Danger from the Deep: A Gap Affordance Study in Augmented Reality

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ABSTRACT

It is an open question as to whether people perceive and act in augmented reality environments in the same way that they do in real environments. The current work investigated participants' judgments of whether or not they could act on an obstacle portrayed with augmented reality. Specifically, we presented gaps of varying widths and depths to participants in augmented reality using the Microsoft HoloLens. We asked users to indicate whether or not they believed that they could step across the virtual gaps given their widths and depths. Averaging across changes in width and depth, users generally underestimated their abilities to cross gaps. However, this underestimation was significantly greater when the gaps were deep. Thus, our findings suggest that users in augmented reality respond with more conservative judgments when presented with risky stimuli—a response that mimics real world behavior. Their altered reactions to deeper gaps may provide early evidence for augmented reality's capacity to evoke a sense of realism or immersion and its use in evaluating perception and action.

Keywords: Augmented reality, Affordances, Perception

Index Terms: I.3.7 [Computer Graphics]: Three-Dimensional Graphics and Realism—Virtual Reality; J.4 [Computer Applications]: Social and Behavioral Sciences—Psychology

1 INTRODUCTION

Our understanding of how users perceive virtual objects in real world environments with optical see-through augmented reality displays remains unclear. In these devices, virtual graphics are superimposed onto the user's view with optical combiners, which leverage partial reflections off of glass or plastic. A virtual object—or hologram, as it is often called commercially—is generated as a two-dimensional (2D) overlay, rendered with additive light to display color. In this paper, we will refer to optical see-through augmented reality as augmented reality or AR for simplicity.

AR holds tremendous potential. Its ability to provide context to the surrounding world with direct, heads-up information could revolutionize the way we perform many tasks. For example, a surgeon may use 3-dimensional (3D) visualizations to guide her incisions during an operation [16]. Or a student, running late to class, may use his AR display to quickly find where he left his laptop [1]. For these applications, AR system developers must convincingly align and display virtual objects in the real world. This necessitates a firm understanding of the physical and perceptual limitations of the technology.

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Open questions remain about how the visual properties of virtual objects influence our perception in augmented reality. Both in the real world and in virtual reality (VR), when people experience fear and anxiety, their perceptions of what they can and cannot do are altered [5, 8, 10, 24]. It is unknown if current AR systems can evoke this same response with fear- or risk-inducing visualizations. Behavioral responses that resemble those expected in the real world would provide evidence that visual cues in AR are perceived similarly to the real world. Furthermore, these types of visualizations may be important for future applications in gaming or the clinical treatment of emotional disorders. For instance, AR game designers may want to reliably elicit fear or caution in response to seemingly dangerous virtual stimuli [12].

Whether or not AR can evoke fear and then affect users' perceptions of space has not been tested. In the current study, we utilized *affordance judgments*, which have previously been used to assess users' perception of scale (e.g., size, distance, etc.) in virtual and augmented reality environments. Specifically, we asked participants to judge their ability to step over AR gaps with a shallow, medium, and deep pit. Based on the notion that emotional states can change one's perceived action capabilities [8, 10, 25], we predicted that users would become more conservative with their judgments of which gaps they could cross as the gap increased in depth, or as the implication of risk in the visualization increased.

2 BACKGROUND

In prior work, researchers have investigated how users perceive virtual spaces with *affordance judgments*. Affordances are possibilities for action that an individual perceives, with respect to his or her own action capabilities, in a given environment [7]. For example, one can only walk through a doorway if it is wider than one's body. An individual's perception of affordances is thought to be accurate due to the constant feedback they receive from the environment with every action taken. Therefore, judgments made about affordances can be used to measure the degree to which individuals perceive virtual spaces similarly to the real world (also known as *perceptual fidelity*).

Users of VR may perceive spaces differently, as evidenced by a tendency of observers to underestimate distances in immersive virtual environments [6]. However, ergonomic and display improvements for virtual reality devices have reduced this effect over time [2]. Research evaluating the accuracy of distance perception in AR is comparatively muddled. Some AR research has revealed egocentric depth underestimation at medium and far-field distances [9, 26]. Yet other work has found accuracy or even overestimation of distance in comparison to judgments made to real-world targets [11, 19]. More recently, researchers have assessed the perceptual fidelity of AR and have found underestimation in affordance judgments that are in near space (i.e., reaching space) but not far space (i.e., space beyond reaching, but still actionable) [19]. These studies suggest that users may perceive the scale (e.g., size, distance, etc.) of AR objects differently depending on where they are presented in space.

