previous research than distance and size estimation. We hypothesized that in particular speed estimation would improve based on the provided information in Phases II and III, and that the less familiar entities would benefit more than the familiar entities. While we used a fixed order of conditions, focusing on a subset of the potential combinations that could be tested, our results provide interesting support for speed estimation improving when size and distance information is provided.

The remainder of this paper is organized as follows. Section 2 discusses related work. Section 3 presents our experimental design and formalizes our hypotheses. Section 4 reports our results. Section 5 discusses the results with respect to our hypotheses as well as the limitations of our study. Finally, Section 6 concludes the paper.

2 Related Work

In this section, we provide an overview of related work on distance, size, and speed estimation in AR.

2.1 Distance Estimation in AR

Most previous studies related to perception in AR have focused on proximal egocentric distances as opposed to longer, out-of-reach distances [13, 19, 49, 60]. In particular for training applications, where users may engage with objects at long distances in AR and then apply their training in the real world, it is important to understand how these longer distances are perceived [13]. Some studies have shown that distances in AR tend to be underestimated [1, 9, 39, 50], and longer distances are less accurate to assess than shorter ones up to 20 meters [69]. Swan et al. [59] reported an experiment in which they used an optical see-through (OST) HMD to evaluate egocentric distance perception at distances ranging from 5 to 45 meters in a indoor corridor. For close distances up to 23 meters the results indicated that the distances of the virtual objects were overestimated, while for distances beyond 23 meters were underestimated. Livingston et al. [31] conducted a study that used a similar method but with both indoor and outdoor environments ranging in distances up to 40 meters. Their findings indicated that the distances of virtual objects were overestimated in all indoor conditions but were underestimated when observed outside. Adams et al [1] designed an experiment to evaluate distance measurements in a Microsoft HoloLens 2, and a video-see-through (VST) display, the Varjo XR-3. Participants had to determine the distance of spheres that were placed on the ground absent of shadows and spheres that were floating with shadows rendered below. Their results show distance underestimation for all target spheres, but the spheres with shadows were estimated significantly more accurately than those without shadows. One of their hypotheses suggested that there will be an interaction between the height of the spheres and shadows, but the authors concluded that regardless of the object's height, distance judgements were influenced by the shadows. Additionally, they also state that distance was underestimated more in a VST HMD than an OST HMD, confirming prior work [7, 48, 66].

It is difficult to determine precisely how participants perceive the egocentric distance of real or virtual objects that they see. Perception is a cognitive state that cannot be directly quantified, and researchers must rely on indirect approaches to glean insights [19]. A range of different methodologies have been proposed, evaluated, and validated for distance estimation in VR and AR, including blind walking, triangulated walking, blind throwing, timed imagined walking, blind pointing, perceptual matching, two-alternative forced choice tasks, and verbal reports [4, 5, 10, 19, 25, 37, 55, 57]. However, it was found that overall these methods all provide useful estimates of perceived distances, indicating similar patterns of overestimation or underestimation effects, though with different magnitudes, as well as different constraints with respect to VR/AR environments and situations in which they can be applied [28, 29, 33, 62, 66, 68].

In this paper, we decided to leverage verbal reports, which are characterized by participants expressing the distance they perceive in familiar units, e.g., imperial or metric units. Verbal reports have been found to be comparable to other methods. For instance, Klein et al. [25] performed a study that measured egocentric distance estimation in a CAVE, a tiled display wall, and a real-world outdoor field, while comparing action-based methods, timed imagined walking, and triangulated blind walking, in addition to verbal reports. Their results from the action-based methods were similar to the verbal estimations in all three environments. According to Gagnon et al. [13], verbal reports are more feasible than action-based measures in many situations since they do not require participants to travel long distances, which they applied in two AR studies. Furthermore, Kunz et al. [27] conducted an experiment to determine the effect of graphics quality on two distance estimates techniques, verbal reporting and blind walking. The authors stated that the blind walking technique resulted in an underestimation of distance walked when viewing low and high quality environments. Verbal judgments, on the other hand, were underestimated in terms of target distances but more accurate in high-quality environments.

2.2 Size Estimation in AR

Previous research has overall suggested that sizes are perceived reasonably accurately in VR/AR [15, 16, 23, 54] when rich familiar size cues are present in the environment, while other studies observed underestimation or overestimation in certain situations. For instance, Ahn et al. [2] conducted an experiment that focused on size perception of an augmented object (a box) through three devices: a hand-held mobile device, a VST HMD, and an OST HMD. Their results indicate that the participants overestimated the size of the box when it was viewed through the hand-held mobile device, and underestimated it when viewed through the OST HMD. Combe et al. [8] compared size estimation of a cockpit in virtual and augmented reality, a large cylindrical projection screen and the physical cockpit, where participants were tasked with adjusting the size of the virtual cockpit to match the physical one. Their results indicate that participants overestimated sizes in AR.

