The Effect of Feedback on Estimates of Reaching Ability in Virtual Reality

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Abstract

Immersive virtual environments (VEs) are most useful for training and education when viewers perceive and act accurately within them. Judgments of action capabilities within a VE provide a good measure of perceptual fidelity — the notion of how closely perception and action in the VE match that in the real world — and can also assess how perception for action may be calibrated with visual feedback based on one's own actions. In the current study we tested judgments of action capabilities within a VE for two different reaching behaviors: reaching out and reaching up. Our goal was to assess whether feedback from actual reaching improves judgments and if any recalibration due to feedback differed across reaching behaviors. We first measured participants' actual reaching out and reaching up capabilities so that feedback trials could be scaled to their actual abilities. Participants then completed blocks of alternating perceptual adjustment and feedback trials. In adjustment trials, they adjusted a virtual target to a distance perceived to be just reachable. In feedback trials, they viewed targets that were farther or closer than their actual reach, decided whether the target was reachable, and then reached out to the target to receive visual feedback from a hand-held controller. The first feedback block manipulated the target distance to be 30% over or under actual reach and subsequent blocks decreased the deviation to 20%, 10% and 5% of actual reach. We found that for both reaching behaviors, reach was initially overestimated, and then perceptual estimations decreased to become more accurate over feedback blocks. Accuracy in the feedback trials themselves showed that targets just beyond reach were more difficult to judge correctly. This study establishes a straightforward methodology that can be used for calibration of actions in VEs and has implications for applications that depend on accurate reaching within VEs.

Index Terms: Human-centered computing—Human computer interaction (HCI)—Interaction paradigms—Virtual reality; Human-centered computing—Human computer interaction (HCI)—Interaction paradigms—Collaborative interaction

1 Introduction

J. J. Gibson [27] defined *affordances* as the opportunities for action provided by the environment. The ability to accurately perceive these capabilities for actions within immersive virtual environments (VEs) is important for applications that support learning, training, and navigation. Affordances depend not only on environmental features but also on the actor's own body dimensions or capabilities. For example, a doorway is passable if it is wider than the widest part of the actor's body [58], and a step's utility as a riser depends on the length of one's legs [57]. A number of studies have begun to test perceived affordances in VEs, most often with the intent of assessing perceptual fidelity, or how closely perception and action within the VE match that of the real world (e.g. [4, 25, 53]). One significant advantage of the study of perceived affordances in VEs is that visual feedback that the viewer experiences based on their own movements can be easily manipulated. This feedback could be very useful for calibrating judgments about action if they are biased or inaccurate.

Our goal in the current paper is to assess judgments of reaching capabilities—which are typically biased both in the real world and VEs—and test how visual-motor feedback showing the outcome of performed actions recalibrates these judgments. We included a more typical *reaching out* judgment that has been explored in VEs, as well as a novel *reaching up* VE judgment. Using a within-subjects design, we asked whether two different reaching behaviors are calibrated at a similar rate when visual feedback is given via the movement of the hand-held Vive controller (visually displayed within the virtual world), rather than an avatar arm or body. Previous studies on throwing and reaching have shown the importance of having a visible self-representation [5, 17], and reaching is a fundamental activity that supports numerous potential goals within one's environment. Determining how feedback can improve the accuracy of reaching judgments in VEs and how visible self-representation affects these judgments could impact the utility of many applications. We establish that feedback is helpful for reaching performance, but not uniformly helpful, i.e., direction matters. Also, while we reproduce prior work that shows some overestimation in reaching performance, our feedback method eventually produces accurate reaching judgments, which has implications for use as a training mechanism.

2 Related Work

Affordances have been studied extensively in perceptual psychology in the context of Gibson's [27] original definition—that we perceive the environment in terms of the actions that it affords to the observer. Features in the environment are perceived not just for their absolute size or shape, but as opportunities for action depending on their relationship to the observer's body dimensions. Decades of work in real world environments shows that the perception of affordances is reliably scaled to body dimensions. For example, Warren and Whang [58] demonstrated that the size of an aperture that observers walked through before turning their shoulders was scaled at a consistent ratio to the participants' shoulder widths. Likewise, actions such as stepping and sitting are also scaled to relevant body parts (such as leg length) and intrinsic body information such as eye height [40, 57]. Furthermore, people show reliable environment-body relationships when making *affordance judgments*: judging their ability to complete an action without actually performing it. In some

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instances, these judgments tend to be underestimated compared to actual capabilities, allowing for a margin of safety (e.g., setting an aperture to be wider than shoulder width in order to perceive that one can pass through). Notably, in reaching affordance judgment tasks, *reaching out* abilities (horizontally, as if to grasp an object) are overestimated by anywhere between 10% and 30% of actual reach depending on the constraints imposed on reaching and the experimental paradigm [6, 8, 18, 23, 29, 30, 51, 52, 59]. In contrast, the few studies that have tested *reaching up* to a target above the head have typically shown underestimation relative to actual reach of 10-20% [8, 55, 56].

