Affordances as a Measure of Perceptual Fidelity in Augmented Reality

Grant Pointon* University of Utah, USA
Chelsey Thompson† University of Utah, USA
Sarah Creem-Regehr‡ University of Utah, USA
Jeanine Stefanucci§ University of Utah, USA
Bobby Bodenheimer¶ Vanderbilt University, USA

Abstract

The utility of mediated environments increases when environmental scale (size and distance) is perceived accurately. This paper presents the use of perceived affordances—judgments of action capabilities—as an objective way to assess space perception in an augmented reality environment. The paper extends the use of affordance judgments in a similar context from completely virtual environments. In the current study, we asked observers to judge whether they could pass through a holographic aperture presented at different widths and distances, and then to judge the distance to the aperture. We demonstrate that affordances for passing through apertures in a partially mediated environment are similar to those previously measured in an immersive virtual environment and in the real world.

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

1 Introduction

An enduring question for the design of applications that involve perceiving virtual spaces is how accurately the size of the space in these displays is perceived. For example, if architects model a new space virtually, then it is important that they understand how large the space will look in reality in order to facilitate effective action in the space. Our prior work has used the term *perceptual fidelity* to refer to the degree to which a mediated environment is perceived similarly to the real world. In this prior work, we focused on how viewers perceive environmental scale in virtual reality (VR) as compared to the real world. For the current study, we leverage the same methods used in our past work to assess the perceptual fidelity of an augmented reality (AR) device (Microsoft HoloLens). AR applications such as spatial training for navigation become much more useful when the augmented environment is acted upon as if it were a completely real space. Specifically, we draw on *affordance judgments* and action-based measures that we have demonstrated to be an effective and objective measure of perception for action in virtual environments [6, 7]. We asked people to view a holographic aperture grounded to the real world and to report whether or not they could pass through it at different widths. As a converging measure, we then asked viewers to walk without vision to the center of the aperture in order to determine whether distance to the aperture was accurately perceived. Our preliminary results are compared to our prior work, which used the same experimental design to test these perceptions in the real world and in a head-mounted-display immersive virtual environment [6].

*e-mail: grant.pointon@psych.utah.edu
†e-mail: zephcatgames@gmail.com
‡e-mail:sarah.creem@psych.utah.edu
§e-mail:jeanine.stefanucci@psych.utah.edu
¶e-mail: bobby.bodenheimer@vanderbilt.edu

2 Background

Action-based measures of perception offer a reliable and objective way of assessing the perceptual fidelity of a mediated environment [1, 6]. In this work, we use two action-based measures of space perception: affordance judgments and blind walking. Affordance judgments derive from J. J. Gibson's theory of affordances [8], which claims that users' perception of the environment reflect the relationship between the properties of their bodies and the properties of the environment. In other words, humans perceive environments in terms of the action possibilities within that environment. For example, an aperture affords passage if a user's shoulder width is smaller than the aperture's width [26]. Previous work has shown that people judge affordances for passage in immersive virtual environments in a similar manner to a visually matched real environment [6]. Also, users can accurately judge whether or not a cube is graspable and an aperture affords reaching when viewing a desktop virtual environment displayed in stereo [23]. However, whether users can accurately judge affordances in an augmented reality environment is unknown.

We use the the term *affordance* judgments in the current study as it is traditionally used in the field of visual perception—a measure that indicates viewers' direct perception of action possibilities. Affordance judgments in this context provide an objective measure of whether actors perceive environmental features that are displayed virtually similarly to their perception of actual environmental features in the real world. It is noteworthy that within the HCI community, affordances take on a somewhat different meaning, defined by Norman [20] as design features or principles that encourage actions. It is this concept of affordances that has been explored in AR, with the goal of providing cues, sometimes called *cognitive affordances*, that guide users about the best way to interact with the AR system. For example, different visual cues may signal users about how to interact with a gesture-based interface [5, 15, 21]. While AR has the potential to create or enhance affordances, this is not the goal of the current paper. Instead, we use affordance methodology to evaluate and further understand humans' perception in AR.