When estimating the size of an object, it is important that we can see other objects we are familiar with as references [42]. For instance, Jung et al. [22] evaluated size perception of virtual boxes in a VST HMD condition, showing that the boxes were estimated more accurately if participants were able to use their own personalized hands as a reference.

Though not involving AR, Matlz et al. [36] conducted a study where participants compared the size and distance of two objects: a Rubik's cube and a die. The study sought to see whether familiar size would influence how an object is perceived, and if it did, whether the Rubik's cube would be perceived as being larger than the die. Their results showed that the Rubik's cube was consistently perceived to be larger and farther away than the playing die, which indicates that familiar size cues affected size estimation.

2.3 Speed Estimation in AR

Speed estimation denotes the task of judging the distance an entity is moving per time [32], which in humans relies on various perceptual cues, including those used for distance estimation as well as retinal motion detectors related to optic flow [12]. While some research looked at self-speed estimation when participants are moving in VR, e.g., walking speed [40, 56, 67] or driving speed [3, 52] in the field of redirected walking, or driving simulators [20], we are not aware of many studies looking at speed estimation in AR. Moreover, compared to these studies that focused on self-speed estimation, we are not aware of many studies looking at the speed of other moving objects. However, in general, it has been demonstrated that participants' speed estimates were significantly affected by the contrast of the visual stimuli [58], where the speeds of low contrast stimuli were underestimated [53]. Further, since long distances tend to be underestimated in AR contexts [9, 39], it stands to reason that this could potentially cause second-order effects where observed speeds are also underestimated.

3 Experiment

In this section we describe the experiment we conducted to assess size, distance, and speed perception of different entities at different distances with different amounts of provided information in AR.

3.1 Participants

We recruited 20 participants, all of whom were students at our local university, and studying STEM-related majors. 17 participants identified as male, and 3 identified as female, ages 18–39 ($M = 24.1$, $SD = 5.8$). One participant reported to have a limitiation in red-green color perception but was able to complete the study without problems. No other visual impairments were reported. All participants reported to not have any motor or cognitive impairments. Eleven of them had prior experience with AR. None of the participants reported a fear of dinosaurs (Ornithoscelidaphobia) or animals (Zoophobia). The participants received compensation for completing the experiment.

3.2 Material

In this experiment, participants wore a Microsoft HoloLens 2 OST AR HMD, which has a resolution of 2048 × 1080 pixels per eye and a diagonal field of view of 52 degrees. We used the Unity Engine version 2019.4.15f1 LTS to build the AR experience. Imagery was streamed to the HoloLens 2 using the Holographic Remoting Unity feature from a nearby laptop. The laptop that ran Unity was an Alienware 17 R4 with an i7 Intel CPU and 16 GB of RAM.

The experiment was conducted in an urban outdoor environment at our local university. Specifically, we placed the different AR entities in the area between two distant buildings (see Figure 1).

The HoloLens 2 was set to full brightness during the experiment, and we attached a neutral density filter to the front of the display. Direct illuminance measurements made from the participants' eye positions resulted in values ranging between 344 to 9742 lux ($M = 3497.13$, $SD = 4415.86$). The neutral density filter we chose for this outdoor experiment was attached directly to the visor of the HoloLens 2, resulting in a 85.3% light reduction, which we confirmed with a Konica-Minolta CS-100 luminance meter. In other words, participants could see the animals in AR clearly at all times of day when we ran the experiment.

For the visual stimuli in AR we used six different outdoor animals, three of which were unfamiliar animals and three modern-day familiar animals (see Figure 1). We took the models of these animals from Microsoft's 3D Viewer[1] and Sketchfab[2] which included running and idle animations. We verified and tuned the sizes and running speeds of these models in our AR environment to common values reported for these Familiar or Unfamiliar animals in the literature. As listed in Table 1, the sizes of these outdoor animals ranged from 1.5 to 5.2 meters (i.e., the vertical extent of these 3D characters from their feet on the ground to the highest point on their body), and their running speeds ranged from 1.5 to 16 meters/second. The locations at which we presented these animals were 30, 60, and 90 meters away from the participants in the outdoor environment (see Figure 2), which we marked in the real environment using a laser distance meter and ensured to match the animals presented in the HoloLens 2's view. Our participants completed the Interpupillary Distance (IPD) calibration procedure of the HoloLens 2 before the start of the experiment.

[1] https://apps.microsoft.com/store/detail/3d-viewer/9NBLGGH42THS

[2] https://sketchfab.com/

Table 1: Animal stimuli with their characteristics used in the experiment (references added in brackets behind the values).

