Reaching Between Worlds: Calibration and Transfer of Perceived Affordances from Virtual to Real Environments

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Abstract

Accurate perception of one's action capabilities, or affordance perception, is essential for successful interaction with both real and virtual environments. Affordance perception can potentially be improved by receiving feedback. It is unknown what specific types of feedback are needed for improvements in affordance perception to occur, particularly in virtual environments where cues may be impoverished. The current work studied perception of horizontal reachability in virtual and augmented reality (VR and AR), specifically whether it would improve with feedback, and if any improvement transferred to the real world. Multiple types of feedback were studied in VR or AR: exploratory behavior, static outcome, and action outcome feedback. Our results indicate that exploratory behavior is sufficient for improvement in perceived reachability in VR, but in AR, outcome feedback is necessary. In both VR and AR, outcome feedback was required for improvement in perceived reachability to transfer to the real world. These findings have practical implications for training in virtual environments. If virtual environments are used for training actions that ultimately need to be performed in the real world, outcome feedback should be provided.

Index Terms: Applied computing—Psychology; Human-centered computing—Mixed/augmented reality; Human-centered computing—Virtual reality; Human-centered computing—Empirical studies in HCI

1 Introduction

One of the great promises of virtual and augmented reality (VR and AR) is their ability to provide safe, controlled, and effective training scenarios for situations that may be difficult or impossible to simulate in the real world. Such training is increasingly being developed for situations like education [46], natural disasters [30], and construction [31]. However, for VR and AR to reach their full potential as training systems, two things must happen. First, people must be able to successfully interact in VR and AR with environments and the objects within them; and second, the training that people experience in VR and AR must successfully transition to the real world.

To successfully interact with objects and environments, we must accurately perceive our action capabilities. Possibilities for interaction with objects and the environment are dependent on one's body and capabilities as they relate to relevant environmental or object properties (termed 'affordances' [24]). For example, a chair only affords sitting if the observer is a certain height. The perception of affordances is thus calibrated, or scaled, to the relevant properties of one's body. Experience and interaction with the environment can help calibrate affordance perception. Calibration is particularly important when considering actions performed in VR or AR environments where body scaling might be initially uncertain or different than in the real world. However, different experiences provide different types of feedback about the relationship between the environment and one's action capabilities. Some forms of experience may be more effective at calibrating perception than others [13]. For example, when participants receive feedback about the outcome of their actions, their subsequent judgments become calibrated to their ability (e.g., [13]). Under some circumstances, feedback about action outcomes is not necessary for calibration to occur, such as when affordances become calibrated based on more general experience with moving in the world (e.g., postural sway or walking [36]). In the current work, we classify feedback experiences into three categories: exploratory behavior, static outcome, and action outcome. Exploratory behavior involves interacting with the environment without receiving feedback about the outcome of one's action capabilities. In static outcome feedback, participants receive verbal feedback about their ability to complete an action (prior work has also referred to this as "verbal feedback" [14]). In action outcome feedback, participants attempt to complete the afforded action, thus receiving feedback about whether they can perform the action or not (prior work has also referred to this as "practice" [14]). Understanding how different types of feedback influence affordance perception calibration can elucidate the informational variables that are necessary for calibration to occur. Additionally, AR and VR can use various types of virtual objects and environments, so it is important to test whether feedback effects on calibration are similar across situations.

Prior work on affordance perception calibration in AR and VR has primarily tested action outcome feedback in VR, showing that this type of feedback changes affordance judgments similarly to the real world. However, the effects of static outcome feedback and exploratory behavior on affordance perception calibration in VR and AR remain relatively unexplored. Moreover, little research has examined affordance perception calibration in AR, which may differ from perception in VR due to the availability of different cues.

The contributions of this paper are two novel studies that investigate whether affordance perception can be improved in AR and VR, and if that improvement transfers to the real world. We investigate how three different types of feedback calibrate perceived affordances for reaching ability in VR and AR, and then we assess whether this calibration transfers from these environments to the real world. By directly comparing three types of feedback within the same experiment, we are better able to understand which types of information are necessary for affordance perception calibration to occur. Our main findings are that exploratory behavior, a mild form of feedback, is sufficient for calibration in VR, but outcome feedback is necessary for calibration in AR. For transfer to the real world, outcome feedback is required in both AR and VR.

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2 RELATED WORK

Everyday actions such as passing through a doorway, reaching for a cup, and sitting on a chair may seem simple and automatic, but they rely on the accurate perception of one's capabilities and surrounding environment. The ecological theory of perception posits that we perceive the environment in relation to our ability to interact with it [23, 24]. Affordances are opportunities for action that are present in the environment and related to one's body and capabilities [24]. Affordances are necessarily calibrated, or scaled, to certain information and properties. This scaling informs an observer about whether an action is afforded or not – an actor can only pass through a doorway without rotating their shoulders if the width of the doorway is larger than their shoulder width. The point at which an affordance transitions from being impossible to possible is referred to as the critical boundary [47, 48].

Perceived affordances can be measured through affordance judgments– where an observer decides whether an action is possible in a given situation. There are two common methods of obtaining affordance judgments. In the method of constant stimuli, the observer is presented with an action possibility (e.g., a doorway of a specific width) and asked to provide a yes or no response as to whether they would be able to successfully complete the action (e.g., walk through the doorway) (e.g., [3]). In the method of adjustment, participants are asked to adjust an object until they believe it could be successfully acted upon (e.g., adjusting the width of a doorway until it is the smallest width that could be walked through without turning) (e.g., [18]). Measuring affordance perception serves as a metric to observe the process of affordance perception calibration.

Calibration is the scaling of actions and judgments to the relevant relationships between properties of the environment and oneself [6, 50]. Experience and feedback facilitate calibration. For example, when observers wore blocks that increased their maximum sitting height, experiencing postural sway calibrated their perceived maximum sitting height to their altered capability [36, 44]. Understanding how feedback informs calibration can shed light on the mechanisms underlying affordance calibration and recalibration. Types of feedback can be broadly grouped into two categories: outcome feedback and exploratory behavior. Outcome feedback provides information about the accuracy of a judgment or action performance [14]. In *static* outcome feedback, the observer makes an affordance judgment and receives feedback on the accuracy of that judgment (e.g., verbally) without performing the action [14]. In *action* outcome feedback, the observer executes an action and consequently receives feedback about the success or failure of their performance (e.g., attempting to sit on a chair) [14]. Exploratory behavior is perceptual-motor feedback that does not provide information about the outcome of the affordance judgment or action such as in the example described above with postural sway affecting judgments of sitting [36]. Although the effects of these different types of feedback on affordance judgments have been assessed individually in the real world, few studies have compared them directly or studied different types of feedback in VR or AR. The present study directly compared these three types of feedback within the same experiment in VR and AR. This study also examined whether different types of feedback differentially affect affordance calibration transfer from VR and AR to the real world.