For virtual objects placed on the ground, gap affordance studies provide an opportunity to evaluate the perceptual fidelity of augmented reality in users' near space. This methodology has been

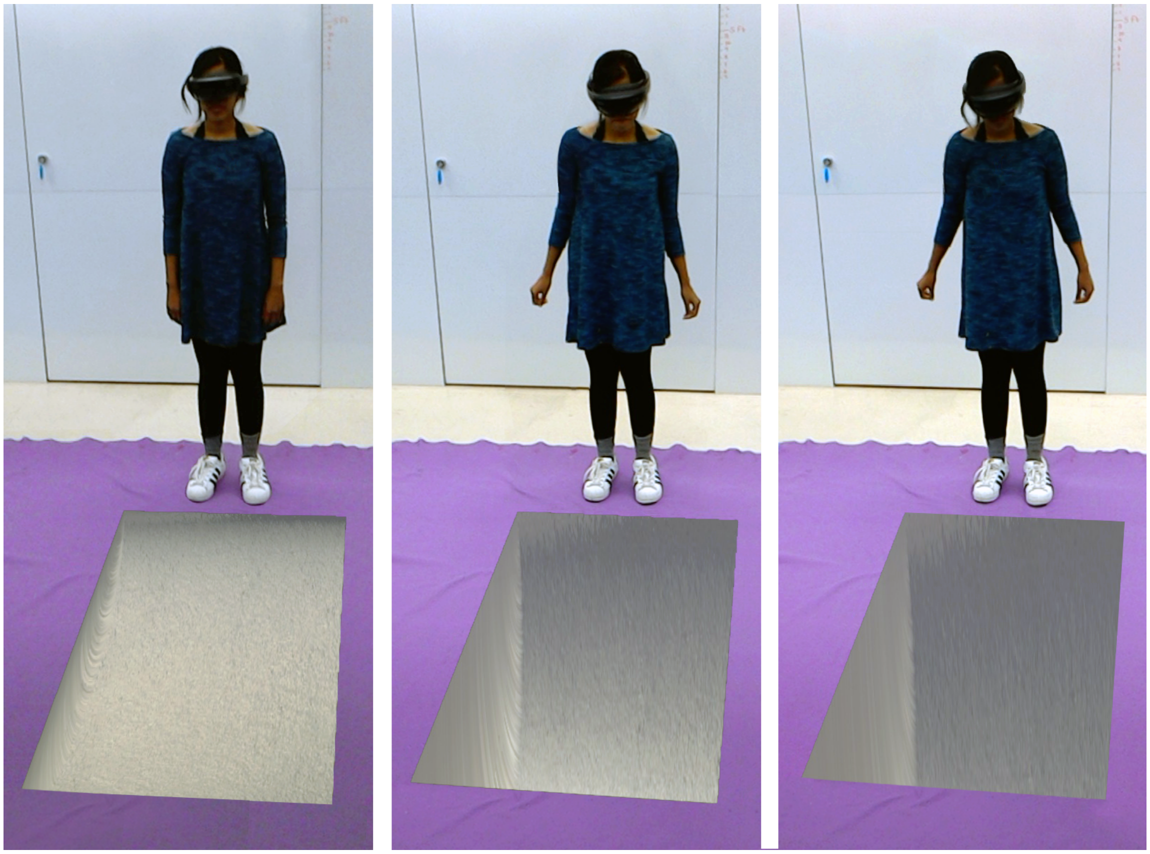

Figure 1: A participant views the shallow, medium, and deep pit depths in augmented reality. Screen captures have been altered to remove artifacts not present in the live display of the HoloLens.

used in immersive VR, where underestimation of action capabilities–relative to those measured in the real world–has been demonstrated in gap crossing judgments [13]. Similarly, one's ability to step down from a ledge was also underestimated in VR [13, 14]. Both of these effects were mitigated with the presence of an avatar. Related work in AR shows a comparable effect of underestimation when flat, unlit, and non-textured gaps are presented to a user [19]. However, less work has studied how users' affordance perception is influenced by AR simulations that may evoke emotional responses.