In addition to measuring space perception via affordance judgments, we also employed another reliable and well known action-based measure of space perception: blind walking. In a blind walking task, people view a target and then are asked to walk without vision to the targets previously perceived location. Many studies have used blind walking as a measure of distance perception in the real world, and they typically find that individuals are highly accurate at blind walking to distances up to 20 meters [19]. In addition, a number of studies have assessed peoples ability to blindwalk to previously viewed targets in immersive virtual environments. People tend to show underestimation (ranging from 20-50%) when replicating the distance up to 10 meters or so, but recent work suggests that accuracy is increased in the newer, commodity-level HMDs, such as the HTC Vive or the Oculus Rift [2, 13, 27]. Several studies have previously used blind walking measures to assess distance perception to virtual targets presented in the real world with augmented reality as well. For the majority of studies, less distance underestimation has been seen in AR compared to matched VR studies [11, 24], perhaps because of the additional real environment cues for distance, however this may also depend on the amount of feedback or calibration that is experienced [9, 25]. We introduce blind walking to our study of AR affordances to test whether different, but converging measures of space perception produce consistent results.

Accurate perception of scale in AR may be even more of a challenge than in VR because of the conflicting distance cues from the real world background and the superimposed display of the virtual objects. For example, Smith et al. [22] report greater variability in distance judgments of real-world objects in the presence of AR graphics than without. Other challenges may result from the severely reduced field of view, the limited range of ideal hologram placement 1.25 - 5m from viewer) recommended by the HoloLens developers (https://developer.microsoft.com/en-us/windows/mixed-reality), and the transparent nature of the virtual objects that makes them difficult to ground within the real space (for an overview, see Kruijff et al. [14]). However, the presence and context of the real environment, as well as the visibility of the viewer's body and location within the environment, could counteract these challenges and support affordance judgments, which rely on the scaling of one's own body dimensions.

The current study will provide a preliminary assessment of whether affordance judgments can be used to assess the perceptual fidelity of a mediated augmented reality environment, and whether any biases seen are consistent across judgments of action capabilities and distance. Technology for AR is developing rapidly, which leads to many open questions as to how it can be used for various applications. Understanding whether it can accurately display the size and distance of objects within a real space will be important for designing more complex future applications, specifically focused on spatial navigation tasks that involve locomotion and use of landmarks. Thus, in this experiment, we compare judgments of whether an aperture is passable and the distance blind walked to the aperture to our prior work, which used the same methodology in head-mounted displays for immersive virtual environments and to the real world. Benchmarking an augmented reality against the previously collected data will allow us to assess its potential for accurate portrayal of distance and size in future experiments and applications.

3 Experiment

3.1 Participants

Participants for the AR experiment were recruited from the University of Utah's Psychology department. In total, 13 individuals participated in the experiment but 3 were excluded due to technical issues. Therefore, we were left with 10 total participants (7 female, 3 male, *M* age = 25.6 yrs, $SD = 4.6$). All participants completed informed consent and were compensated for their time. In our previous study, 10 individuals participated in the real world experiment (6 female, 4 male, *M* age = 25.9 yrs, $SD = 7.77$) and in the virtual reality experiment (5 female, 5 male, mean age = 25.9 yrs, $SD = 1.5$)(see [6] for more detail).

3.2 Apparatus and Stimuli

The experiment was built with Unity (version 2017.3) on a Windows 10 laptop and ran as a standalone application on the Microsoft HoloLens. A separate experiment build was created for each participant in order to pre-randomize experimental trials. The HoloLens weighs approximately 579g, and has a field of view of approximately $30^\circ \times 17^\circ$. The experiment was conducted in an rectangular real room (8.5 m x 11.5 m) with two vertical virtual poles (20 cm diameter and 183 cm tall), see Figure 1 and Figure 2.