2.1 Reaching Perception in the Real World

Affordance judgments for maximum standing horizontal reach are scaled to arm length and actual maximum standing reach [8, 37], but these judgments are consistently overestimated, usually by about 10% [7, 8, 25, 37, 41, 42, 49]. There has not been extensive research examining the effects of different types of feedback on calibrating horizontal reachability perception in the real world. Recently, Jones and Widlus [27] investigated whether exploratory arm movements contribute to maximum reachability judgments. Participants judged their maximum horizontal reach by walking toward a hanging object and stopping when they felt they were at the distance where they would just be able to grasp the object. Judgment error decreased when natural arm movement was allowed, but not when arm movements were restricted, indicating that exploratory arm movement is required for calibration of maximum horizontal reachability judgments.

2.2 Affordance Perception and Calibration in VR and AR

It is possible that affordance perception might differ in VR or AR compared to the real world. The real world provides a rich environment of multi-sensory cues and experiencing these cues during action execution can inform subsequent affordance judgments [15]. However, many of these cues are absent, difficult to implement, or perceived differently in VR and AR. For example, distance perception in VR is consistently underestimated, although advancements in technology and interaction within the virtual environment can alleviate this misperception [9, 10].

2.2.1 Virtual Reality

Studies that have included a distinct calibration phase for affordance judgments in VR have only provided action outcome feedback [4, 5, 11, 12, 20] . The majority of these experiments examined affordance perception for horizontal reachability. Practice reaching with a tool or an extended arm calibrated participants' affordance perception, as evidenced by overestimating their ability to reach once the manipulation was removed [11]. When participants practiced reaching in a virtual environment where only the controllers were rendered, reaching judgments became more accurate and resembled judgments in the real world [12]. Receiving outcome feedback by physically reaching out or up after making a judgment calibrated affordance perception to be closer to participants' actual reaching ability [20]. Outside of the context of reaching, practice walking through doorways while holding an object and receiving visual and auditory collision feedback improved the accuracy of subsequent passability judgments [5].

Mantel et al. [35] and Masoner et al. [38] did not include a calibration phase, but they uniquely examined the role of movement during affordance judgments of maximum horizontal reaching ability in VR. In Mantel et al. [35], participants judged their ability to reach a virtual target presented against a solid black background. Participants walked or rolled in a wheelchair toward the target until they felt that they were at the maximum distance from the target where they could still reach the object. Judgment accuracy was higher in the wheelchair condition, which suggests that having fewer balance requirements during locomotion might elicit more accurate reachability judgments (see [8]). In contrast, Masoner et al. [38] found that more complex movements in postural sway increased the accuracy of reachability judgments in VR. Participants either stood normally, in tandem with one foot in front of the other, or with one foot raised in a "tree pose." Reachability judgments improved across trials, even in the absence of outcome feedback, suggesting that experiencing more postural sway led to more accurate affordance judgments.

Due to the lack of studies explicitly manipulating types of feedback in VR, it is difficult to draw strong conclusions about the information that is necessary for calibration of affordances in virtual environments. Generally, it appears that a visual representation of the body facilitates calibration of affordance judgments [5, 32–34]. However, providing a body representation alone does not always provide enough information to calibrate affordance judgments; outcome feedback from action performance is often required.

2.2.2 Augmented Reality

AR presents virtual stimuli while still allowing the user to view the real world, and thus, can be applied in interactive real-world situations where VR may not be relevant or as useful. For example, AR can present virtual cues for navigation in situ or aid in medical procedures in real time. Additionally, it is possible that perceptual calibration from training in AR may transfer to the real world more readily than VR because there are more similarities between real-world and AR environments. However, affordance perception and calibration are only just beginning to be explored in AR, primarily conducted using optical see-through devices [18, 19, 21, 39, 40, 51].

Two studies have explicitly assessed affordance judgment calibration using different forms of feedback in AR [18, 19]. Gagnon et al. [18] provided evidence that static verbal outcome feedback can successfully calibrate passing-through judgments in AR using the Microsoft HoloLens 1. In feedback trials, participants were presented with an aperture, made a yes/no judgment on whether they could successfully pass, and then the HoloLens provided auditory feedback ("correct" or "incorrect") on the accuracy of that judgment. Baseline aperture width judgments were overestimated compared to shoulder width, as expected, and the just-passable aperture width adjustments became closer to shoulder width following the feedback blocks. Gagnon et al. [19] implemented the same stimuli and trial procedure, except that in the feedback trials, participants walked through the AR aperture and received auditory outcome feedback indicating whether a collision occurred during passage. Baseline perception of the just-passable aperture width was overestimated, but perceived just-passable aperture width increased following the collision-based feedback blocks. Taken together, the results of the two studies demonstrate that affordance perception can be calibrated in AR, but the direction of calibration may depend on the type of feedback that is provided. Additional research is needed to determine how different affordances are perceived in AR and to further examine the extent and type of feedback that is sufficient for calibration.

2.3 Affordance Perception Calibration Transfer

Little research has examined whether affordance perception calibration transfers between virtual and physical environments. This is an important question for both theory and practice. If calibration occurs in virtual environments but does not transfer to the real world, then this would suggest that individuals rely on different perceptual information variables when gauging their perception in virtual environments compared to the real world. The relationships that they perceive between their capabilities and the virtual environment could also be different than the relationship between the same action in the real world due to the availability of different cues in the virtual and real environments.

The question of whether affordance perception calibration transfers from VR or AR to the real world is especially relevant for training applications where it is desirable for training to take place in a virtual environment and then be applied in real-world situations. Some research shows that training in VR can transfer to the real world for police training [2], maintenance procedures [22], surgical skills [26], and wayfinding tasks [29]. Most relevant to the current project, Day et al. [11] found that calibration to altered reaching capabilities in VR transferred to the real world. Participants who practiced reaching with an extended arm in VR believed they could reach farther in a post-practice test phase in the real world compared to participants who practiced reaching with an unaltered avatar arm in VR. Kondo et al. [28] also found evidence of calibration transfer from VR to the real world. In a real-world testing phase following practice with walking through virtual apertures, they found that participants modified their behavior to be more efficient at passing through doorways. However, the VR setup of Kondo et al. [28] was more similar to AR in that participants still saw their real body while watching a projection of the virtual environment on a large screen.