2.1 Affordance Judgments in VEs

Work in immersive VEs has demonstrated that affordances can be assessed in these environments and that judgments made in them are similar to those made in the real world, suggesting a high level of *perceptual fidelity* for VEs in the context of affordance perception. For example, Geuss et al. [25] showed that judgments of passing through an aperture are similar when made in an immersive VE as compared to the real world. Ratios of aperture widths judged as passable when taking into account participants' actual shoulder widths were remarkably alike when shown in an immersive virtual environment compared to the real world. Follow-up work replicated this similarity in passability judgments between a VE displayed on a back-projected screen, a VE portrayed in a head-mounted display, and the real world [26]. The similarity in judgments of passability between virtual environments and the real world has also been investigated with highly realistic sliding doors [3], with some difference reported between real and virtual estimates. In addition to judgments of passing through, other work has investigated the perception of whether cubes can be grasped or apertures can be reached through in desktop virtual environments as well as stereo screen displays [53]. The presence of stereoscopic information improved accuracy in judgments of grasping and reaching through, but these judgments were similar to those made in the real world even in desktop displays without stereo.

Immersive VEs provide a means for assessing the perception of affordances, but for the aforementioned studies, users were unable to "see" their bodies in the context of the virtual environment. This lack of visual representation of the body could have affected users' abilities to scale their judgments of affordances to their body size. Thus, improvements in the ability to portray a visual representation of the body or its parts (e.g., self avatars) in immersive virtual environments have made the assessment of affordance perception even more feasible when comparing to the real world. But the addition of a self avatar or visual body part in the virtual world also offers a unique opportunity to test the role of the visual body in scaling the perception of affordances. For instance, affordance judgments in a virtual environment improved with the presence of a self-avatar compared to no avatar for stepping over and ducking under [37] as well as for stepping up, onto, or down off from a ledge [38, 39]. Further, in estimates of stepping over a gap, larger virtual feet led to overestimation of abilities compared to smaller feet [32]. These findings provide support for the claim that the virtual body is used to scale affordances in that participants clearly used the size of the avatar representation to re-scale their judgments of stepability. Most relevant to the current studies, judgments of reaching out in VEs have been studied in several contexts and tend to match the pattern of overestimation of capabilities seen in real-world studies [13, 17, 36, 42]. As seen in many of the other affordances described above, varying the presence [17] and size [36] of avatar arms influences the perception of reach-ability. The question posed in this paper is how feedback affects affordance judgments and consequently the perceptual fidelity of the virtual environment.

2.2 Feedback and Affordance Calibration

Self avatars may serve to re-scale the perception of affordances because they provide a visual reference with which to compare the environment to the body, but another way of re-scaling the perception of affordances is by providing feedback about judgments. In real-world affordance studies, there is clear evidence that people adjust their estimates of capabilities based on experience from their own actions. With regard to judgments of what one can pass through, research has demonstrated that pregnant women (or those wearing simulated "pregnancy packs") adjusted their judgments for passing through apertures to their changing body dimensions [20], and that after experience moving in a wheelchair, normally walking observers will adjust their estimates of whether they can roll through apertures when in the wheelchair [31, 54]. A question exists as to what it is about movements that underlies these examples of re-scaling–is it simply moving around in an altered body, or is it necessary to receive feedback about the success or failure of the relevant action? Some work suggests that calibration of affordances occurs with basic movements that generate optic flow, even if the movements are not specific to the affordance task at hand [41, 54, 60]. One example is a study in which actors who wore platform shoes that changed their leg length adjusted their affordance judgments for sitting even though they only gained practice standing and moving with their modified body. However, they did not recalibrate further once they were given practice with sitting [41]. But, recent studies suggest experiencing feedback directly as a result of the action—termed *outcome feedback* [21]—can be important for improving the accuracy of some affordance judgments. For example, judgments of squeezing sideways through narrow apertures were inaccurate prior to outcome feedback but improved rapidly after practicing squeezing through apertures [21, 22]. In the current study, we adopted a similar paradigm to Franchak and Somoano [21] by providing outcome feedback in blocks of trials to assess the recalibration rate of different types of reaching judgments: reaching up and reaching out.

In immersive VEs, the role of feedback has been studied mostly in the context of performing actions, although a few studies have examined how feedback from real actions influences estimates of action capabilities. For actual actions, researchers have studied how perceptual-motor feedback can address underestimation in VE distance perception, both in reaching and walking. Distances of 3-10 meters are typically underestimated in VEs, but numerous studies have demonstrated that the dynamic visual information experienced while walking within VEs recalibrates these estimates to make them more accurate [1, 34, 35, 43, 44, 50]. Similarly, in reaching, both visual-proprioceptive and visual-haptic feedback provided during reaching calibrates reaching actions [2, 14–16].

With regard to the effect of feedback on judgments of affordances in virtual environments, rather than actual performance of an action, research has predominantly focused on estimates of when to cross a street and how far one can reach out. For street crossing in a large screen VE, when children have experience actually crossing a virtual street, they become more accurate in estimating the appropriate size of a gap needed between cars to cross without danger given their own capabilities [9, 47, 48]. For reaching affordances, Ebrahimi and colleagues [17] tested the effects of actual reaching on estimates of reach boundaries by varying the presence and visual representation of a self-avatar. Feedback was varied in a pre-test, calibration, post-test design. In the pre-test, participants first made reach-ability judgments, and if perceived as reachable, they physically reached to the target without visual feedback. In the calibration phase, participants first judged reach-ability, but then always attempted to reach for the target and received visual feedback. The feedback varied as to whether they saw a high fidelity self-avatar, a low fidelity avatar, or just the end effectors (hand-held controllers). Participants' estimates of what they could reach became more accurate in the post-test after all calibration conditions, but when compared to the real world, the high fidelity condition was most similar.