3.3 Design

We used a pre-randomized block design that was modeled off of our previous work [6]. In the first block of trials, participants judged whether or not they could pass between two holographic poles without turning their body and with their arms at their side. The poles had a height of 183 cm and were presented at a distance of 3m, 4.5m, or 6m. Each distance was repeated twice, once where the width between the poles started wide (60cm) and moved inward, and another where the poles started narrow (30cm) and moved outwards. The width between the poles for all distances changed in 5cm increments every 7 seconds and trial order was pseudo-randomized such that no one distance occurred twice in a row. For the second block of trials, participants viewed the same two holographic poles as in block 1. The poles were presented for 7 seconds at one of three distances (3m, 4.5m, or 6m) with a fixed gap width (60cm) and then disappeared. We chose the widest gap because we did not want participants to be concerned about 'walking into' one of the holographic poles. Once the poles disappeared, participants were instructed to close their eyes and walk forward until they felt as if they were standing in between the two holographic poles that were recently presented (termed blind walking). In addition to the blocks above, we also constructed a practice block of trials that mimicked two pass through judgment trials and two blind walking trials. The pole distances in the practice trials were presented at 3.5m and 5m for both tasks.

3.4 Procedure

After completing informed consent, all participants were first familiarized with the HoloLens via a brief built-in tutorial. The tutorial calibrated the participants' HoloLens fit to maximize their field of view. The experimenter then explained the experimental tasks and the participants began with the practice block of trials. For the affordance judgment block (always first and directly following the practice), the experimenter instructed the participant to indicate whether or not they perceived the gap as passable with a verbal 'yes' or 'no.' Additionally, participants provided the experimenter with a confidence rating for each response on a 0 - 100 scale. A confidence rating of 100 indicated that participants were 100 percent sure in their answer whereas a 0 indicated that they were totally unsure in their answer. A 50 indicated that the participant felt that they could have potentially given the alternative when they answered (e.g., a yes when they said no). The distance judgment block followed all of the affordance judgment trials. In this block, participants were told to view the poles and form an image of their location relative to the room as best they could. When the poles disappeared, participants were instructed to walk with their eyes closed to what they believed to be the center of the gap between the poles. Once they stopped, the experimenter recorded the distance that they had walked. The experimenter then guided the participant back to a pre-defined start line in a nonlinear fashion and began the next trial. After completing all experimental trials, the participants' shoulder widths and eye heights were recorded.

4 Results

4.1 Affordance judgments for passing through

In order to understand the point at which participants decided that they could or could not pass through the aperture, we calculated a crossover point for each participant. The crossover point is the largest aperture width at which participants stated they could no longer pass through for at least two consecutive trials, averaged with the smallest aperture width that participants stated that they could pass through for two consecutive trials. Calculating this crossover point for the two trials in which the aperture moved out or in (and across the 3 distances) allowed us to get a fairly sensitive estimate of the exact width that participants perceived as "just passable." Once we calculated that crossover point for each trial, we then created a ratio by scaling the crossover point to the participant's shoulder width. Scaling to the shoulder width allowed us to determine how accurate participants' perception of passing through were when taking into account individual differences in shoulder widths. If the ratio was greater than 1, then participants overestimated the size of the aperture needed to pass through (i.e., they left a margin of error),

Figure 1: Image of a participant standing in the real world lab as if performing the affordance judgment task.

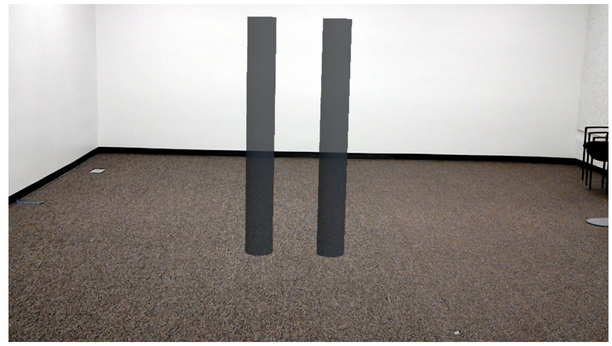

Figure 2: A screen shot taken from the HoloLens that depicts the holographic poles used in the experiment. Note that participants' experience was different than the screen shot depicts. Specifically, the field of view was smaller and the poles appeared more transparent.