We are aware of only one study that has examined affordance perception calibration transfer between VR and AR [17]. In this study, participants judged their ability to walk through a virtual doorway while holding a pole at a 45° angle. In the pretest, participants judged whether they could walk through AR doorways. In the calibration phase, they judged whether they could walk through doorways in VR. They also practiced walking through VR doorways and received feedback about collisions with the doorway. In the posttest, participants returned to AR to make passability judgments. The results showed that receiving feedback in VR calibrated passability judgments in VR, and this calibration transferred to the AR environment. The present research expands upon these studies by investigating whether different types of feedback (exploratory behavior and outcome feedback) result in calibration transfer from VR to the real world and AR to the real world.

3 Overview of Experiments

The goal of the current work is to better understand how humans perceive affordances for reaching by providing different forms of feedback and analyzing their effect on the calibration and transfer of perceived reachability across virtual and physical environments. In two experiments, participants made judgments about whether they believed they could touch a cube by reaching straight out, horizontally. We used a pretest-calibration-posttest design (Figure 1). Participants completed a pretest in the real world and a pretest in VR or AR. In these pretest phases, participants viewed cubes placed at specific distances and made yes/no judgments about their ability to reach them. In the calibration phase, participants made judgments to cubes in VR or AR and experienced one of three feedback conditions. After the calibration phase, participants completed a posttest in VR or AR and a posttest in the real world. The only difference between the experiments was that the calibration phase for Experiment 1 took place in VR, and the calibration phase for Experiment 2 used AR.

We had the same two objectives for both experiments. First, we aimed to compare the effects of three different feedback types on perceptual calibration of horizontal reaching ability to virtual objects. In each experiment, feedback type (exploratory behavior, static outcome, and action outcome) was manipulated between subjects. In the exploratory behavior condition, participants did not receive feedback about the outcome of their judgment. Instead, they experienced the "exploratory behavior" of moving their arm to the left or right, which provided general visual and motor experience about their arm. In the static outcome condition, participants received auditory feedback about the accuracy of their judgment. In the action outcome condition, participants attempted to reach the cube, thus receiving visual and motor feedback about their horizontal reaching ability and the accuracy of their judgment. These feedback conditions are described in more detail in the Procedure.

Our first hypothesis (**H1**) was that static and action outcome feedback would calibrate affordance judgments in VR and AR, and to a greater extent than exploratory behavior, given that these conditions provide more information directly related to the affordance than exploratory behavior feedback. Similarly, for (**H2**) we predicted that calibration would occur faster in the outcome feedback conditions (static and action) than in the exploratory behavior condition.. Our second aim was to determine whether perceptual calibration transfers from VR and AR to the real world and if the transfer depends on feedback type. This aim compared the difference between the real-world pretest and posttest judgments with the difference between VR or AR pretest and posttest judgments to see if they were correlated. We predicted (**H3**) that there would be a significant, positive correlation: if affordance judgments change with virtual objects from pre- to posttest, affordance judgments in the real world would change in the same direction, showing transfer of calibration. We also predicted (**H4**) that transfer would depend on feedback type, such that transfer would occur for the outcome feedback conditions but not the exploratory behavior condition.

4 Experiment 1: VR

Experiment 1 examined the effect of providing feedback on affordance judgments for horizontal reachability in the real world and in VR. In the pretest phase, participants made verbal yes/no judgments on their ability to reach a cube in the real world and in VR. Then, they experienced one of three feedback conditions in VR: exploratory behavior, static outcome, or action outcome. After the feedback phase, participants completed the posttest phase where they made more verbal yes/no judgments for reaching a cube in VR and the real world.

4.1 Method

4.1.1 Participants

Data were collected from 69 participants. All participants provided informed consent and volunteered or were compensated with course credit for their time. Participants had self-reported normal or corrected-to-normal vision. Nine participants were excluded due to technical difficulties with the VR program. This left 60 participants for analysis (35 Female, $M_{\text{age}} = 21.12$ years, $SD = 3.71$). Participants were right-handed (N = 51) and left-handed (N = 8). There were 20 participants in each feedback condition (exploratory behavior, static outcome, and action outcome).

4.1.2 Materials

The experiment took place in a small laboratory room (3.85 m (L) x 2.64 m (W) x 2.73 m (H)). A rectangular table (151.5 cm x 75.5 cm) was centered against the width of the back wall of the room. A chair without wheels or armrests was placed at the other end of the table. The target stimulus was a 3D-printed 8 cm cube. Cubes were placed on the table at a 45° angle, centered in front of the participant. This real-world environment was modeled in VR. The VR program was created using Unity (2020.3.39f1) and ran as a standalone application using SteamVR on a Windows 10 computer. The virtual environment was presented in the Varjo XR-3 head-mounted display (HMD). The Varjo XR-3 weighs 980 g and has a 115° horizontal field of view with a 90 Hz refresh rate. Leap Motion was used to track participants' hands during the feedback trials. Hands were the only body feature rendered in the experiment (neither an avatar nor arms were rendered).

4.1.3 Design

The study had a pretest-calibration-posttest design (Figure 1). For the pretest and posttest trials, the cube was placed at 21 distances ranging from 30-110 cm in 4 cm increments. The distances were measured from the front end of the table. Each distance was presented three times, resulting in a total of 63 trials. The distances were presented in a random order. The pretest and posttest trials in the real world and in VR followed the same design.

The calibration phase took place in VR and consisted of adjustment trials and feedback trials. There were three blocks of feedback trials. Each block presented two distances, yielding a total of six feedback trials. Feedback trial distances were +/- 10%, 20%, and 30% of participants' actual reach. Half of the participants experienced the feedback trials in ascending order of percentage: Block 1 = +/- 10%, Block 2 = +/- 20%, Block 3 = +/- 30%. The other half of participants experienced the trials in the reverse order. Within each feedback block, the feedback trial with the smallest distance was always presented first.

Participants completed two adjustment trials before and after each feedback block within the calibration phase (Figure 1), similar to the procedure in [20] and described in more detail below. To control for hysteresis, within each adjustment trial pair, one trial started with the cube at the front edge of the table, and in the other trial, the cube started 140 cm from the front edge of the table. The presentation order of the close and far adjustment trials were randomized by participant.

