Estimating Distance in Real and Virtual Environments: Does Order Make a Difference?

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Abstract

This investigation examined how the order in which people experience real and virtual environments influences their distance estimates. Participants made two sets of distance estimates in one of the following conditions: 1) real environment first, virtual environment second; 2) virtual environment first, real environment second; 3) real environment first, real environment second; or 4) virtual environment first, virtual environment second. In Experiment 1, participants imagined how long it would take to walk to targets in real and virtual environments. Participants' first estimates were significantly more accurate in the real than in the virtual environment. When the second environment was the same as the first environment (real-real and virtual-virtual), participants' second estimates were also more accurate in the real than in the virtual environment. When the second environment differed from the first environment (real-virtual and virtual-real), however, participants' second estimates did not differ significantly across the two environments. A second experiment in which participants walked blindfolded to targets in the real environment and imagined how long it would take to walk to targets in the virtual environment replicated these results. These subtle, yet persistent order effects suggest that memory can play an important role in distance perception.

Virtual environments have gained widespread use in recent years as a tool for studying human behavior (e.g. Fajen & Warren, 2004; Loomis, Blascovich, & Beall, 1999; Plumert, Kearney, & Cremer, 2004). Problems ranging from how children make road-crossing decisions (Plumert et al., 2004) to how adults respond to social situations (Pertaub, Slater, & Baker, 2001) have been studied using various kinds of immersive virtual environments. Virtual environments have also been used as a tool for training new skills, particularly in cases where training in the real environment can be risky or dangerous. For example, immersive virtual environments have been used for training fire fighters, medical doctors, and military personnel (e.g., Johnson & Stewart, 1999). Two questions that arise when using virtual environments for such research and training purposes are: 1) How well does perception in virtual environments correspond to perception in the real environment? and 2) How does experience in a virtual environment affect subsequent perception in the real environment and vice versa? To date, much of the work on perception in virtual

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environments has focused on determining how well distance perception in virtual environments corresponds to that in the real environment. Relatively little work, however, has addressed the issue of how perception might change as a result of experience in virtual environments. We addressed both of these issues in the present investigation by examining how people perceive distance in real and virtual environments both before and after experience in each environment.

Studies of distance perception in the real environment typically use *visually directed action tasks* in which participants carry out actions toward previously seen targets. The gold standard in this area of research is blindfolded walking, in which participants view a target and then immediately attempt to walk to the target while blindfolded (Loomis, Da Silva, Fujita, & Fukusima, 1992; Philbeck & Loomis, 1997; Rieser, Ashmead, Taylor, & Youngquist, 1990). A number of recent studies comparing blindfolded walking in real and virtual environments have shown that people are generally quite accurate at walking without vision to previously seen targets in the real environment (e.g. Creem-Regehr, Willemsen, Gooch, & Thompson, 2005; Interrante, Anderson, & Ries, 2006; Jones, Swan, Singh, Kolstad, & Ellis, 2008; Messing & Durgin, 2005; Swan, Jones, Kolstad, Livingston, & Smallman, 2007; Waller & Richardson, 2008; Witmer & Sadowski, 1998), particularly within what is called *action space* (up to about 30 m; Cutting & Vishton, 1995). For example, Swan et al. (2007) found that blindfolded walking estimates in the real environment were 96% of the actual distance for distances ranging between 3 and 7 m. Other visually directed action tasks used to assess distance perception are throwing and triangulated walking (e.g., Richardson & Waller, 2005, 2007; Sahm, Creem-Regehr, Thompson, and Willemsen, 2005; Thompson, Willemsen, Gooch, Creem-Regehr, Loomis, & Beall, 2004). In triangulated walking tasks, participants view a target and then are instructed to turn and walk in a different direction from the target (e.g. 70 degrees to the right) for a predetermined distance. When participants stop, they are instructed to either turn, point, or walk in the direction of the target. The triangulated walking task therefore provides a measure of participants' mental representation of their distance and direction to the target, which is updated as they walk. Using this task, Thompson et al. (2004) found that estimates were 95% of the actual distance for distances ranging between 5 and 15 m in the real environment. Similar results have been observed for throwing to targets between 3 and 6 m (Sahm et al., 2005). These studies have led to a general consensus that perception of distance within action space in the real environment is quite accurate.

Most studies of distance perception in virtual environments have used head-mounted display (HMD) systems because they allow participants to physically move within a virtual environment. This feature of HMD systems allows researchers to use visually guided action tasks to assess distance perception. These studies have shown that people underestimate distance in virtual environments relative to the real world (e.g., Creem-Regehr et al., 2005; Loomis & Knapp, 2003; Messing & Durgin, 2005; Richardson & Waller, 2007; Sahm et al., 2005; Thompson et al., 2004; Willemsen & Gooch, 2002; Witmer & Sadowski, 1998). For example, Messing and Durgin (2005) found that people estimated 77% of the actual distance when walking to targets without vision in a virtual environment. Studies using triangulated walking or pointing have shown even greater underestimation of distance in virtual environments. Thompson et al. (2004) found that people estimated only 44% of the actual distance in a triangulated walking task. Likewise, Richardson and Waller (2007) found that, before implicit feedback training, people estimated only 54% of the actual distance in a triangulated walking task. People also undershoot distances when throwing to targets in virtual environments. Sahm et al. (2005), for example, found that virtual environment throws were 30% more compressed than real world throws. Together, these studies indicate that distances appear more compressed in virtual environments than in the real environment.