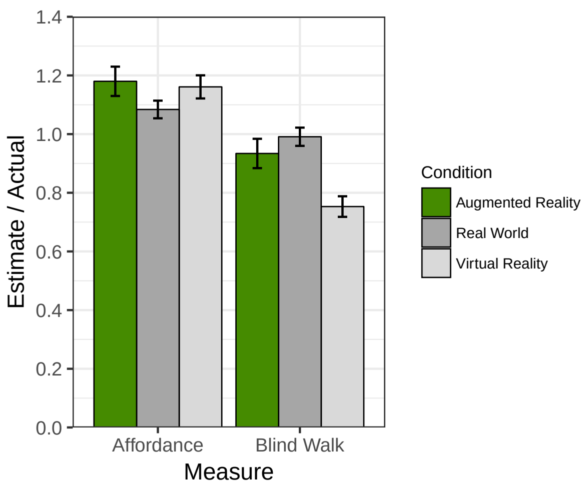

Figure 3: Accuracy of affordance judgments and blind walking for augmented, virtual, and real world environments. Real world and virtual reality data is reported from [6].

and if the ratio was less than 1, then participants estimated that they could pass through an aperture that was smaller than their actual ability.

To first examine the new AR estimates, we ran a 3 (distance: 3m, 4.5m, 6m) x 2 (starting position of poles: far or near) ANOVA on the crossover ratios, showing first, that passing through estimates were relatively accurate, but judged somewhat larger than actual shoulder width (Mean ratio = 1.18). This is consistent with classic findings in the real world on affordances for passing through. For example, Warren and Whang [26] found that participants judged an aperture as passable when it was 1.16 times their own shoulder width. In the current study, we found no differences in estimates as a function of distance ($p = .55$, $M = 1.20$, $SE = .059$, $M = 1.16$, $SE = .064$, $M = 1.18$, $SE = .062$, for 3m, 4.5m, and 6m, respectively). There was also no effect of starting position of the poles ($p = .49$).

Next, we compared our current results with the findings of Geuss et al. [6], since the same methodology and tasks were used in the real world and in VR (with NVIS n Visor SX HMD, 42°x 34°FOV). A 3 (environment: real, virtual, augmented) x 3 (distance: 3m, 4.5m, 6m) x 2 (starting position of poles, far or near) analysis of variance (ANOVA) revealed that there was no difference across environment in estimates of the passability of apertures, $F(2,27) = 0.77$, $p = 0.47$. (M Real $= 1.08$, $SE = 0.06$, M Virtual $= 1.16$, $SE = .06$, M Augmented $= 1.18$, $SE = 0.06$), see Figure 3.

To test whether participants' confidence in their affordance judgments made in AR varied with distance, we calculated average confidence ratings across the widths presented at each distance (i.e., averaged ratings for 30 through 60 cm) and compared these at each distance. We found little indication of variation of confidence across distance ($M = 88.81$, $SE = 3.27$ for 3m, $M = 87.32, SE = 3.74$ for 4.5m, $M = 84.21, SE = 4.3$ for 6m).

4.2 Blind walked estimates of distance

Participants in the augmented reality condition walked, on average, 93% of the physical distance. When comparing this to our previously collected data [6], it is apparent that the average walked distance in AR is similar to what was obtained in the real world (99%), but not the virtual world (75%). In order to test if the distance walked in AR really differed from the other environments, we conducted a 3 (environment: real, virtual, augmented) x 3 (distance: 3m, 4.5m, 6m) x 2 (repeated distance) repeated measures ANOVA with environment as a between-subjects factor and distance as within-subjects. The analysis revealed an effect of environment, $F(2,27) = 3.46$, $p = 0.05$. Planned comparisons showed that while VR distance estimates were different from the real world ($p = .02$), AR distance estimates were not different from the real world ($p = .55$), see Figure 3.