4.1.4 Procedure

Participants began the experiment by completing consent and demographics forms. The demographics form asked for age, gender, and handedness. Participants completed a stereovision test and their interpupillary distance (IPD) was measured and was used to adjust the IPD of the HMD. They were seated at the table and adjusted the chair until they were as close as possible to the front of the table. The participant's shirt was clipped to the back of the chair to help them maintain an upright position and discourage them from leaning forward. At this point, three measurements were collected: seated eye height, horizontal reach, and arm length. To measure horizontal reach, participants closed their eyes and reached straight forward horizontally with their dominant hand. A cube was placed on the table at the end of the participants' fingertips. The participant returned their hand to their body while keeping their eyes closed. The experimenter measured the distance from the front edge of the table to the front of the cube that marked the participant's reach and recorded the measurement in centimeters. Once the measurement was complete, the participant was instructed to open their eyes. To measure arm length, participants reached straight out to their side with their dominant arm at shoulder height. They were instructed to use their other hand to find the divot on their back where their shoulder met their shoulder blade. The experimenter measured the distance from that point to the end of the fingertips on the participants' outstretched arm and recorded the measurement in centimeters. Participants were then given a verbal overview of the study.

Pretest. The first phase of the study was the real-world pretest phase (baseline). Participants kept their hands in their lap for these trials. For each real-world pretest trial, participants closed their eyes while the experimenter placed a real cube on the table at one of the 21 distances. Once the cube was placed, participants were instructed to open their eyes and provide a verbal yes or no response as to whether they thought they would be able to reach the cube with the end of their fingertips, keeping their back against the chair. The experimenter recorded participants' responses using a Vive controller. Then participants closed their eyes, and the experimenter placed the cube for the next trial. After completing 63 trials in the real world, participants donned the HMD and started the VR pretest phase. The VR pretest phase was the same as the real-world pretest phase, except participants did not close their eyes between each trial. Instead, in between each trial they saw the table without a cube for 2 seconds before the next cube was presented.

Calibration. Participants then proceeded to the calibration phase, which took place in VR. The calibration phase began with two baseline adjustment trials. Participants adjusted the distance of the cube on the table using the trackpad on the Vive controller while keeping their hands in their lap or at the edge of the table. They adjusted the cube until they perceived that it was the farthest distance that they would be able to touch with the end of their fingers while keeping their back against the chair. Next, they completed the first block of feedback trials. Each feedback trial presented the virtual cube at a specific distance (+/- 10%, 20%, and 30% of the participant's measured maximum horizontal reach). When the participant was ready to make their judgment, they used their dominant hand to select a virtual box corresponding to their response. A red "no" box was positioned directly to their left side, and a green "yes" box was positioned directly to their right side (Figure 2). When the participant's hand collided with the yes or no button, the next trial or audio feedback (depending on the feedback condition) was triggered. In the *exploratory behavior* feedback condition, the participants did not receive feedback on their judgment; after they made their judgment selection, they proceeded to the next trial. Viewing their hand as they made their judgment served as exploratory feedback. In the *static outcome* feedback condition, participants made their judgment selection and received auditory feedback from a nearby computer speaker as to whether their judgment was correct or in-

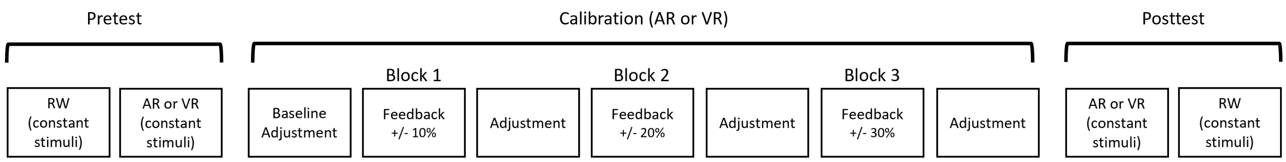

Figure 1: Trial progression.

Figure 2: VR environment. View of environment during feedback trials (left). Reaching out in the action outcome feedback trials (right).

correct. In the *action outcome* feedback condition, after making their judgment selection, participants received auditory feedback as to whether their judgment was correct or incorrect. Then they reached out toward the cube to see if it was reachable (Figure 2). Thus, these three feedback conditions incrementally presented more information: judgment only (exploratory), judgment and auditory outcome feedback (static outcome), and judgment, auditory outcome feedback, and visual-motor outcome feedback (action outcome). As in the other types of trials in the experiment, they saw an empty table for 2 seconds before the presentation of the next trial. After completing the first block of feedback trials, participants completed two adjustment trials, followed by the second block of feedback trials, then two adjustment trials, followed by the third block of feedback, and then two final adjustment trials (Figure 1).

Posttest. Participants then proceeded to the VR posttest phase followed by the real-world posttest phase. The VR posttest always took place before the real-world posttest in order to test whether calibration occurred in VR before testing transfer to the real world. The posttest phase trial design was the same as the pretest phase. After finishing the trials, participants completed a short survey about their video game and VR experience. Participants were debriefed and thanked for their time at the end of the experiment.

4.2 Results

Statistics were performed using R (version 4.0.2). Two dependent variables used in the analysis are crossover ratios and adjustment ratios. The "crossover point" is the point at which judgments (from the pretest and posttest phases) switch from "yes" to "no". It is calculated by averaging the distances where judgments switched from consistently "yes" to consistently "no". For example, if a participant responded "yes" for at least two out of the three 58 cm trials and "no" for at least two out of the three 62 cm trials, their crossover point would be 60 cm. The crossover point was divided by the participants' actual reach to create the *crossover ratio*. A ratio equal to one means that participants perfectly judged their reaching ability. A ratio less than one indicates that they underestimated their reaching ability, and a ratio greater than one means that they overestimated their reaching ability. Each participant had a total of four crossover ratios: real-world (RW) pretest crossover, VR pretest crossover, VR posttest crossover, and RW posttest crossover. Averaged across feedback conditions, the mean RW pretest crossover ratio was 1.15 (SD = 0.18). The mean RW posttest crossover ratio was 1.06 (SD = 0.16). The mean VR pretest crossover ratio was 1.07 (SD = 0.21). The mean VR posttest crossover ratio was 1.01 (SD = 0.15). These results indicate that reachability judgments in the real world were overestimated at pretest, similar to the 10% overestimation found in prior work (e.g., [49]). In VR, the pretest crossover ratios were already close to accurate, which is different than the overestimation of about 20% found in VR (e.g., [20, 38]). However, it is important to note that in [20, 38], participants made reachability judgments while standing, which may affect reachability judgments differently than those made while seated [16].

To calculate the *adjustment ratio*, the average distance of the two adjustment trials for each feedback block was divided by participants' actual reach. This yielded four adjustment ratios for each participant: Block 0 (baseline) adjustment ratio, Block 1 adjustment ratio, Block 2 adjustment ratio, and Block 3 adjustment ratio. Averaged across feedback conditions, the mean Block 0 adjustment ratio was 0.93 (SD = 0.17). Similar to the VR pretest crossover ratios, the baseline adjustment ratio in VR was close to accurate.