Name	Familiarity	Size (in m)	Speed (in m/s)
Rhino	Familiar	1.5 [44]	11.2 [44]
Giraffe	Familiar	4.58 [41]	16.0 [14]
Elephant	Familiar	2.75 [30]	11.2 [21]
Velociraptor	Unfamiliar	1.67 [46]	11.2 [63]
Stegosaurus	Unfamiliar	4.2 [34, 35]	1.5 [63]
T-Rex	Unfamiliar	5.2 [47]	11.2 [63]

3.3 Methods

This section describes the methods we chose for our experiment.

3.3.1 Conditions

In this experiment, we used a within-subject design with the following factors:

- **Phase (3 levels):** This experiment was divided into three phases. Each phase provided participants with an increased amount of information about the animals they were looking at. In Phase I, participants were not provided with any information about the animals, and were left to make their size, distance, and speed estimations based solely on what they observed. In Phase II, participants were informed of the *size* of the animals prior to making distance and speed estimations. Finally, in Phase III, participants were informed of both the *size* and *distance* of the animals prior to making speed estimations.
- **Familiarity (2 levels):** The animals displayed to the participants were split into two groups based on whether they are familiar or are unfamiliar. The dinosaurs were classified as *Unfamiliar Animals* and the modern-day animals were classified as *Familiar Animals*. We chose three specific animals in each group to that are suitable for an outdoor environment, and cover an ecologically valuable range of sizes (tall, medium, and short) and speeds (fast, medium, slow). Details are shown in Table 1.
- **Location (3 levels):** In line with previous studies in this field, we have chosen three locations at which the animals were presented during the experiment. The first location was 30 meters away from the participant, the second location 60 meters, and the third location 90 meters (see Figure 2). We decided to only evaluate locations in public space as most of the animal stimuli we used in our experiment were not considered to occur in social or personal space. Each of the animals was evaluated at all three locations.

The study was counterbalanced into two blocks A and B. In Block A, the first half of the participants saw the *Familiar Animals* at each of the three *Locations*, then the *Unfamiliar Animals* at each of the *Locations*. In Block B, the second half of the participants had the reverse. They were presented the *Unfamiliar Animals* first and then the *Familiar Animals*, both at each of the *Locations*. For each animal, the order of the *Locations* was randomized. The viewing time for each animal was its distance / speed.

Figure 1: Visual stimuli used in the experiment: The left column images (a), (c), and (e) show the three *Familiar Animals* while the right column images (b), (d), and (f) show the three *Unfamiliar Animals*. The images were captured with Microsoft's live preview of the HoloLens 2's imagery.

3.3.2 Measures

We included the following dependent variables in our experiment:

- **Size, Distance, and Speed Estimates:** In three phases, participants estimated the size, distance, and speed of animals. They used their preferred units and reported real numbers. Size was the animal's height from feet to highest point, distance was from the participant, and speed was the running speed, which was kept constant. To be able to compare the responses between the different animals and locations, we ***normalized*** the estimates by first converting the participants' units to meters or meters/second and then dividing these values by the veridical size, distance, or speed of the animal.

- **Confidence Estimates:** We used a post-experiment questionnaire with questions asking participants how confident they felt in their estimates of the animals' sizes, distances, and speeds on a scale from 1 to 7 (1 = very low, 7 = very high).

3.3.3 Procedure

Before the start of the experiment, the participants gave their informed consent to participate. The participant and the experimenter then proceeded to an area outside of our lab at the local university to begin the experiment. The participant then donned the HMD and was instructed to remain standing on a marked location during the experiment. As described in Section 3.3.1, we counterbalanced the order of *Familiar* and *Unfamiliar Animals*, which were completed in two separate blocks (with the three phases) for each participant, where they first experienced all *Familiar Animals* and then all *Unfamiliar Animals* or vice versa. In each block, participants completed the following three phases.

- **Phase I**: In the first phase, participants were not given any information about the size, distance, or speed of the entities presented. They were asked to verbally estimate the size of the animals in their unit of choice (e.g., meters or feet). Size was explained to them as the height of the animals from their feet on the ground to the highest point on their body. Participants then estimated the distance to the animals by answering the question: "From your perspective, what is the distance from you to the animal?" Lastly, participants saw the entity running towards them, after which they were asked to estimate the running speed of the animal over the ground in their unit of choice (e.g., kmh or mph). The process was performed for each of the three animals (per Familiar/Unfamiliar block) at

Figure 2: Images showing the T-Rex at three locations: (a) 30 meters, (b) 60 meters, and (c) 90 meters away from the participants.

each of the three locations. The order of the three animals was randomized. The *Location* variable was tested in random order for each animal.

- **Phase II**: In the second phase, participant were provided accurate *size* information about all of the animals. Specifically, they were told the size of the animal they were currently seeing in their unit of choice. With this knowledge, the participants then performed the same procedure for distance and speed estimates as outlined in Phase I. As we provided the participants with size information, we did not ask them to estimate the size of the animals in this phase.
- **Phase III**: In the third phase, participants were provided both accurate *size* and *distance* information about all of the animals. Specifically, they were told the size of and distance to the animal they were currently seeing in their units of choice. Otherwise, participants performed the same procedure for speed estimates as in the aforementioned phases.