5 Discussion

In this preliminary study, we assessed the perceptual fidelity of an augmented reality system, the HoloLens, using affordance judgments for passing through apertures and a converging measure of blind-walked distance estimates. As we might have expected from prior research [10], viewers were nearly accurate at walking to previously viewed holographic targets. Whether or not they would be able to accurately make body-scaled judgments of passing through a holographic aperture was an open question. The severely restricted field of view of the HoloLens and the transparent objects could have made judgments about action capabilities in AR different from the real world. However, our preliminary results show that estimates of passing through were similar to what we have previously observed both with an aperture in a real environment and in a fully mediated immersive virtual environment. However, it is important to note that the current study was run in a different room than the previous real world study used as a comparison, but the rooms were roughly the same size (13m x 10m). Additionally, Microsoft recommends the ideal hologram placement for the HoloLens is 1.25 - 5m from the user. Given that we presented holograms outside of this range, it is surprising that our participants' confidence in their perceptions remained stable. These results suggest that affordance judgments are a useful way to evaluate observers' perception of the scale of mediated environments and demonstrate potential for virtual objects to be perceived and acted upon similarly to real objects when presented through an AR interface.

There are a number of depth cues available to be rendered in AR, only some of which were utilized in the current study, e.g., perspective scaling. A detailed discussion of such cues and their effects on depth perception can be found in Diaz et al. [4]. An interesting topic for future work would be to add some of the depth cues back in the AR rendering to determine how that affects performance in both the affordance and blind walking tasks.

It will be important to generalize the use of perceived affordances as a measure of perceptual fidelity for other types of environmental features and action goals. Our previous work in VR has examined affordances such as stepping over obstacles, stepping up and down steps, and walking under horizontal barriers [12, 16–18]. These affordances require rendering of features of different dimensions in different locations in space (e.g., those on or off the ground, below or above eye-level) which could be differentially affected by AR displays, especially when taking into account the narrow field of view of the HoloLens.

Moreover, a greater understanding of the affordances within mediated environments will help to develop applications of AR for use in more complex tasks. For example, if holographic objects are treated similarly to real objects in the environment with regard to action, then they could be used to train observers about how to interact or navigate in novel spaces.

Additionally, more direct comparisons between emerging AR technologies and current VR technologies are needed. It is notable that the Geuss et al. [6] results used as a comparison to our current AR study found distance underestimation in their VR condition, also consistent with a body of work in HMD-VEs over the last decade, see [1] for a review. However, as mentioned above, the new lightweight commodity-level HMDs have shown a reduction in this distance estimation bias. It is likely that a direct comparison of distance estimation performed in AR and VR with the new HMDs would lead to similar performance than the comparison made here.

Although we included holograms outside of the range of ideal hologram placement (1.25 - 5m from viewer), we did not explicitly test the influence of placement on space perception. It could be the case that extreme hologram placement (e.g., 0 - 1m or 6m+) would produce perceptual disadvantages such as reduced accuracy or increased variability in affordance judgments. Future work could compare the influence that virtual object placement has on viewers' space perception in both AR and immersive VR technologies.

Finally, it is important to note that unlike immersive virtual reality, which requires one to don some type of head-mounted display, augmented reality can be achieved with a variety of technologies. In this paper, we explored both perception of affordances and distance perception using the HoloLens. We were surprised that the narrow field of view of the device did not produce large underestimations of distance or differences in affordance judgments compared to the real world. Narrow field of view has been proposed to be one possible factor influencing previously found distance underestimation in VR, although real-world studies that have restricted field of view have found relatively accurate distance judgments as long as head rotation is allowed [3]. Other work has explored distance perception in AR using tablet-based AR technology [25]. Findings suggest that with tablets and phones, users can also estimate the distance to holographically portrayed targets when asked to use a bisection task. More work is needed to understand whether different types of AR technologies can be used to assess affordance judgments. The current work is an important first step toward understanding affordance perception in one of these technologies.

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