Using a similar design, Day et al. [12] tested the effects of experiencing reaching with an avatar arm that was longer than the participant's actual arm and found that subsequent reaching estimates were greater than participants' actual reaching capabilities. Recent work examined the effect of feedback on the perception of reach by consistently or randomly varying the ability to reach during a calibration phase with a virtual arm that changed size [36]. In a calibration phase, viewers experienced visual feedback during reaching from a virtual arm that was matched to their actual arm size or 50% shorter or longer than their actual arm. With consistent feedback, later estimates were recalibrated in the direction of the manipulation of the arm—estimates became more liberal (perceived reach was judged to be farther) when viewing a longer virtual arm and more constricted when viewing a shorter virtual arm. However, in the variable feedback condition including both shorter and longer arms, perceived reach estimates were also judged to be farther. These liberal estimates for reach in both the consistent long virtual arm condition and the variable virtual arm condition could be considered adaptive given they would result in observers deciding to reach more often, especially in cases such as the one investigated where there was no negative consequence for reaching.

Overall, the literature on calibrating actual reaching and perceived affordances for reaching in virtual environments suggests that recalibration can occur via visual feedback about the extent of one's virtual reach. An open question is how much feedback is needed in order to produce reliable recalibration in judgments of reach. Further, it is not clear whether feedback affects other types of reaching, such as reaching up rather than out. Previous studies on reaching out affordances demonstrated recalibration as a result of a single calibration phase. In contrast to these studies, our work is novel in that we employ a paradigm based on Franchak and Somoano [21] that assesses how perception of reaching affordances changes over time as a result of experience with success or failure when performing a reach after making a verbal estimate of whether a target can be reached, e.g., an affordance judgment. Subsequent judgments may then be adjusted to account for the feedback received across trials, resulting in an ability to assess change in judgments over time due to feedback. Thus, this experimental paradigm approach allows us to compare the rate of calibration of judgments for two directions of reaching (up and out) that differ in a number of ways, including biomechanical constraints and the functional goals that they serve. Our interest in understanding rate of change of calibration is motivated by applications that may need to adjust perception quickly, such as training of motor skills within virtual environments.

3 Experiment

The current experiment tested initial affordance judgments and subsequent rates of calibration for two reaching behaviors within a high fidelity VE. By rate of calibration we mean the rate at which the estimated reach converges to the actual reach, which generally happens as people repeat the task [28]. We examined this rate by structuring feedback in blocks of trials that parametrically varied the extent to which targets were close to actual reach. The first feedback block presented "coarse feedback" where the target distance greatly differed from actual reach (by $\pm 30\%$ of actual reach). Subsequent feedback blocks progressively reduced this difference to "fine feedback" with blocks of 20%, 10%, and 5% of actual reach. Viewers experienced visual-motor feedback associated with actual reaching after a judgment was made. Based on prior work in real and virtual environments, we expected initial overestimation of reaching out and underestimation of reaching up. Prior work also suggested that we would find different tuning effects of course and fine feedback over time [21]. Thus, we tested the following hypotheses:

H1 Participants will overestimate horizontal reaching out abilities but will underestimate vertical reaching up abilities.

H2 Judgments will become more similar to actual reach (estimated/actual reach ratio = 1.0) as feedback blocks progress from coarse to fine feedback.

H3 Fine feedback will be more challenging—and thus more useful for learning—compared with coarse feedback because it has greater proximity to participants' actual reaching ability.

3.1 Participants

Data were collected from 23 participants (12 from the University Of Utah, 11 from Vanderbilt University). Four participants were excluded due to missing data resulting from an error in the program settings and 1 participant was excluded due to inadequate baseline measurements, leaving 18 participants for analyses (8 Female, M_{age} = 23.89, SD = 3.05). Participants had normal or corrected-to-normal vision and gave written consent for their participation in the study. Participants volunteered their time and were not compensated. Participants' prior experience with VR was not formally recorded, but many of them mentioned that they had been in VR at least once before. Given the constraints of following COVID-19 testing protocols, we could not adjust the interpupillary distance (IPD) for individual participants. The IPD was set to 63 mm for all participants, which is the average male and female adult IPD.

3.2 Materials

The VE was presented in the HTC Vive Pro head-mounted display (HMD). The Vive Pro has 110° diagonal field of view and weighs 555 g. The VR program was created using Unity (version 2019.2.3f1) and Steam VR (version 1.14.16) and ran as a standalone application on a Windows 10 computer. Baseline measurements were taken using the zero point of the HTC Vive (2018) controller to simulate the end of the participant's hand. Additional Vive trackers were attached to Crocs shoes and used to track the participant's feet. Crocs are a lightweight clog-style shoe that have holes on the top part of the shoe, which allowed us to easily attach the Vive foot trackers.

3.3 Procedure

Upon arrival, participants were screened for potential COVID-19 infection then asked to read and sign an informed consent form. Participants were sufficiently warned and educated about the potential risk of simulation sickness while inside the VE. Next, they were instructed to remove their shoes, put on the Crocs with Vive trackers attached, and firmly secure the Vive headset to their head.

The experiment began by taking baseline measurements of how far in front of, and above, the participant could reach. These measurements were taken by having the participant stand on the footprints depicted on the ground and reach with the Vive controller along a horizontal and vertical line (that had markings similar to a ruler, but no numbers) presented within the VE (see Figure 1). The foot trackers ensured that all participants stood in the same, correct position relative to where they would be reaching to estimate reach. Participants freely chose which hand they used to hold the Vive controller. For the baseline measurements, the farthest point that the participant could reach was automatically recorded by the program in meters once they extended their arm either out or up. A a red marker was added on the end of the virtual controller to simulate the end of the participant's hand (see inset of Figure 1). Participants were told that this location marked the point that would be measured for their farthest reach. Throughout these baseline measurements and the following experimental trials, participants could see their tracked self-avatar feet and the visual representation of the Vive controller, but they did not see any other self-avatar body parts.