After completing both blocks with all three phases of the experiment, the participants were led back into our lab to complete a post-questionnaire. The experimental procedure was approved by our university's Institutional Review Board (IRB).

3.3.4 Hypotheses

Based on related work in this field (see Section 2) and our own reasoning, we developed the following hypotheses, which we evaluated in this experiment.

H1 Estimates for *Distance* and *Speed* will improve as information is provided in later phases.
As distance estimation relies on a variety of cues that take into account the size of an object, we expected that providing size information in Phase II will improve distance estimates over Phase I. Similarly, speed estimation depends on the distance covered per time, which we expected to improve in Phase II over Phase I, and even more in Phase III over Phase II. As we did not provide participants with any other feedback about their estimates, we did not expect to see other notable carry-over effects due to the fixed order of our phases.

H2 Estimates for *Unfamiliar Animals* will be less veridical than those for *Familiar Animals*, and information provided in later phases will benefit estimates for *Unfamiliar Animals* more than *Familiar Animals*.
While we can not rule out that participants may have notions of the properties and abilities of Unfamiliar animals from museums, movies, and theme parks, we expected them to be more familiar with Familiar than Unfamiliar animals. We expect that familiar size and speed cues and corresponding priors in cue integration will improve estimates for more familiar entities over less familiar entities.

H3 All animals will be underestimated with respect to distance, overestimated with respect to size, and underestimated with respect to speed.
Based on the literature, we expected ego-centric distances to be underestimated for the long distances tested in our experiment. Overall, we expected estimates in AR to be closer to veridical than for studies run in VR. Similarly, we expect speed to be underestimated as well. If speed relies on distance cues, and if distances are underestimated, we anticipate similar effects on speed estimates. Based on the limited related work on size perception, we hypothesized that the estimates would be overestimated, but closer to veridical than the distance and speed estimates.

H4 Estimates will deviate more from veridical the farther the animal is away from the participant.
As visual acuity is reduced over distance, and cues become less reliable, we expected to see a larger variance in responses and potentially a systematic shift towards near accuracy or underestimation of size, distance, or speed.

4 Results

In this section, we present the results of our experiment for the three dependent variables. Note that size estimates were only collected in Phase I, distance estimates in Phases I and II, and speed estimates in Phases I, II, and III. Following our experimental design, we focused on the analysis of our hypotheses stated in Section 3.3.4.

As described in Section 3.3.2, we normalized the size, distance, and speed estimates by dividing participants' responses by the veridical values. We analyzed the responses with repeated-measures ANOVAs (RM-ANOVAs) and Tukey multiple comparisons at the 5% significance level. We found through QQ plots that the normality assumption of the RM-ANOVA was not supported. We hence applied a ***log transform*** to the data, which then supported the normality assumption. The resulting log-transformed values indicate overestimation for >0 and underestimation for <0. Degrees of freedom were corrected using Greenhouse-Geisser estimates of sphericity when Mauchly's test indicated that the assumption of sphericity was not met.

4.1 Size Estimates: Phase I

The results for size estimates are shown in Figures 3(a) and 4(a), and Table 2. We analyzed the results for the effects of the *Familiarity* and *Location* factors on size estimates. We performed statistical tests with a two-way RM-ANOVA and pairwise comparisons. Our results show a significant main effect for *Location* but not for *Familiarity*.

Specifically, we found no evidence for our Hypothesis **H2** that size estimates for *Familiar Animals* were more veridical than for *Unfamiliar Animals*. We found no support for our Hypothesis **H3** that the sizes in our study were overestimated, showing results that were overall very close to veridical. With respect to Hypothesis **H4**, our results show that size estimates decreased for longer distances of 60 and 90 meters compared to shorter distances of 30 meters.

4.2 Distance Estimates: Phases I, II

The results for distance estimates are shown in Figures 3(b) and 4(b–c), and Table 3. Following our experimental design and hypotheses, we analyzed the results for the effects of the *Familiarity*, *Location*, and *Phase* factors on distance estimates. We performed statistical tests with a three-way RM-ANOVA as well as further one-way RM-ANOVAs, focusing on the main hypotheses of our experiment related to *Familiarity* and *Phase*. Our results show significant effect only for *Location*.

Specifically, we found no support for our Hypothesis **H1** that distance estimates improved in Phase II compared to Phase I. Neither did we find support for our Hypothesis **H2** expecting more veridical responses for *Familiar Animals* than *Unfamiliar Animals*. However, related to our Hypothesis **H3** we found that distances were underestimated for all animals. Further, we found support for Hypothesis **H4** that distance estimates deviated more from veridical the farther the location of the animal was from the participant.