Embodied approaches to perception and action suggest that physical and mental states can influence one's perception of space in order to encourage or discourage particular actions [20]. For example, individuals may perceive that their ability to reach towards objects or to reach through small apertures is reduced when anxious [8]. And individuals may perceive themselves as higher than they actually are when they are more afraid [24]. This effect has also been shown to increase when individuals imagined themselves falling from a height, were more aroused, or when additional risk factors were added to the height such as a dangerous landing surface [3, 23, 25]. Most relevant to the current study, individuals' perception of their ability to cross a gap in the real world has been shown to decrease if there is a deep pit that lies between the gap [10].

The effect of emotion on action judgments has been studied in virtual spaces, as well. People perform tasks more cautiously and express heightened anxiety in virtual reality [21, 29]—a response similar to what has been seen in real world studies. In general, VR has been widely successful in arousing a sense of fear through immersion with pit or ledge simulation [15, 22, 27]. Researchers have even successfully manipulated users' affordance perception when placed in a high risk environment [5]. Specifically, participants in this study were asked to estimate their ability to step over a gap when they were standing on the ground and when they were standing on one of two floating platforms at a height. When participants were standing on the floating platforms, they indicated that they would need smaller gaps to cross over compared to when they were on the ground. Additionally, their actual stepping behavior also changed such that they stepped farther when they were afraid of the height compared to when they stepped on the ground plane. This study showed that virtual spaces can elicit changes in users' perception of space by inducing fear via an environment associated with physical danger or risk. However, this study was conducted in immersive VR, which may be a more effective medium for inducing fear than AR, in which real world information is still visible to ground the user.

There are several unique challenges that could prevent AR users from experiencing emotional responses strong enough to influence their perception of space. Unlike immersive VR, AR technologies combine elements from the real and virtual world in order to create a mixed reality. This combination may not fully immerse the user in the mixed reality world, thereby making it difficult for AR objects or images to convincingly induce emotional states. Such limitations could be particularly relevant for emotions that rely on the illusion of risk or physical harm such as fear or anxiety [4]. AR graphics may also limit the degree to which users are emotionally triggered because AR objects or images typically have transparent qualities. Most AR devices also have a limited field of view, which could break users' immersion even if the AR objects or images are presented in a convincing manner.

Although these challenges exist, whether or not AR is able to influence users' perception of space with emotionally charged visual stimuli has not been tested. We sought to test this question by replicating and expanding prior work in the real world and immersive virtual reality on gap crossing affordance judgments. We asked participants to estimate their ability to cross over a gap with a shallow, medium, and deep pit holographically portrayed between the edges of the gap. We predicted that participants would reduce their estimates of which gaps were crossable as the pit depth increased.

3 Experiment

3.1 Participants

Fourteen undergraduate students (9M, 5F) aged 19–21 from the University of Utah were recruited to participate in the experiment. Each subject was compensated with $10 USD for their time. Our experiment and methods were approved by the local institutional review board, and written consent was obtained from all subjects prior to participation.

3.2 Materials and Apparatus

We used the Microsoft HoloLens to present all experimental stimuli. The HoloLens is an optical see-through augmented reality device with an approximate field of view of $30^\circ \times 17^\circ$ and a weight of 579g. Users are only able to see virtual objects within the HoloLens' FOV. Outside of this viewing area, users' experience is neither augmented nor occluded by the device.

For the virtual pit objects, a concrete texture was applied to provide texture gradient as a depth cue. Recall that in prior work with gap affordances in AR, only 2-dimensional, unlit surfaces were tested [18]. The textured virtual objects can be seen in Figure 1. We developed our application in Microsoft Visual Studio and the multi-platform game engine Unity (version 2017.4.4). The experiment itself was conducted in a large, well-illuminated room (7.3 m $\times$ 8.5 m) with a large purple fabric laid across the floor. The solid fabric was used to cover tiles on the floor, which could have served as a cue for distance.

3.3 Design and Procedure

The experiment employed a fully within-subjects design. Each participant completed 63 total trials where they judged whether or not they could cross virtual pits of three distinct depths: 0.25 m, 1.0 m, and 1.5 m. We will refer to these three depth conditions as the shallow, medium, and deep pit conditions, respectively. Images for each pit can be seen in Figure 1. For each depth condition, seven widths were presented, three times each. The widths ranged between 0.6 m and 1.5 m wide and varied by 0.15m increments. The order of the presented gap was randomized in such a way that no depth-width pair occurred consecutively.