After taking baseline measurements, the participant was transported to a different room, which was modeled after the Hogwarts Great Hall from Harry Potter. It was a large, open room with a

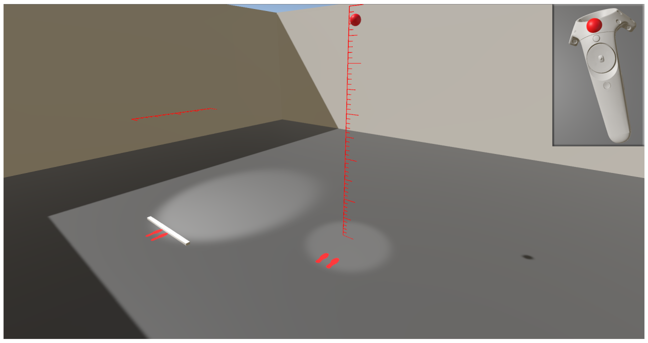

Figure 1: View of the initial room where baseline reaching was measured. Observers stood at the location of the footprints and reached out horizontally or vertically. Modified controller pictured in the corner of image.

stone-tiled floor and brick walls (see Figure 3). The room was 12 m x 33 m with a triangular roof with peak ceiling height of 8.6 m. The room contained a floating broom and a floating snitch from Harry Potter (a small golden ball with wings). These two objects represented the two reaching affordance conditions examined in the present experiment, with the snitch moving horizontally (reaching out) and the broom moving in a vertical path (reaching up), see Figures 2 and 3. There were no other objects or furniture in the VE. All of the experiment trials took place in this room.

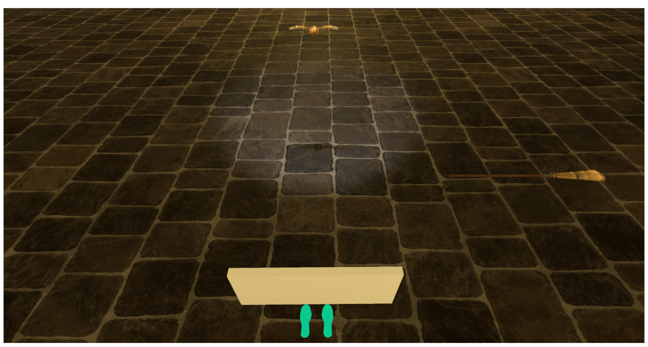

Figure 2: A view of the reaching out affordance judgment. Observers stood at the location of the footprints and moved the snitch horizontally toward or away from the body.

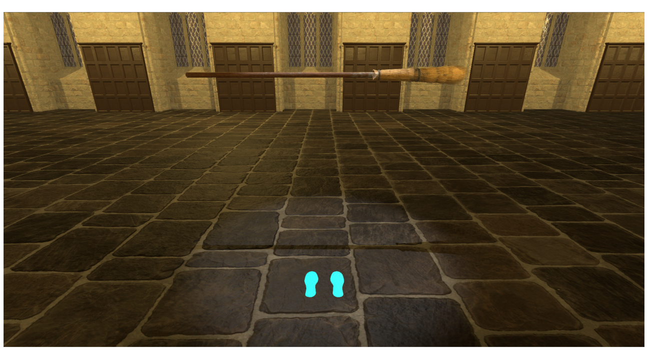

Figure 3: A view of the reaching up affordance judgment. Observers stood at the location of the footprints and moved the broom vertically up or down.

The experiment consisted of a series of five blocks for each reaching affordance (i.e., reaching out and reaching up). There were two different types of trials that participants experienced within these blocks: adjustment trials and feedback trials. Each reaching condition began with an initial adjustment phase (Block 0) which was followed by four blocks (Blocks 1-4) that each contained a feedback phase followed by an adjustment phase (see Figure 4). Each adjustment phase consisted of two adjustment trials, and each feedback phase consisted of two feedback trials. This design resulted in a total of 10 adjustment trials and 8 feedback trials per participant per reaching condition. The order of reaching conditions was counterbalanced across participants.

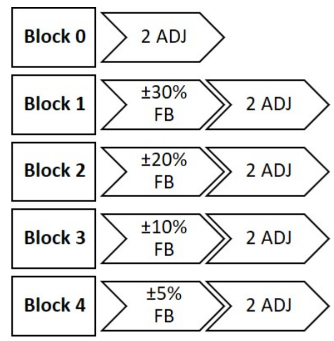

Figure 4: Trial progression for each affordance condition. Block 0 consisted of two initial adjustment trials. Blocks 1-4 each consisted of 2 feedback (FB) and 2 adjustment (ADJ) trials.

In adjustment trials, participants used the touchpad on the Vive controller to position the snitch or broom at the distance they believed that they could just barely touch it if they were to reach out or up, respectively. Importantly, during these trials participants kept their arms at their sides and were instructed not to move them. Each *adjustment phase* consisted of two adjustment trials: in one trial, the object started at the participant location (for reaching out) or on the ground (for reaching up) and was moved away/higher, and in the other adjustment trial the initial object distance started far from the participant, at a distance that was twice their measured actual reach (either up or out). The order of object starting distance (close or far) was randomized for each set of adjustment trials within each block for each participant.