4.3 Speed Estimates: Phases I, II, III

The results for speed estimates are shown in Figures 3(c) and 4(d–f), and in Table 4. Following our experimental design and hypotheses, we analyzed the results for the effects of the *Familiarity*, *Location*, and *Phase* factors on speed estimates. We performed statistical tests with a three-way RM-ANOVA as well as further one-way RM-ANOVAs, focusing on the main hypotheses of our experiment related to *Familiarity* and *Phase*. Our results show significant main effects for *Location* and *Phase*.

Specifically, we found support for our Hypothesis **H1** that speed estimates improved between the phases. In particular, related to our Hypothesis **H2**, the one-way RM-ANOVAs revealed that speed estimates improved from Phase I to II and from Phase II to III for *Unfamiliar Animals*, but less so for *Familiar Animals*, which showed no effect between Phases I and II. In line with our Hypothesis **H3**, we found that speed was underestimated in our experiment. Further, we found support for our Hypothesis **H4** that speed estimates deviated more from veridical for the locations that were farther away from the participants.

4.4 Participant Self-Assessed Confidence

Our post-experiment questionnaire included questions asking participants how confident they felt in their estimates of size, distance, and speed on a 1 to 7 scale (1 = very low, 7 = very high). Participants were asked to assess their confidence separately for each dependent variable as well as the independent variables *Familiarity* and *Location* (see Section 3.3.1). Overall, participants' confidence scores were very similar between all conditions. We found no significant main effect of *Familiarity*.

We found a significant main effect of *Location* on participants' confidence in their size estimates, $F(1.19, 22.56) = 12.79$, $\boldsymbol{p<0.001}$, $\eta_p^2 = 0.40$. Pairwise comparisons showed that participants felt their estimates at 30 meters ($M = 4.45$, $SD = 1.43$) were significantly more accurate than at 60 meters ($M = 3.65$, $SD = 1.23$), $\boldsymbol{p=0.03}$, and at 30 meters more accurate than at 90 meters ($M = 2.95$, $SD = 1.43$), $\boldsymbol{p<0.001}$, which supports our Hypothesis **H4**.

We further found a significant main effect of *Location* on participants' confidence in their speed estimates, $F(2, 38) = 3.57$, $\boldsymbol{p=0.04}$, $\eta_p^2 = 0.16$. However, pairwise comparisons revealed no significant differences.

We found no significant main effect of *Location* on participants' confidence in their distance estimates.

5 Discussion

In this section, we summarize our main findings. Overall, our results gave interesting insight into participants' estimation of sizes, distances, and speeds, as well as their perceptual relationships.

5.1 Estimates of speed improved as information was provided in later phases

In partial support for **H1**, our results indicate that *speed* estimates were improved through the provision of information in later phases but *distance* estimates were not. In particular, Figure 3 shows that the speed estimates generally improved between phases. In Phase I, without any provided information, the animals' speeds were underestimated by on average 43% (mainly due to the drastic underestimation of Unfamiliar Animals), while in Phase II, they were only underestimated by on average 40%, and in Phase III, the underestimation decreased to only on average 25%.

Our results suggest that the provided size information in Phase II helped participants estimate the speed of the animals. Providing additional distance information in Phase III further helped participants estimate their speed. Before we ran the study, we anticipated that distance information would likely provide stronger benefits for speed estimation than size information, as speed is defined as covered distance per time, and only indirectly relies on accurate estimates of sizes. Our results confirmed this notion. However, the particular study design we used does not allow us to make any claims about whether distance information *alone* (i.e., without provided size information) would have sufficed to see the observed improvements in Figure 3, which may be an interesting question for future work.

Compared to speed estimates, we did not find a similar effect for distance estimates. In Phase I, distances were underestimated by on average 50%, while in Phase II they were underestimated by on average 47%. Providing size information in Phase II did not make a noticeable difference in participants' distance estimates. This surprised us, as retinal size cues and familiarity with an entity's size are an important part of distance perception at the long distances we tested in our experiment [43]. However, the overall highly accurate size estimates in our experiment may not have necessitated the provision of size information for accurate distance estimation.

5.2 Information provided in later phases benefited unfamiliar more than Familiar animals

We found only partial support for Hypothesis **H2**. Our results did not show any statistically significant main effects between *Familiar* and *Unfamiliar Animals*. Based on related work (e.g., [17]), we expected to see that estimates for familiar objects would be more accurate than unfamiliar objects. However, as noted in Section 3.3.4, considering the depiction of the unfamiliar animals (dinosauers) in museums as well as movies and other media, it is difficult to confirm just how familiar participants were with the outdoor animals we tested. That said, our results did show that speed estimates significantly improved from Phase I to II for the *Unfamiliar Animals*, which was not the case for the *Familiar Animals* (see Figure 3). This improvement in speed estimates implies that the provision of size information in Phase II benefited the *Unfamiliar Animals* more than the *Familiar Animals*.