4.2.1 Aim 1: Effect of Feedback in VR

Our first aim was to examine whether the type of feedback affects calibration in VR. Two questions are addressed in Aim 1. First, does feedback type influence the magnitude of calibration (**H1**)? Second, does feedback type influence the progression of calibration (**H2**)?

The VR pretest and VR posttest crossover ratios were compared to determine the magnitude of calibration. A multilevel model was used to analyze the crossover ratios. First, a baseline model $VRCrossoverRatio = (1|subid)$ was used to determine the intraclass correlation (ICC). The ICC was 0.59, indicating that differences between participants accounted for 60% of the variation in the data. The model for the primary analysis was:

$$VRCrossoverRatio = (1|subid) + Phase + FeedbackCondition + Phase * FeedbackCondition \quad (1)$$

Phase was a factor with two levels: pretest and posttest. FeedbackCondition was a factor with three levels: exploratory, static, and action.[1] In the effect-coded model, there was a significant effect of Phase ($B = -0.06$, $SE = 0.02$, $p < 0.01$); VR posttest crossover ratios ($M = 1.01$) were significantly lower than VR pretest crossover ratios ($M = 1.07$), showing 6% change due to feedback. If the magnitude of feedback (i.e., the change from pretest to posttest) depended on feedback type, we would expect to see an interaction between FeedbackCondition and Phase. However, the interaction was not significant ($p > 0.05$). These results indicate that crossover ratios became more accurate in VR following feedback, but this change was not dependent on feedback condition (Figure 3). Thus, we found only partial support for our first hypothesis.

The adjustment ratios were analyzed to determine whether feedback type influenced the progression of calibration. The ICC for the

[1] First, the model was run using effect coding for FeedbackCondition in order to determine the main effect of Phase (i.e., averaged across feedback conditions, was there an effect of phase?). The model was then run using dummy coding, once with exploratory as the base level and again with action as the base level in order to test all condition comparisons. In the dummy-coded models, Phase values were mean centered, so that the main effects of the feedback conditions were in reference to adjustment ratios averaged across pretest and posttest.

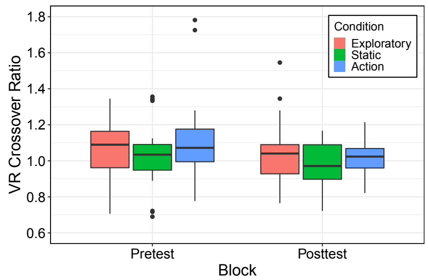

Figure 3: VR crossover ratios. Averaged across feedback conditions, VR posttest crossover ratios were significantly lower than VR pretest crossover ratios. There were no differences between feedback conditions.

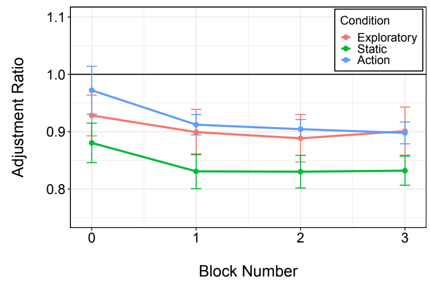

Figure 4: VR adjustment ratios. Averaged across feedback conditions, adjustment ratios significantly decreased from Block 0 to Block 1. Error bars represent +/- 1 standard error.

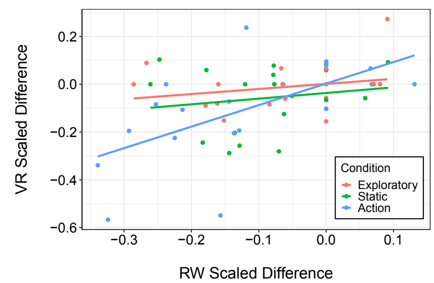

Figure 5: VR to real world transfer. The correlation between RW and VR scaled difference scores was only significant for the action outcome feedback condition.

baseline model was 0.77. The multilevel model for the analysis was:

$$AdjustmentRatio = (1|subid) + Block + FeedbackCondition + Block * FeedbackCondition \quad (2)$$

Block was treated as a numeric variable and FeedbackCondition was a factor with three levels. Effect and dummy coding was used as described above. The effect-coded model revealed a main effect of Block ($B = -0.02$, $SE = 0.004$, $p < 0.001$). Averaged across feedback conditions, as block number increased, adjustment ratios decreased. To determine whether there were differences between blocks, the effect-coded model was rerun with Block coded as a factor with backward difference coding (i.e., the mean of each block compared to the previous block). The results indicated that only the difference between Block 0 and Block 1 was significant ($B = -0.05$, $SE = -0.01$, $p < 0.001$). Therefore, adjustment ratios decreased by about 5% following the first block of feedback and did not change following subsequent feedback blocks (see Figure 4). If feedback type influenced the progression of calibration, we would expect an interaction between FeedbackCondition and Block. However, there were no significant interactions in the adjustment ratio model, nor a significant main effect of feedback. In sum, while we did find calibration due to feedback, we did not find support for the predicted differences between the feedback conditions for either magnitude (**H1**) or rate of progression (**H2**).

4.2.2 Aim 2: Transfer from VR to Real World

Our second aim investigated whether calibration from feedback in VR transfers to the real world and if feedback type affects that transfer. To answer these questions, we used scaled difference scores based on the crossover ratios. The VR scaled difference scores were created by subtracting the VR pretest crossover ratio from the VR posttest crossover ratio and dividing by the VR pretest crossover ratio.

$$VR\ Scaled\ Difference = \frac{VRpost - VRpre}{VRpre}$$

The real-world scaled difference scores were created by subtracting the real-world pretest crossover ratio from the real-world posttest crossover ratio and dividing by the real-world pretest crossover ratio.

$$RW\ Scaled\ Difference = \frac{RWpost - RWpre}{RWpre}$$

Thus, these difference scores scaled each participants' amount of change between pretest and posttest to their pretest judgments. We chose to use these scaled scores because the amount of change may depend on baseline judgments (i.e., if a participant's pretest crossover ratio was close to one, we would not expect much change to occur between pretest and posttest).

To test for an overall effect of transfer of calibration from VR to the real world, we correlated the VR scaled difference scores with the real-world scaled difference scores not separated by feedback condition. The correlation was significant ($r = 0.39$, $p < 0.01$), supporting our hypothesis that calibration of affordance judgments in VR would transfer to the real world (**H3**). Next, we conducted three separate correlations where we correlated the VR and real-world scaled difference scores for each feedback condition. The correlations for the exploratory behavior feedback condition and the static outcome condition were not significant. However, the correlation for the action outcome condition was significant ($r = 0.55$, $p < 0.05$). These findings indicate that calibration transfer only occurred for the action outcome feedback condition (see Figure 5), partially supporting **H4**, as we had expected transfer for both types of outcome feedback.