In feedback trials, the object was presented at a set distance based on percentages of the extent of the participants' actual reach that was measured at the beginning of the experiment (+30%, -30%, +20%, -20%, +10%, -10%, +5%, -5%). For example, in the +30% feedback trial, the object was placed 30% beyond the participants' reach; in the -30% trial, the object was placed 30% within the participants' reach. Thus, negative percentages correspond to objects presented within reach while positive percentages correspond to objects presented outside of reach. Without moving their arms, the participant verbally reported whether or not they believed they could reach the object if they tried. After their verbal response, they moved their arm to check whether or not they could, in fact, reach the object, given the location of the visual representation of the red ball attached to the controller in the VE. Each *feedback phase* consisted of two trials of identical percentages above and below the participant's baseline, for example +30% and -30%. The order of percentage presentation (positive or negative) was counterbalanced across participants. Percentage values were presented in the same order for every participant, starting with the ±30% trials (Block 1) and decreasing in value each block, ending with the ±5% trials (Block 4). After each phase of feedback trials, the position of the object relative to the participant rotated slightly, requiring the participant to re-orient themselves before continuing to the adjustment phase. This was done to reduce participants' ability to use environmental cues as a strategy to aid them in their affordance estimates. Participants completed the five blocks for one reaching task and then walked in the VE to the location of the second reaching task. The order of tasks was counterbalanced across participants.

4 Analysis and Results

4.1 Reaching Judgments: Adjustment Trials

We analyzed the distance adjustment trials before feedback (Block 0) and after each feedback block (Blocks 1-4) to assess initial reaching affordance judgments and recalibration of these judgments following feedback (Hypotheses 1 and 2). The perceived reachable distances were recorded in meters for the two trials (starting close and far) in each adjustment phase and averaged. Reaching affordance ratios were calculated by dividing the mean perceived reachable distance by the extent of the participant's actual reach. Thus, a ratio of 1.0 indicates that participants accurately perceived how far they could reach, a ratio greater than 1.0 indicates they perceived they could reach farther than was possible, and a ratio less than 1.0 indicates their perceived reaching distance was closer than their actual reach extent. Mean ratios were calculated for each participant at each block for the two reaching affordances. We initially tested for a potential effect of affordance order (whether participants completed reaching out first or reaching up first). There was no effect of order, so we did not include it in the full model reported below.

A 2 (Affordance: reaching up or reaching out) X 5 (Block) repeated-measures analysis of variance (ANOVA) was conducted to analyze the mean ratios. Affordance and Block were both within-subjects factors. Mauchly's Test of Sphericity indicated that the assumption of sphericity was violated for Block and the Affordance x Block interaction (Block: $X^2(9) = 32.45, p < 0.001$; Affordance x Block: $X^2(9) = 17.71, p < 0.05$). Therefore, degrees of freedom were corrected using Greenhouse-Geisser estimates of sphericity (Block: $\varepsilon = 0.52$; Affordance x Block: $\varepsilon = 0.64$), and we report the Greenhouse-Geisser corrected results below.

The results revealed a main effect of Affordance ($F(1,17) = 19.51, p < 0.001, \eta_p^2 = 0.53$). Ratios were overall higher in the reaching out affordance ($M = 1.11$, $SD = 0.16$) compared to the reaching up affordance ($M = 0.99$, $SD = 0.64$), partially supporting our first hypothesis that participants would overestimate reaching out abilities. There was also a main effect of Block ($F(2.07,35.23) = 10.14, p < 0.001, \eta_p^2 = 0.37$). As feedback blocks progressed, ratios decreased. There was an interaction between Affordance and Block ($F(2.57,43.73) = 2.94, p = 0.051, \eta_p^2 = 0.15$) which suggests that the rate of recalibration differed for the two affordances (see Figure 5). Within Blocks 0, 1, 2, and 3, pairwise comparisons revealed that reaching out ratios were significantly larger (indicating overestimation) compared with the more accurate reaching up ratios (all $ps < 0.01$). However, by Block 4 there was no significant difference between ratios between the two affordances ($p = 0.21$), suggesting that calibration of reaching out affordances became similarly accurate to reaching up after all 4 blocks of feedback. To further interpret this interaction, we conducted separate repeated-measures ANOVAs with Block as a within-subjects factor for each affordance condition (reaching out and reaching up).

Mauchly's Test for the reaching out ANOVA indicated that the assumption of sphericity had been violated ($X^2(9) = 29.70, p < 0.01$). Therefore, degrees of freedom were corrected using Greenhouse-Geisser estimates of sphericity ($\varepsilon = 0.54$), and we report the Greenhouse-Geisser corrected results. The results from the reaching out ANOVA revealed a main effect of Block ($F(2.17,36.94) = 9.27, p < 0.001, \eta_p^2 = 0.35$). As feedback blocks progressed, ratios decreased. Planned repeated contrasts indicated that ratios significantly decreased from the initial adjustment block (Block 0; $M = 1.22$, $SD = 0.15$) to the first block following feedback (Block 1; $M = 1.13$, $SD = 0.12$) ($F(1,17) = 7.09, p < 0.05, \eta_p^2 = 0.29$) and from Block 3 ($M = 1.08$, $SD = 0.12$) to the final block ($M = 1.03$, $SD = 0.14$) ($F(1,17) = 7.45, p < 0.05, \eta_p^2 = 0.31$). Ratios did not differ from Blocks 1 to 2 or Blocks 2 to 3 ($ps > 0.05$). We also ran planned contrasts comparing each block to the initial baseline adjustment. All blocks following feedback had significantly lower ratios compared to baseline (all $ps < 0.05$). These were planned orthogonal contrasts that do not require corrections for multiple comparisons. These results support our second hypothesis that judgments would become more similar to actual reach following feedback.