5.3 Distances and speeds were underestimated, while sizes were near-accurate

Although we found no evidence that the sizes of the animals in our experiment were overestimated, we could confirm that distances and speeds were underestimated, in partial support for Hypothesis **H3**.

We believe that the plethora of familiar size cues in the environment, e.g., the structures and buildings shown in Figure 1, which

Table 2: Statistical test results for size estimates.

RM-ANOVA	Factor	df$_G$	df$_E$	F	p	η_p^2	Pairwise Comparisons
Two-way	Familiarity	1	19	0.05	0.82	0.003	N/A
	Location	1.49	28.33	12.84	**<0.001**	0.40	All **p<0.05**, except pair (60 m, 90 m)

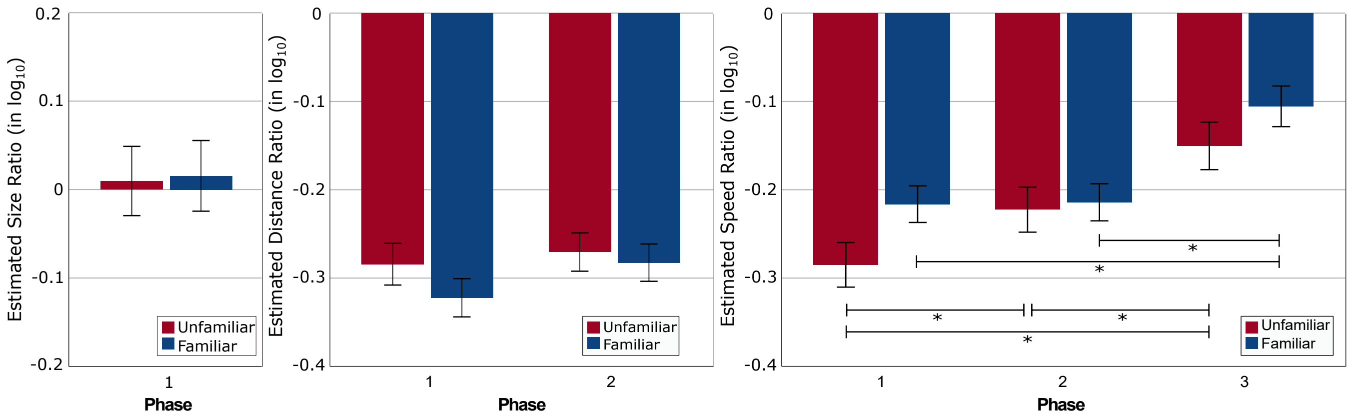

Figure 3: Results for (a) size, (b) distance, and (c) speed estimates. The estimates were computed as the ratio between participants' judged sizes, distances, and speeds divided by the veridical values, after which we applied a log transform as described in Section 4. Values >0 indicate overestimation and values <0 underestimation. The error bars show the standard error. The whiskers indicate significant pairwise differences (with $^*p < 0.05$).

Table 3: Statistical test results for distance estimates.

RM-ANOVA	Factor	df$_G$	df$_E$	F	p	η_p^2	Pairwise Comparisons
Three-way	Familiarity	1	19	2.12	0.16	0.10	N/A
	Location	2	38	51.91	**<0.001**	0.73	All **p<0.05**
	Phase	1	19	0.48	0.49	0.03	N/A
One-way							
for Familiar Animals:	Phase	1	19	0.67	0.42	0.03	N/A
for Unfamiliar Animals:	Phase	1	19	0.24	0.63	0.01	N/A
One-way							
for Phase I:	Familiarity	1	19	0.70	0.41	0.03	N/A
for Phase II:	Familiarity	1	19	1.05	0.32	0.05	N/A

Table 4: Statistical test results for speed estimates.

RM-ANOVA	Factor	df$_G$	df$_E$	F	p	η_p^2	Pairwise Comparisons
Three-way	Familiarity	1	19	3.66	0.073	0.16	N/A
	Location	2	38	9.71	**<0.001**	0.34	All **p<0.05**, except pair (60 m, 90 m)
	Phase	2	38	15.51	**<0.001**	0.45	All **p<0.05**
One-way							
for Familiar Animals:	Phase	1.38	26.22	3.92	**0.048**	0.17	All **p<0.05**, except pair (Phase I, II)
for Unfamiliar Animals:	Phase	1.43	27.14	8.82	**0.003**	0.32	All **p<0.05**
One-way							
for Phase I:	Familiarity	1	19	1.90	0.19	0.09	N/A
for Phase II:	Familiarity	1	19	0.62	0.44	0.03	N/A
for Phase III:	Familiarity	1	19	0.43	0.52	0.02	N/A

participants could use as a reference, positively influenced their ability to estimate the sizes of the animals. In contrast, participants had comparatively few distance and speed cues to work with in our study. The distances were long enough to where binocular vision provided little to no help in estimating the distances or speeds of the animals.