The results from the Aim 1 analyses show that there was a statistically significant difference between VR ratios before and after feedback. However, this difference was relatively small ($\sim$ 6% change) likely because of the relatively high accuracy in the VR pretest. It is possible that, because initial RW judgments were overestimated more, there would be more change from pretest to posttest judgments in the real world, comparatively. To examine whether real-world judgments changed following feedback in VR, we conducted a multilevel model:

$$RWCrossoverRatio = (1|subid) + Phase + FeedbackCondition + Phase * FeedbackCondition. \quad (3)$$

Phase and FeedbackCondition were factors coded the same as in Equation 1. Effect and dummy coding was used as described above. The ICC of the baseline model was 0.65. In the effect-coded model, Phase was significant ($B = -0.09$, $SE = 0.01$, $p < 0.001$). Averaged across feedback conditions, RW crossover ratios decreased by 9% after experience feedback in VR, becoming more accurate (RW pretest crossover ratio = 1.15; RW posttest crossover ratio = 1.06). In the dummy-coded models, the only significant effect was that, averaged across blocks, crossover ratios in the action outcome condition were significantly higher than adjustment ratios in the static outcome condition ($B = -0.11$, $SE = 0.05$, $p < 0.05$).

In all, our Aim 2 results support evidence of calibration transfer from VR to the real world in two ways. First, there was a significant correlation between the VR scaled difference scores and the RW scaled difference scores. Further analysis for each feedback condition separately supported transfer only for action outcome feedback. Second, there was a significant change from RW pretest to posttest, again supporting that the feedback received in VR influenced subsequent real-world judgments. The implications of these findings are further discussed in the Discussion following Experiment 2.

5 Experiment 2: AR

Experiment 2 was the same as Experiment 1, except that the virtual component was conducted in AR instead of VR. This is the first experiment to study perceived reachability in AR. Additionally, before this experiment, the only feedback types that have been examined in AR were static and outcome feedback. The research questions and hypotheses for this experiment were the same as Experiment 1, as described in the Overview of Experiments.

5.1 Method

5.1.1 Participants

Data were collected from 66 participants. All participants provided informed consent and volunteered or were compensated with course credit for their time. Participants had self-reported normal or corrected-to-normal vision and passed a stereo vision test. Six participants were excluded due to technical difficulties with the program or misunderstanding instructions. This left 60 participants for analysis (36 Female, 21 Male, 3 Nonbinary, M_{age} = 21.38 years, *SD* = 3.75). Participants were right-handed (N = 55) and left-handed (N = 5). There were 20 participants in each feedback condition.

5.1.2 Materials

The study took place in the same location and had the same experimental setup as Experiment 1. Instead of modeling the real-world environment in VR, only a virtual cube was rendered in AR for Experiment 2. The AR program was created using Unity (2020.3.39f1) and ran as a standalone application using SteamVR on a Windows 10 computer. The program was presented in the Varjo XR-3 HMD. The HMD presented participants with a video feed of the real world with a virtual cube superimposed (see Figure 6). The position of the cube was localized to a Vive tracker puck adhered to the left wall. Leap Motion was used to track participants' hands during the feedback trials.

Figure 6: AR environment. View of environment during feedback trials (left). Reaching out in the action outcome feedback trials (right).

5.1.3 Design

Experiment 2 had the same pretest-calibration-posttest design as Experiment 1 (see Figure 1), except that the presentation distances for the pretest and posttest trials were 20-100 cm in 4 cm increments. We shifted the presentation distances 10 cm from the distances presented in Experiment 1, because in Experiment 2, participants were seated 35.5 cm from the front of the table (see Procedure). The calibration phase was the same as Experiment 1, except that it was presented in AR instead of VR. The feedback conditions were also the same as in Experiment 1.

5.1.4 Procedure

As in Experiment 1, participants completed a consent form and demographics form. They completed a stereovision test and their IPD was measured and entered into the HMD. Participants were seated at the table. They adjusted the chair until the back of the chair was 35.5 cm from the front of the table. The chair was placed at the same distance from the table for all participants because it was critical to maintain the same viewing distance so that the AR cube appeared at the correct distance on the real-world table. The participants' shirt was clipped to the back of the chair and the same three measurements were collected as in Experiment 1: seated eye height, horizontal reach, and arm length.

The procedure for the pretest, calibration, and posttest phases was the same as in Experiment 1. However, in the adjustment trials, instead of using the trackpad to adjust the cube, participants pressed the menu button to move the cube farther from them and the trigger button to move the cube closer to them. This change was made because these buttons were found to be more responsive than the trackpad.

5.2 Results

The analysis for Experiment 2 had the same structure as Experiment 1. R was used to perform the statistics. Crossover ratios and adjustment ratios were calculated in the same manner described in Experiment 1. Averaged across feedback conditions, the mean RW pretest crossover ratio was 1.29 ($SD = 0.16$). The mean RW posttest crossover ratio was 1.12 ($SD = 0.17$). The mean AR pretest crossover ratio was 1.25 ($SD = 0.20$). The mean AR posttest crossover ratio was 1.14 ($SD = 0.17$). Averaged across feedback conditions, the mean Block 0 adjustment ratio was 1.09 ($SD = 0.20$).

5.2.1 Aim 1: Effect of Feedback in AR

To determine whether feedback type influences the magnitude of calibration in AR (**H1**), we used the same multilevel model and effect and dummy coding as in Equation 1, except the dependent variable was *ARCrossoverRatio*. The ICC was 0.33. In the effect-coded model, there was a significant effect of Phase ($B = -0.10$, $SE = 0.02$, $p < 0.001$). Averaged across feedback conditions, AR posttest crossover ratios were about 10% less than AR pretest crossover ratios. The dummy-coded models revealed that, averaged across Phase, AR crossover ratios were higher in the exploratory behavior condition compared to the action outcome condition ($B = -0.13$, $SE = 0.05$, $p < 0.01$). All other effects were insignificant (see Figure 7).

We analyzed the adjustment ratios to examine whether feedback type influenced the progression of calibration (**H2**). The multilevel model was the same as in Equation 2, except the dependent variable of $AdjustmentRatio$ was the adjustment ratios in AR. The ICC was 0.75. In the effect-coded model, there was a main effect of Block ($B = -0.03$, $SE = 0.004$, $p < 0.001$). Averaged across feedback conditions, as block number increased, adjustment ratios decreased. To determine whether there were differences between blocks, the effect-coded model was rerun with Block coded as a factor with backward difference coding. Adjustment ratios decreased from Block 0 to Block 1 ($B = -0.05$, $SE = 0.01$, $p < 0.001$) and from Block 1 to Block 2 ($B = -0.03$, $SE = 0.01$, $p < 0.05$).