Mauchly's Test for the reaching up ANOVA indicated that the assumption of sphericity had been violated ($X^2(9) = 28.73, p < 0.01$). Therefore, degrees of freedom were corrected using Greenhouse-Geisser estimates of sphericity ($\varepsilon = 0.55$), and we report the Greenhouse-Geisser corrected results. The results from the reaching up ANOVA revealed a main effect of Block ($F(2.20,37.31) = 4.22, p < 0.05, \eta_p^2 = 0.20$). As feedback blocks progressed, ratios decreased. Planned repeated contrasts indicated that there was a marginal difference between the initial adjustment block (Block 0; ($M = 1.06$, $SD = 0.18$)) and Block 1 ($M = 0.99$, $SD = 0.12$) ($F(1,17) = 4.15, p = 0.057, \eta_p^2 = 0.20$). Ratios did not differ from Blocks 1 to 2, 2 to 3, or 3 to 4 ($ps > 0.05$). Planned contrasts comparing each block to the baseline adjustment showed that ratios were significantly lower at Block 2 ($M = 0.96$, $SD = 0.13$) compared to Block 0 ($F(1,17) = 7.16, p < 0.05, \eta_p^2 = 0.30$) and at Block 3 ($M = 0.96$, $SD = 0.12$) compared to Block 0 ($F(1,17) = 7.20, p < 0.05, \eta_p^2 = 0.30$). Ratios did not differ between Block 0 and Block 4 ($p > 0.05$).

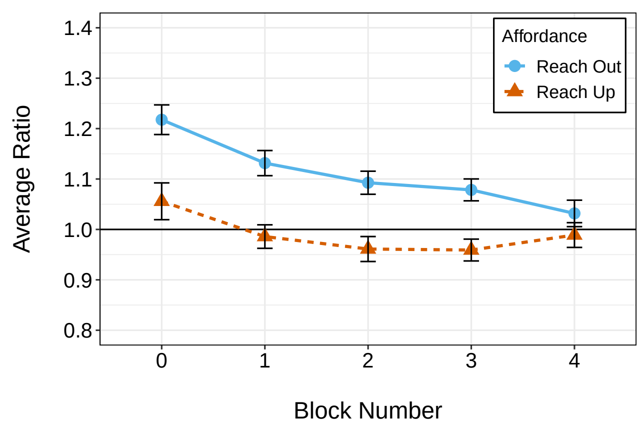

Figure 5: Average perceived affordance ratios at each block for reaching up and reaching out affordances. The solid blue line depicts the mean reaching out affordance ratios. The dotted orange line depicts the mean reaching up affordance ratios. The horizontal black line at 1.0 indicates perfect accuracy. Error bars indicate one standard error above and below the mean ratio.

4.2 Reaching Judgments: Feedback Trials

We analyzed the accuracy of yes/no reach-ability judgments during the feedback trials to test the prediction that fine feedback (feedback trials with reach distances closer to actual reaching ability) would be more challenging—and thus more informative—than coarse feedback (Hypothesis 3). In feedback trials, participants were presented with the object at a set distance and were asked to respond whether or not they would be able to reach it. Object presentation always occurred in the same order, such that the proximity of the object to actual reach for Block 1 was ±30% of actual reach, for Block 2 it was ±20%, Block 3 was ±10%, and Block 4 was ±5%. In other words, as block number increased, object placement moved closer to the boundary of the participant's actual reach extent. If the participant made a correct reach judgment (responded "yes" when the object was within reach or "no" when the object was beyond reach), the accuracy for that trial was given a value of 1. If the participant made an incorrect reach judgment (responded "yes" when the object was beyond reach or "no" when the object was within reach), the accuracy for that trial was given a value of 0. Accuracy values were analyzed with a separate repeated-measures ANOVA for each affordance condition (reaching out and reaching up), with Object Proximity to actual reach (30%, 20%, 10%, 5%) and Object Reach-ability (within reach or beyond reach) as within-subjects factors.

The assumption of sphericity was not violated for the reaching out accuracy ANOVA ($X^2(5) = 8.81, p = 0.74$). The results from the reaching out accuracy ANOVA indicated that there was a main effect of Object Reach-ability ($F(1,17) = 27.54, p < 0.001, \eta_p^2 = 0.62$). Reaching judgments were more accurate when the snitch was presented within reach ($M = 1.00$, $SD = 0.00$) than when it was presented beyond reach ($M = 0.49$, $SD = 0.50$) (see Figure 6). There was no main effect of Object Proximity, but planned repeated contrasts showed that accuracy decreased from the 10% proximity block ($M = 0.78$, $SD = 0.42$) to the 5% proximity block ($M = 0.67, SD = 0.48$) ($F(1,17) = 4.86, p < 0.05, \eta_p^2 = 0.22$). This was qualified by a significant interaction between the 10% and 5% proximity blocks ($F(1,17) = 4.86, p < 0.05, \eta_p^2 = 0.22$), which indicated that the difference between the two blocks was driven by the beyond reach condition. When the snitch was presented beyond reach, accuracy decreased from 55.56% to 33.33%, while the accuracy for when the snitch was presented within reach did not change. In other words, when the snitch was presented within reach, it was always correctly judged as reachable. However, when the snitch was presented beyond reach, it was sometimes incorrectly judged to be reachable, especially when it was presented close to actual reach (+5% proximity). These results support our third hypothesis that fine feedback would be more challenging: accuracy was lowest for the finest feedback block, although this only occurred when the snitch was presented beyond reach (+5% proximity).