Overall, our results for distance and speed indicate underestimation, which is in line with related work in VR/AR as discussed in Section 2. In particular, long distances such as those evaluated in our experiment tend to be underestimated in VR/AR. For instance, in a study by Gangon et al. [13] they compared distance estimates with real and virtual humans in AR at distances ranging from 10 m to 35 m, showing that the distances to the virtual humans were underestimated. Moreover, in a study using a perceptual matching task with virtual objects at distances from 15 to 75 meters, Hertel & Steinicke [19] showed that the distances to the close objects were overestimated but the longer distances between 45 and 75 meters were underestimated. Last but not least, as speed perception integrates distance cues, we argue that since the distances in our experiment were underestimated, it may in turn have effected similar underestimation of speeds, which is indeed reflected in our results.

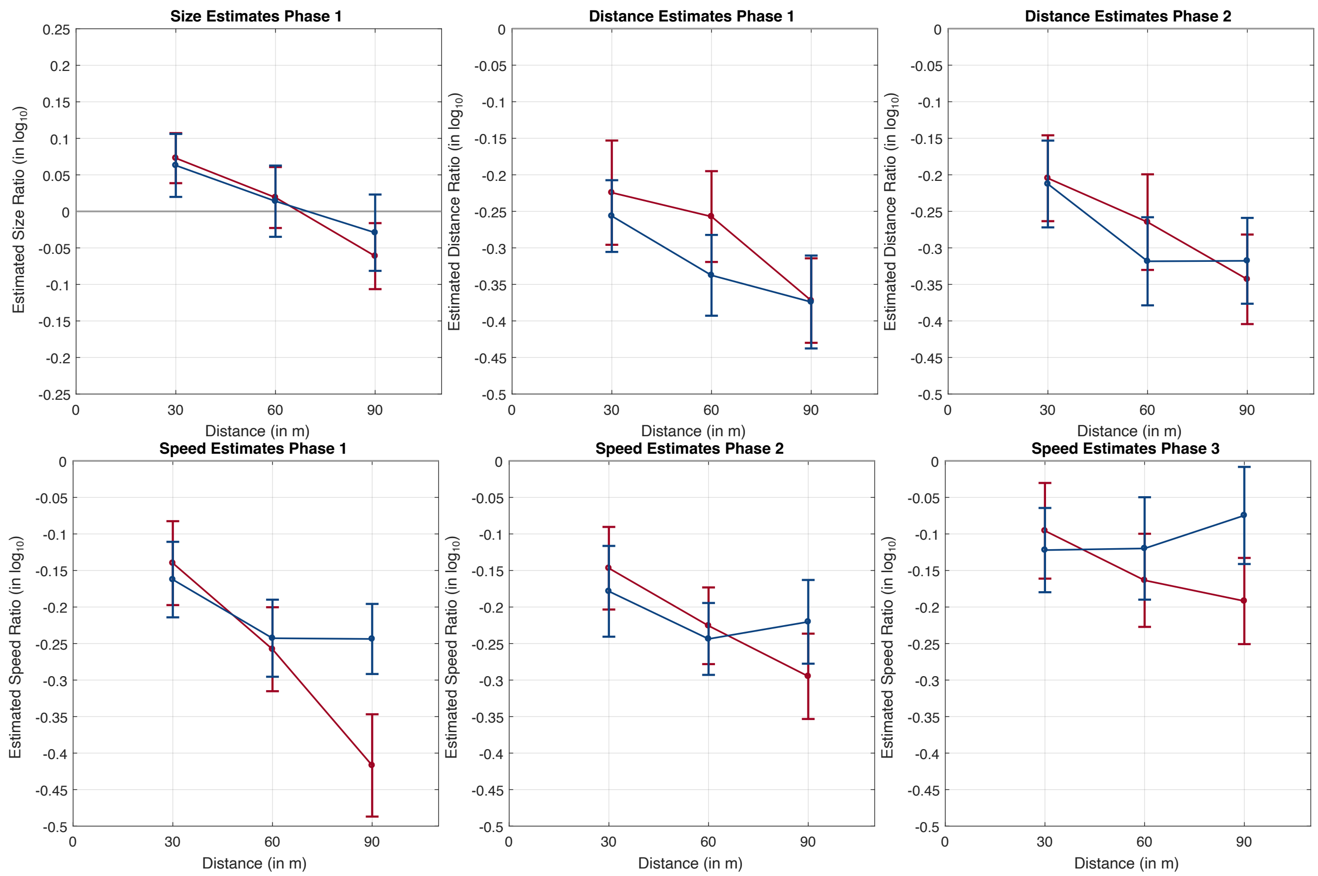

Figure 4: The red lines indicate the estimates for *Unfamiliar Animals* and the blue lines for *Familiar Animals*. Values >0 indicate overestimation and values <0 underestimation. Plots showing the log-transformed ratios between participants' estimates divided by the veridical sizes, distances, and speeds of the animals for the three tested locations (at 30, 60, 90 m): (a) size estimates for Phase I, (b,c) distance estimates for Phases I and II, respectively, and (d,e,f) speed estimates for Phases I, II, and III, respectively. The error bars show the standard error.