As mentioned above, the majority of studies examining distance perception in virtual environments have used HMD systems (e.g. Witmer & Sadowski, 1998; Interrante et al., 2006; Creem-Regehr et al., 2005). However, studies using large screen immersive display (LSID) systems appear to show less distance compression than HMDs. In a recent study using a LSID system, Plumert, Kearney, Cremer, and Recker (2005) asked people to estimate how long it would take to walk to targets in real and virtual environments by starting and stopping a stopwatch while imagining walking to a target (a virtual or real person) standing between 20 and 120 ft. away. The real environment was a large grassy lawn in front of a university building. This scene was replicated in a virtual environment using a nonstereoscopic, large-screen immersive display system. Participants made estimates either in the real or virtual environment first. Within-subject comparisons indicated that time-to-walk estimates did not differ across real and virtual environments when people made estimates in the real environment first. When people made estimates in the virtual environment first, however, estimates were significantly shorter in the virtual than in the real environment. In addition, it appeared that virtual environment estimates made in the virtual-real condition were less accurate than virtual environment estimates made in the real-virtual condition. Likewise, it appeared that real environment estimates made in the real-virtual condition were more accurate than real environment estimates made in the virtual-real condition. Although these findings lend some support to the notion that distance estimates are similar in real and LSID virtual environments, it is also clear that the order in which people made judgments in real and virtual environments affected their distance estimates. The exact nature of these order effects, however, is difficult to pin down because order and environment were not completely crossed in the design.

The question of how experience in a virtual environment affects distance perception in the real environment and vice versa has only begun to receive attention. Witmer and Sadowski (1998) had participants walk to targets while blindfolded in either a real hallway or a virtual environment model of a hallway. Though the effects were subtle, they found carryover from the first set of distance estimation trials to the second set. When participants judged distances in the virtual hallway first, they did slightly worse in their subsequent real world distance estimations. However, when participants judged distances in the real world hallway first, they showed less distance compression in the virtual hallway. Interestingly, the positive carryover from the real environment to the virtual environment was stronger than the negative carryover from the virtual environment to the real environment. Interrante et al. (2006) also found that when participants were given experience with the real space prior to making distance judgments in the virtual environment model of that same space, they did not exhibit the typical distance compression in the virtual environment. The virtual environment was an exact model of the real environment in which the participant was located during testing (an empty lab room). After entering the lab and filling out consent forms (about 2 minutes of exposure to the room), participants were asked to complete a series of blindfolded walking distance estimates in both environments. Participants were randomly assigned to complete estimates in either the real environment or the virtual environment first. Interrante et al. (2006) found no significant distance compression in the virtual environment compared to the real environment, even for first estimates. They note that in typical HMD studies, participants are cognizant of the fact that the virtual environment in which they are moving does not match the physical room in which they are located. When this disconnect is removed, the difference between real and virtual environment estimates disappears.

Other researchers, however, have found no effects of experience in a virtual environment on real-world distance estimates. Mohler, Creem-Regehr, and Thompson (2006) had participants complete pretest and posttest distance estimates with either verbal report or blindfolded walking to targets 3–7 m away in either a real hallway or a virtual hallway. In

between pre- and posttest, participants experienced a 5- to 7-minute adaptation period in the virtual environment during which they walked to targets with either implicit (walking with eyes open), explicit (opened their eyes at the end of the estimation to see how close they were), or verbal (walked with eyes closed until experimenter told them they were at the target location) feedback. Mohler et al. (2006) found that adaptation in the virtual environment had no effect on distance estimations completed in the real environment. However, when they altered the optic flow rate in the virtual environment to be twice as fast as the normal walking pace during adaptation, participants showed significant underestimation in the real world posttest as compared to pretest.

Given the contradictory nature of the findings, additional work is needed to understand how experience in a specific virtual environment changes distance perception in the corresponding real environment and vice versa. This work is important not only for practical reasons, but for theoretical reasons as well. On a practical level, documenting possible carryover effects is important for evaluating whether training in a virtual environment can be accurately transferred to the real environment. For example, if military personnel conduct a virtual walk-through before they conduct an actual walk-through of a town, they may expect distances to be much shorter than they really are. On a theoretical level, inducing changes in distance perception through experience can provide information about the processes involved in making distance estimates. For example, carryover effects from one environment to the other may shed light on the role that memory plays in the visually directed action tasks used to assess distance perception.