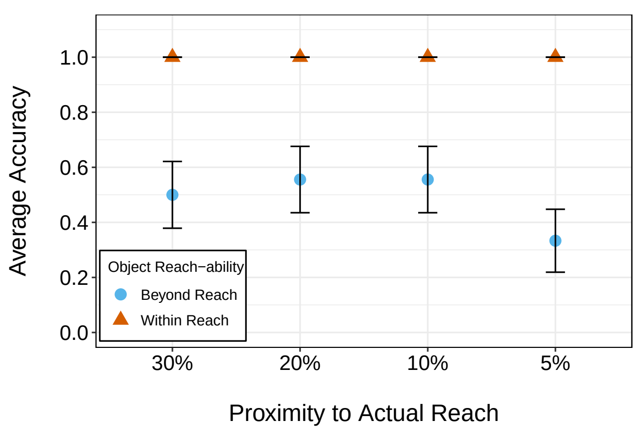

Figure 6: Average accuracy for reaching out feedback trials. Orange triangles depict the mean accuracy for trials where the snitch was presented within reach. Blue circles depict the mean accuracy for trials where the snitch was presented beyond reach. Proximity to Actual Reach labels correspond to the percentage within or beyond reach that the object was presented at. Error bars represent one standard error above and below the mean accuracy.

Mauchly's Test for the reaching up accuracy ANOVA indicated that the assumption of sphericity had been violated (Object Proximity: $X^2(5) = 16.93, p < 0.01$; Object Proximity x Object Reach-ability: $X^2(5) = 17.82, p < 0.01$). Therefore, degrees of freedom were corrected using Greenhouse-Geisser estimates of sphericity (Object Proximity: $\varepsilon = 0.68$; Object Reach-ability: $\varepsilon = 0.69$), and we report the Greenhouse-Geisser corrected results. The results from the reaching up accuracy ANOVA revealed a main effect of Object Reach-ability ($F(1,17) = 10.56, p < 0.01, \eta_p^2 = 0.38$). Reaching judgments were more accurate when the broom was presented within reach ($M = 0.99$, $SD = 0.12$) compared to when it was presented beyond reach ($M = 0.71$, $SD = 0.46$) (see Figure 7). There was no main effect of Object Proximity, but planned repeated contrasts showed that accuracy decreased from the 10% proximity block ($M = 0.86$, $SD = 0.35$) to the 5% proximity block ($M = 0.75$, $SD = 0.44$) ($F(1,17) = 4.86, p < 0.05, \eta_p^2 = 0.22$). When the broom was presented close to actual reach, judgments were less accurate (i.e., the broom was judged to be reachable when it was not). In contrast to the reaching out results, in reaching up, accuracy decreased from the 10% to 5% proximity blocks for both reach-ability conditions, although the decrease for the beyond reach condition (10% proximity: $M = 0.72$, $SD = 0.46$; 5% proximity: $M = 0.56$, $SD = 0.51$) was numerically larger than the within reach condition (10% proximity: $M = 1.00$, $SD = 0.00$; 5% proximity: $M = 0.94$, $SD = 0.24$). As in the reaching out judgments, results support our third hypothesis that fine feedback would be more challenging, since accuracy was lowest for the finest feedback block (±5% proximity).

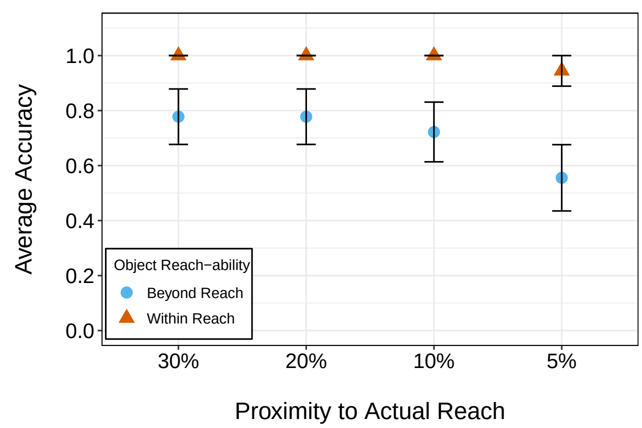

Figure 7: Average accuracy for reaching up feedback trials. Orange triangles depict mean accuracy for trials where the broom was presented within reach. Blue circles depict mean accuracy for trials where the broom was presented beyond reach. Proximity to Actual Reach labels correspond to the percentage within or beyond reach that the object was presented at. Error bars represent one standard error above and below the mean accuracy.

5 General Discussion

With two different reaching affordances, we found that feedback can improve the perception of how far someone can reach up or out in a virtual environment. However, feedback led to a greater change in reaching out estimates compared to reaching up. Our first hypothesis, that reaching judgments would be overestimated while reaching up judgments would be underestimated, was only partially supported by the data. There was overestimation of ability in estimates of reaching out, but reaching up estimates were closer to accurate at baseline (not underestimated as expected from real world experiments). This difference in baseline performance likely led to the rate of change for calibration being larger for reaching out judgments over blocks of feedback as compared to reaching up. However, both judgments recalibrated across blocks of feedback, showing ratios that approached 1.0, supporting our second hypothesis. But, given the larger overestimation in reaching out judgments at baseline, we observed more change in the first block of feedback (compared to reaching up) and continuous improvement until Block 4. Reaching up judgments started relatively close to 1.0, were underestimated by Block 2, but then settled back around 1.0, likely due to the continuous feedback given across blocks. Important to note is that both reaching affordances were close to 1.0 by the last block of feedback, suggesting that the feedback methodology used here can produce quite accurate perceptions of reach-ability.