The dummy-coded models revealed effects of feedback conditions. Averaged across blocks, adjustment ratios were higher in the exploratory feedback condition compared to the static outcome condition ($B = -0.10$, $SE = 0.05$, $p < 0.05$) and the action outcome condition ($B = -0.15$, $SE = 0.05$, $p < 0.01$). The static outcome condition was also involved in two significant interactions suggesting that the progression of calibration was different among the feedback conditions. As block number increased, adjustment ratios for the static outcome feedback condition decreased, but the ratios for the exploratory behavior condition did not change ($B = -0.05$, $SE = 0.01$, $p < 0.001$). The static outcome condition also interacted with the action outcome condition, such that, after Block 1, ratios continued to decrease in the static outcome condition, but ratios plateaued for the action outcome condition and did not change from Block 1 to Block 2 ($B = -0.04$, $SE = 0.01$, $p < 0.01$), see Figure 8.

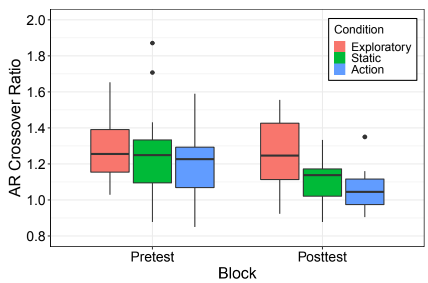

Figure 7: AR crossover ratios. Averaged across feedback conditions, AR posttest crossover ratios were less than AR pretest crossover ratios.

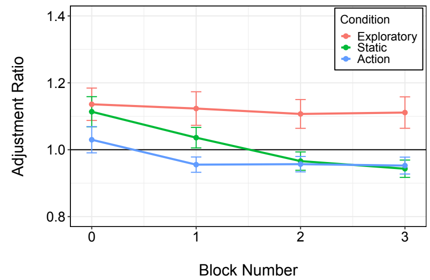

Figure 8: AR adjustment ratios. Averaged across feedback conditions, ratios decreased from Block 0 to Block 1 and from Block 1 to Block 2. Error bars represent +/- 1 standard error.

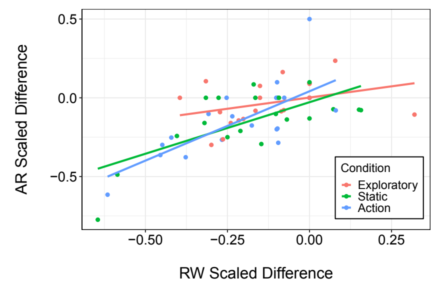

Figure 9: AR to real world transfer. The correlation between RW and VR scaled difference scores was significant for the static outcome and action outcome feedback conditions.

In summary, as in Experiment 1, we found support for an overall calibration effect in AR and it was not dependent on feedback type. The pattern of the magnitude of calibration results were similar to Experiment 1, although there was a greater difference between AR pretest and posttest crossover ratios (11%) compared to the difference between the difference between the VR pretest and posttest crossover ratios (6%). However, in contrast to Experiment 1, there were effects of feedback type on the progression of calibration in AR (**H2**). These results suggest that, as evaluated by adjustment ratios, exploratory feedback did not calibrate reaching judgments, and that action outcome feedback calibrated reachability judgments faster than static outcome feedback.

5.2.2 Aim 2: Transfer from AR to Real World

Similar to Experiment 1, our second aim investigated whether calibration from feedback in AR transfers to the real world (**H3**), and whether feedback type affects that transfer (**H4**). We calculated the scaled difference scores for AR and the real world as described in Experiment 1. To see if there was an overall effect of transfer of calibration from AR to the real world, we correlated the AR scaled difference scores with the real-world scaled difference scores, not separated by feedback condition. The correlation was significant ($r = 0.53$, $p < 0.001$). Next, we conducted three separate correlations where we correlated the AR and real-world scaled difference scores for each feedback condition (Figure 9). The correlation for the exploratory behavior feedback condition was marginal ($r = 0.42$, $p = 0.06$). The correlation for the static outcome feedback condition was significant ($r = 0.51$, $p < 0.01$). The correlation for the action outcome condition was also significant ($r = 0.62$, $p < 0.01$).

Similar to Experiment 1, we conducted a multilevel model using Equation 3 with the *RWCrossoverRatio* as the dependent variable to see if real-world judgments changed regardless of the change in AR. The ICC was 0.07. The effect-coded model revealed a main effect of Phase ($B = -0.17$, $SE = 0.02$, $p < 0.001$). Real-world posttest crossover ratios were 17% lower (and closer to one) than the real-world pretest crossover ratios.

The Aim 2 results show novel transfer effects from calibration in AR to the real world. Consistent with our hypotheses (**H3, H4**), and unlike in VR, transfer effects occurred for both outcome feedback conditions but not for the exploratory behavior feedback condition. In addition, the real-world pretest to posttest change also strongly supports calibration transfer.

6 Discussion

This study set out to address two aims: 1) whether three different types of feedback (exploratory behavior, static outcome, and action outcome) would affect calibration of perceived horizontal reaching ability in VR and AR, and 2) whether calibration achieved in VR and AR would transfer to the real world and if this transfer would be dependent on feedback type. In Experiment 1, participants experienced the calibration phase in VR. In Experiment 2, participants experienced the calibration phase in AR.

6.1 Effect of Feedback in VR and AR

In both VR and AR, there was an overall effect of feedback: crossover ratios in the VR/AR posttest were more accurate than crossover ratios in the VR/AR pretest. Thus, we found evidence that perceived affordances for reaching can be calibrated in both VR and AR. The effects of feedback are novel in two ways. First, in VR we examined three different types of feedback and found that they were all equally effective. Second, this is the first study (to our knowledge) to examine calibration effects for reaching affordances in AR. Here, we again found overall effects of feedback, but we also found a difference in feedback conditions when examining the progression of calibration over blocks of trials. In AR, the static outcome condition more gradually progressed calibration as compared to the exploratory behavior condition (which did not display a calibration effect) and the action outcome condition (where calibration plateaued after the first block of feedback).

This is the first study to explicitly test the effects of three different types of feedback on the calibration of perceived reachability in VR. The overall calibration effect in VR is consistent with prior work. Exploratory behavior has been found to calibrate perceived horizontal reachability in VR [35, 38]. Prior research also supports the finding that action outcome feedback calibrates horizontal reachability perception in VR [11, 12, 20]. The current study provides novel evidence that static outcome feedback can calibrate horizontal reachability judgments in VR as well. In other words, performing the action of reaching is not necessary for calibration to occur, at least in VR.