5.4 Size, distance, and speed estimates decreased for animals that were farther away

Our results showed significant main effects of the *Location* of the animals on size, distance, and speed estimates in partial support for our Hypothesis **H4**. Specifically, the size, distance, and speed estimates *decreased* the farther the animals were away from the participants. When we designed the experiment, we did not necessarily expect to see a decrease in estimates but rather that estimates would show a reduction in accuracy as the availability of cues decreases for farther animals. Since the resolution of the HoloLens 2 was fixed, the animals subtended a gradually smaller visual angle and thus were presented with fewer pixels the farther they were away from the participants.

For size estimates, animals at the closest location (30 meters away from participants) were estimated as significantly larger than those at the farther locations (60 and 90 meters). In other words, participants' size estimates decreased as animals were farther away. As reported in Section 4.4, participants subjectively felt less confident about their size estimates for the animals that were farther away.

For distance estimates, we found a similar effect in that participants' estimates decreased for animals that were farther away from the participants. Distances were increasingly underestimated for the animals that were farther away, making participants' distance estimates gradually less accurate.

For speed estimates, participants' estimates also decreased for animals that were farther away from the participants. Similar to distance estimates, speeds were generally underestimated, resulting in estimates that became gradually less accurate for animals that were farther away.

5.5 Limitations and Future Work

In this study, we decided to look at the three factors size, distance, and speed as these were attractive to us due to their mathematical and physical relationships and related work indicating that they are often misperceived. However, future work should broaden this group by looking at other factors, such as interposition, affordances, etc. Further, we believe it would be interesting to look at alternatives to the fixed order of provided information we used (size in Phase II, size and distance in Phase III). Informing participants about distances first, while evaluating size estimation, or including speed information among these aspects may reveal other interesting relationships. Further, this work could be expanded to include other types of 3D models like robots, virtual humans, or vehicles of different variations, where these entities can be compared to real-world objects.

In this study, we recognize the absence of a baseline condition, which could have provided a comparison between real-world objects and 3D objects. It would have been difficult to obtain access to real-world animals for the specific stimuli used, making comparing between real world animals and 3D animals very difficult. We could not have used generic items like boxes, because to assess the participants judgements of the real objects, it had to be capable of locomotion on its own with an added visual of its gait, which it lacks. If possible, this baseline would have helped give insight into whether the participants could make accurate judgements about the aspects (size, distance, and speed) related to the real-world objects. With this additional baseline, statistical analysis could have revealed more about the misperception of 3D AR content in the real world.

Another limitation of our study was that we chose animals as our AR stimuli, which may or may not generalize to other objects or entities. Some participants may have been more familiar with some of them than others. Future work may apply the methodology introduced in this paper to other classes of objects and entities, from more abstract stimuli to more practically relevant ones such as estimating vehicles in traffic.

Last but not least, we also acknowledge that our participant sample included more male than female participants (17 to 3 out of 20). While we aimed for a balanced gender representation, we were unsuccessful in attracting equal numbers. While, so far, the literature on this topic does not suggest notable gender effects, it may be interesting to confirm our results with a broader and more diverse sample in future work.

6 Conclusion

In this paper, we described an experiment (N=20) in which we evaluated size, distance, and speed estimation in outdoor AR at three locations (30, 60, 90 meters) and for two groups of Familiar and Unfamiliar outdoor animals (i.e., modern day animals and dinosaurs) with the Microsoft HoloLens 2. We further evaluated participants' estimates over three phases, in which we provided them with either no information (Phase I), accurate information about the size of the entity (Phase II), or accurate information about both the size and distance of the entity (Phase III). Our results show that speed estimates benefited from both provided size and distance information, especially for the Unfamiliar animals, while we found no benefits of provided size information for distance estimates. The results further indicate general size near accuracy, distance underestimation, and speed underestimation. Moreover, we found general effects of the distance of the AR entity, with less accurate distance and speed estimates and more accurate size estimates for entities that were farther away. In future work, we propose looking into further relevant second-order effects, where providing AR users with certain relevant information (e.g., information that is often misperceived in AR) to improve their estimation of other aspects of their environment, from spatial aspects such as the interposition of entities to more action-oriented aspects such as affordance estimates.

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