Finally, our third hypothesis addressed the type of feedback given and its potential effectiveness in improving accuracy in performance. As expected, we found that participants exhibited lower accuracy (suggesting greater difficulty) in judging reach affordances that were close to their actual reaching abilities. This difficulty was apparent in both reaching affordances. When the target was grossly out of reach (i.e., the 30% coarse trials in the feedback block), participants showed higher accuracy in their estimates of what they could reach compared to when the target was presented close to their actual reach (5% fine feedback trials). However, in the reaching out affordance, this effect was only found when the object was presented 5% beyond their reach. This result is consistent with a real world study that found that adults' accuracy in affordance estimates (for vertical and horizontal reaching, stepping over, and passing under) was lowest when the task was just beyond (8%) their abilities [46].

While we expected initial overestimation of reach-ability in the reaching out task, it is notable that it was a larger magnitude (greater than 20%) than that found in some real world studies [6,18,29,30,52]. Furthermore, we also found slight overestimation in the reaching up task, which was inconsistent with the 10% underestimation often reported in previous real world studies [8, 56]. One possible contributing factor could be the distance underestimation typically found within immersive virtual environments and head-mounted displays (see [10, 49] for reviews). If distances are perceived to be closer than their intended distance, then they would also be perceived as more reachable. While the extent of distance underestimation in VEs has been reduced with newer commodity-level devices, it is still typical to find about 10% underestimation [7, 11, 33]. A number of factors may contribute to distance underestimation/reach-ability overestimation, even in the newer devices, that could be examined in future studies. Specifically for reaching up—a less studied affordance—there are limited visual cues for distance along the vertical axis and the task required upward pitch of the head that may be uncomfortable or different than that experienced in the real world. Future studies could address these factors by providing different realistic virtual contexts such as a high shelf with objects to be reached that allows for additional close depth cues (e.g., texture and stereo) and does not require viewing a target directly over one's head. While the current study used an engaging context based on the Harry Potter Hogwarts "Great Hall," a possible limitation of this fantasy world is the lack of realism in reaching for a floating broomstick.

Our results clearly show that feedback about reaching ability in VEs can facilitate performance, despite differences in initial reaching estimates that were slightly different in the VE compared to what has been observed in the real world (i.e., underestimation of reaching up). Specifically, we found that reaching estimates improved over blocks of trials as feedback became more precise. However, we acknowledge that block number was confounded with progression from coarse to fine feedback. An open question is whether this progression of feedback is necessary to improve performance. Future work could examine whether randomizing the coarse and fine feedback trials also improves estimates, or if fewer blocks of feedback trials all together (e.g., just the 30% and 5% blocks) could increase accuracy in judgments. Such a finding would be relevant for reducing training time in applications where quick improvements in virtual estimation would be beneficial. In addition to the amount of feedback, the type of feedback could be further tested. Previous findings on whether participants calibrate when practicing a different but related affordance are mixed. Practicing walking through doorways failed to transfer to judgments of squeezing through doorways [19], and practicing reaching did not improve judgments of throwing [45]. In contrast, prior work [56] showed that for reaching up, practice with standing reaching height transferred to estimates for reach-ability while standing on a stool or kneeling on the floor. Reaching out is a fairly easy task to do in VR, but reaching up is more cumbersome due to the weight of the head-mounted display and its field of view necessitating more movement to see the target. Thus, future work could test whether feedback on reaching out transfers to reaching up or even other types of motor tasks like grasping.

In the current experiment, participants received feedback by physically reaching out or up to see whether they would have been able to reach the object. This feedback is actually twofold: motor feedback is provided from the reaching movement, and visual feedback is provided from the virtual controller. Consequently, we cannot tease apart how the visual and motor feedback might have differentially influenced our results. However, future work could manipulate the type of sensory feedback participants receive. For example, motor feedback could be provided without visual feedback by having the participant physically reach without being able to see the controller, and instead receive a verbal or auditory confirmation on whether they would have been able to reach the object or not. In addition, as in prior work, a future manipulation could implement an avatar arm or hand during feedback blocks, rather than just the visual controller and test relative effects on recalibration. Also, feedback does not have to be visual-motor in nature. Previous work has shown that providing verbal feedback to users about their estimates can also adjust estimates toward accuracy over time [21, 24]. In applications where visual-motor feedback is more difficult to execute, verbal feedback could be a possible means for improving estimates. More work is needed to explore these interesting questions for the many applications that may require precise motor estimates or actions.

6 Conclusion

In the current experiment, we show that visual-motor feedback revealing the outcome of actions can be used to improve estimates of one's ability to reach objects in virtual environments. Over only 4 blocks of reaching feedback trials, estimates for both reaching up and reaching out became highly accurate. Improvements in reaching out judgments replicated prior work with a different mechanism of feedback than that employed previously. The current work also expanded the literature by investigating the effect of feedback on a more novel reaching task: reaching up. The findings suggest that virtual environments can be used to assess estimates of action capabilities as well as improve those estimates through fairly limited visual-motor feedback.

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