After giving consent, the participants donned the HoloLens. Initially, participants could only see two augmented objects: a thick, white line on the floor and floating text displaying the word "Start". Participants were instructed to stand behind the virtual line and face towards the floating text. Once they were in position, the experimenter commenced the first trial, and advanced through each subsequent trial with a wireless clicker. When the first trial was initiated, a virtual pit appeared before the participants where the near edge was aligned with their standing position. The experimenter then asked participants to judge whether or not they could step across the gap without running or jumping, without feeling like they would fall, and without picking up their back foot from the ground. Participants were also instructed to inhibit any practice attempts to step over the gap or move as if they were going to step over the gap. The participants indicated their judgments with a 'yes' or 'no' verbal response.

Between each trial, the floating text changed to a unique, six digit number to indicate that the next trial had begun. The participant verbally reported this number, and the experimenter observed it to ensure that the subject was progressing through the trials correctly. After the completion of all 63 trials, the floating text changed to "End" to indicate to the participant that they had completed the experiment.

After completing all experimental trials, additional measures were recorded. The subject's height, eye height, leg length, and step length were measured. Leg length was measured as the distance between the top of the participant's pelvis and ground surface. Step length was measured by asking participants to step as far as they could without running, jumping, and while keeping their back foot on the ground. Participants' step lengths were each measured three times and averaged to ensure an accurate measurement. This distance was measured from trailing toe to leading toe and from trailing toe to leading heel.

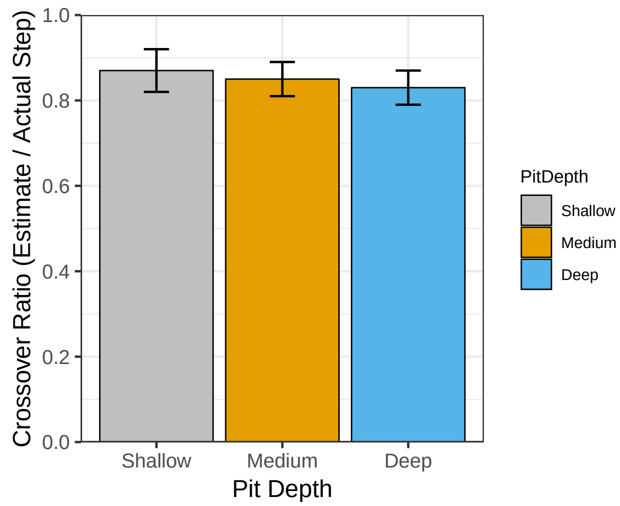

Figure 2: A bar chart depicting the mean crossover ratios as a function of pit depth. Error bars reflect $\pm$ 1 standard error of the mean.

3.4 Results

A *crossover point* was calculated for each depth condition for each participant to determine the gap width that was judged to be "just crossable." This was calculated as an average between the largest gap width that was judged crossable (on at least two out of the three trials) and the smallest gap width that was judged not crossable (on at least two out of the three trials). For example, if a participant answered "yes" at 1.05m at least twice and "no" at 1.2m at least twice, then the crossover point was calculated to be 1.125. The crossover point was then divided by each participant's actual average largest step measured from toe to toe to create a *crossover ratio*.

Crossover ratios were generally underestimated relative to actual performed steps with ratios less than 1.0 (see Figure 2). A repeated measures analysis of variance (ANOVA) with three levels of pit depth (shallow, medium, and deep) was run on the crossover ratios to test whether there was an effect of pit depth on judgments of capability to step across the gap. As predicted, the results revealed a significant effect of pit depth, $F(2,26) = 3.52, p < .05, \eta_p^2 = .21$. Planned contrasts with the deep pit as the reference showed that participants underestimated their capability to step over the gap when presented with the deep pit ($M = .83, SE = .04$) relative to the shallow pit ($M = .87, SE = .05$), $F(1,13) = 5.14, p < .05, \eta_p^2 = .28$. There was no difference between judgments for the medium ($M = .85, SE = .04$) and the deep pits, $F(1,13) = 2.17, p = .17$.