Little was previously known about feedback and calibration effects on reachability perception in AR. Based on our crossover ratio data, we found an overall effect of phase, but no effect of feedback type in AR. This finding suggests that AR is calibrated by any feedback. However, visual inspection of the crossover ratio and adjustment ratio data suggests that there was not strong evidence of calibration occurring in AR for the exploratory behavior condition. This claim is further supported by the interaction between exploratory and static feedback by block, showing no change in adjustment ratios with block for the exploratory feedback condition. It may seem surprising that exploratory behavior calibrated reaching perception in VR but not AR, given the exploratory behavior condition in AR provides more information than the exploratory behavior condition in VR. In AR, participants could see their real hand and arm as they selected their judgment response. In VR, they could only see the virtual hand. Perhaps the exploratory condition was beneficial in VR due to reduced body-based visual cues. When participants made their judgments in VR, they could not see their real hand or arm. Thus, when they reached for the response buttons in the calibration phase, seeing the virtual hand provided valuable information that they did not have available beforehand. In contrast, participants could always see their real hand and arm in AR, so when they reached for the response buttons in AR, this might not have provided significant additional information.

The differences in the progression of calibration in AR suggest that outcome feedback was necessary for calibration to occur, and it appears that richer feedback (action outcome) calibrated judgments faster. The apparent necessity of outcome feedback for calibration to occur for reachability perception in AR is not completely consistent with the reachability calibration research done in the real world. For example, Jones and Widlus [27] found that exploratory movement sufficiently calibrated horizontal reachability perception in the real world, although the exploratory movement in that study involved arm sway while walking, which was different than the exploratory movement in our study. In contrast, Thomas et al. [45] found that outcome feedback was necessary for calibration to occur for vertical reachability perception in the real world. Exploratory behavior was also not sufficient for calibration to occur for the affordance of squeezing sideways through an aperture in the real world (e.g., [13]).

However, a significant difference between the virtual cube used in our AR environment compared to the real world is that the virtual cube did not have a cast shadow. It can be difficult to perceive the precise location of AR objects, in part because it is difficult to "ground" them. In our experiment, it could have been difficult for participants to perceive where the virtual cube intersected with the real table. Recent work on distance perception in AR, and specifically in the Varjo XR-3, shows that distances are about 20% underestimated in the Varjo XR-3. But, using cast shadows on AR objects can improve distance perception [1]. Therefore, the act of reaching out toward the virtual cube in the action outcome condition likely provided valuable information about the location of the virtual cube in relation to the real table and the participants' real hand and arm. As a result, receiving perceptual-motor information directly related to performance of the action calibrated perception more quickly than only receiving static outcome feedback.

6.2 Transfer from VR/AR to Real World

In both experiments, there was an overall effect of calibration transfer; as judgments became more accurate in VR and AR, they also became more accurate in the real world. Further, the outcome feedback conditions were critical in driving this effect. In both experiments, the exploratory behavior condition did not exhibit calibration transfer. This finding is crucial for understanding the utility of training applications, showing that VR and AR training on affordances is going to be most useful when the experience involves explicit feedback about the accuracy of one's actions.

Numerically, the correlation was stronger for AR ($r = 0.53$) compared to VR ($r = 0.39$). It is possible that the transfer effect was stronger for AR because the AR environment, compared to the VR environment, more closely matched the real-world environment. In VR, further examination of the data indicated that calibration only occurred for the action outcome feedback condition. In AR, calibration occurred for the static and action outcome feedback conditions. As mentioned previously, this could be due to the fact that there were fewer visual differences between the AR environment and real-world environment compared to the VR and real-world environments. Static outcome feedback could have facilitated calibration transfer from AR to the real world, but not VR to the real world because in AR participants could see the real table. For example, participants could see the real wood grain patterns on the table, so they may have used the static outcome feedback to perceive and learn about their reaching ability in relation to the real table without having to perform the act of reaching. Because the real table was not visible in VR, the perceptual-motor feedback from the reaching action provided information about one's reaching ability that was necessary in order for calibration to transfer.

6.3 Limitations and Future Directions

There are some limitations to the present study. For example, this study did not include an experiment where the calibration phase occurred in the real world. Considering that exploratory behavior feedback calibrated reaching perception in VR but not AR, it would be interesting to see whether exploratory behavior would calibrate judgments in the real world. Few experiments have examined the role of exploratory behavior feedback on horizontal reachability perception in the real world, but Jones and Widlus [27] did find that walking with unrestricted arm movement improved reachability judgments in the real world.

Additionally, the current experiments cannot specify the perceptual information from the exploratory behavior condition that facilitated affordance calibration. Visual and motor feedback were provided when participants made their judgments. Future work could use VR to manipulate the type of information provided during exploratory behavior in order to determine whether seeing the hand or moving the arm, or both, is needed for calibration to occur. Prior work in the real world [43] and in VR [35] suggests that visual information may not be necessary for reachability calibration, but further research should be conducted explicitly manipulating visual and motor information in virtual environments.

Judging reachability is also inherently related to perception of distance, which we know to be biased in VR and AR, influenced by both HMD specs and visual depth cues (e.g., shadows). Although not the focus of our work here, the initial overestimation of perceived reachability in the pretest could relate to an underestimation of distance. Future work could assess whether using different displays or virtual object characteristics would replicate our current findings.

Our results show that outcome feedback was necessary for reachability calibration to transfer from VR and AR to the real world. Although this finding indicates that information about the outcome of a judgment is important for affordance calibration transfer, it does not elucidate the mechanisms by which reachability perception is calibrated. It is possible that the outcome feedback did not actually recalibrate perception itself but instead facilitated cognitive strategies that participants used to make their judgments. As discussed earlier, participants could have used a cognitive strategy involving the wood grain on the real table in the static outcome feedback condition in AR, which could explain why the static outcome condition in VR did not result in calibration transfer to the real world. Future studies could explicitly manipulate the information available on the table during the calibration and pre/posttest phases.

7 Conclusions

The experiments presented here indicate that the effects of feedback type on calibration differ between VR and AR. In VR, exploratory behavior may be sufficient for calibration to occur within the virtual environment itself, whereas in AR, outcome feedback may be necessary. However, this study also suggests that providing action outcome feedback in *both* VR and AR will yield the best chance of calibration occurring in the virtual environment and transferring to the real world. The latter finding provides an initial step toward better understanding how to design training programs using virtual environments to ensure their reliability in transferring skills to the real world.

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