4 Discussion

In this study we showed that optical see-through displays render visual cues with sufficient quality to evoke conservative action judgments—a response that mimics real world responses to perceived risk. Specifically, participants made more conservative gap crossing judgments for the gaps that were deep (1.6m) compared to the gaps that were shallow (0.25m). This finding indicates that users believed they could not cross gaps as wide when the gaps were also deep, suggesting that not only was the gap width taken into account for these judgments, but also the gap depth. With regard to gap width, we found that participants' gap crossing ratios were generally underestimated across depth conditions, which replicates the findings of prior work [19]. These findings suggest that people may be conservative in their judgments of what they can cross, perhaps because crossing is not a well-practiced estimate. The depth of the pit further exaggerated this underestimation. The results of this research add to a growing body of knowledge aimed at understanding the perceptual limitations of AR displays while also raising new questions for future consideration.

Although it is promising that the depth of our AR pits influenced users' gap crossing judgments, the effect of depth on judgments of an affordance in this study was weaker than what has been observed in real world studies [10]. Jiang and Mark [10] found that asking observers to focus on the opposite edge of the gap instead of the depth of the gap lessened the effect of gap depth on gap-crossing judgments. However, our observers may have varied where they focused given we did not instruct them to look at a particular aspect of the gap. If that were the case, then variability in their estimates could have occurred, which would have reduced the observed effect in AR. Future studies should instruct participants to focus on certain aspects of the gap to see if the real-world effect size observed previously when controlling for gaze location could be captured with AR [10].

It is also possible that we found a weak effect of pit depth because current AR technology may not be able to fully immerse users in mixed reality worlds. Current AR displays suffer from several limitations that may prevent users from feeling as immersed in AR as they have reported feeling in VR. The narrow field of view (FOV) of the HoloLens, for example, abruptly clips virtual objects that are only partially captured by the display. Further, users may feel less immersed in the mixed reality world if the integration of augmented elements with the real world is not convincing. These technical issues could be particularly important in scenarios similar to our experiment, because a lack of immersion may limit emotional arousal which some authors have proposed as a mechanism that alters perceptual judgments in response to risky environments [5,17]. Indeed, several studies have shown that the degree to which users feel immersed in a virtual space leads to stronger emotional reactions to the virtual world (see Diemer et al. [4] for review), particularly with negative emotions such as fear or anxiety. However, we did not collect data on our participants' physiological or emotional states. Therefore, it is difficult to know if the participants in our study experienced relatively more fear or anxiety in response to the deep pit compared to the shallow pit. Further research is necessary to determine if relative differences in emotional arousal influence changes in AR users' perceptual judgments in response to AR stimuli that imply risk and whether emotional reactions to AR stimuli relate to immersion.

Our finding that participants generally underestimated their gap crossing abilities (i.e., regardless of gap depth) replicates prior work in AR using the HoloLens [19]. This replication is promising and supports the use of affordance judgments for evaluation of perception and action in optical see-through displays, especially given the inconsistent results of related research on distance perception in AR [9,11,26]. Future work is needed to determine potential causes of the underlying underestimation of gap crossing abilities. The underestimation may be due to specific properties of the HoloLens that interact with AR stimuli in near space (0 - 2m from user), such as the limited FOV of the HoloLens, the weight of the HoloLens, or a combination of both factors. The weight of the HoloLens may be particularly influential given previous work in virtual reality head-mounted displays (HMDs) has shown an influence of HMD weight on distance judgments to objects on the ground [28]. To isolate this factor, future work should evaluate real world gap crossing judgments while wearing the HoloLens.

Overall, our results suggest that current AR technologies can alter users' perceptual judgments of their action capabilities in response to AR stimuli that imply risk or danger. However, our results leave open several avenues for future research particularly with respect to the generalizability of our findings to other types of 'dangerous' AR stimuli (e.g., fire pit, bed of nails, pits at a height, etc.). In addition, future work could measure actual stepping behavior across AR pits or users' avoidance behavior in response to 'dangerous' AR stimuli. This work could be important for applications where developers want users to perceive and act in different ways in response to virtual or augmented objects. The specific influence of AR device weight and FOV restrictions on distance underestimation should also be investigated. Overall, the results of this study provide a promising first step for understanding the role that visual surfaces and their implied consequences have for perception and behavior in AR.

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