The goal of the current study was to further investigate how experience with making judgments in real and virtual environments influences distance estimation. One problem with the Plumert et al. (2005) study and other studies such as Witmer and Sadowski (1998) that have examined order effects in virtual and real environments is that environment type and environment order have not been completely crossed in the design. That is, participants experienced either virtual-real or real-virtual conditions. With this simple design, unambiguous between-subjects comparisons can be made between real and virtual environment first estimates, but not between real and virtual environment second estimates. More specifically, between-subjects comparisons become problematic in the second set of estimates because changes in performance could reflect either practice with making distance estimates or previous experience with the other environment. The best way to distinguish between these two possibilities is to include both real-real and virtual-virtual conditions, along with the real-virtual and virtual-real conditions. Thus, we aimed to clarify previous work by carrying out a complete 2×2 design in which participants would experience either the real environment (RE) or the virtual environment (VE) first followed by either the real environment or the virtual environment second. This design allowed us to unambiguously address two questions: 1) Are distance judgments made in the real environment more accurate than distance judgments made in a LSID environment? and 2) How does experience in the virtual environment affect subsequent distance estimates in the real environment and vice versa?

EXPERIMENT 1

Method

Participants—Fifty-two undergraduates (23 females) participated for course credit.

Apparatus and Materials—A handheld stopwatch was used to record participants' time estimates. Colored golf tees (not visible to participants) were used to mark the target distances. Sunglasses with the lenses, sides, and nose area blocked out were used to prevent participants from viewing targets while making estimates without vision.

Experimental Settings

Real environment: The real environment was an open, grassy lawn in front of a university building (Figure 1). To keep the real and virtual environments as similar as possible, we made every attempt to keep the testing area free of distractions and objects. For example, we asked people sitting within 30 ft of the testing area to move and picked up all sticks and litter from the testing area.

Virtual environment: The virtual environment was a scene depicting the setting that served as the real environment (Figure 1). This scene was displayed on three 10 ft-wide × 8 ft-high screens placed at right angles relative to one another, forming a three-walled room. Participants stood midway between the two side screens and 8 ft from the front screen. High-resolution, textured graphics were projected onto the screens (1280 × 1024), providing participants with 270 degrees of nonstereoscopic, immersive visual imagery. The viewpoint of the scene was adjusted for each participant's eye height, but the virtual environment was not interactive (i.e., participants could not move through the virtual environment). Participants viewed the scene binocularly.

Design and Procedure—Participants were tested individually in a single session. We first obtained an estimate of each participant's typical walking speed by timing how long it took each participant to walk between two points in a hallway. The first experimenter positioned participants at the starting line and instructed them to walk at their normal speed past a finish line near the end of the hallway. The second experimenter started a stopwatch when participants began walking and stopped the stopwatch as participants crossed the finish line. The distance between the start and the finish lines was 53 ft, falling approximately midway in the range of distances participants estimated in the test portion of the experiment. Participants completed this walking task twice and experimenters calculated the average of these two trials to obtain each participant's baseline walking speed.

Following the baseline-walking task, participants made estimates of how long it would take them to walk to targets in the Real Environment (RE) and Virtual Environment (VE). Participants completed two sets of time-to-walk estimates in one of the following conditions: 1) RE first, RE second (*N* = 13); 2) VE first, VE second (*N* = 14); 3) RE first, VE second (*N* = 12); or 4) VE first, RE second (*N* = 13). Hereafter, we refer to these conditions as real-real, virtual-virtual, real-virtual, and virtual-real.

Participants who made estimates in the real environment were taken outside to a place at one end of the lawn facing the university building. The first experimenter informed participants that the second experimenter would stand at different places on the lawn in front of them and that their task was to imagine walking to the second experimenter. The first experimenter then handed a stopwatch to the participants and told them that they should start the stopwatch when they imagined starting to walk and to stop the stopwatch when they imagined reaching the second experimenter (without ever looking at the stopwatch). Participants were given the opportunity to practice starting and stopping the stopwatch to make sure that they knew how to operate the stopwatch. Before the start of each trial, participants turned around so that they could not see the second experimenter moving into position. The second experimenter moved to each new distance position marked by the colored golf tees. When the second experimenter was in position, participants turned around to face the target (the second experimenter). The first experimenter counted silently for four seconds and then instructed participants to close their eyes and put on the blindfold glasses. Participants were instructed that once their eyes were closed they should start the stopwatch when they imagined starting to walk to the target and to stop the stopwatch when they imagined reaching the target. After participants stopped the stopwatch, the experimenter

recorded the time elapsed. Participants completed time-to-walk estimates for six randomly ordered distances (20, 40, 60, 80, 100, and 120 ft).

Participants who made estimates in the virtual environment were asked to stand in a box marked by tape on the floor of the virtual environment. The box was midway between the two side screens and 8 ft away from the front screen. The experimenter informed participants that they would see a person standing at different places on the lawn in front of them and that their task was to imagine walking to the person. At the start of each trial, the experimenter hit a key on the computer to make the target appear on the lawn. Participants followed the same procedure for making their time-to-walk estimates as was used in the real environment.

After completing the first set of estimates in either the real or the virtual environment, participants were taken to the location where they made their second set of estimates. The time required to travel from the virtual environment to the real environment or vice versa was approximately 3- to 4 minutes. In an attempt to make the real-real and virtual-virtual conditions as similar as possible to the real-virtual and virtual-real conditions, experimenters took participants in the real-real and virtual-virtual conditions on an approximately 3- to 4-min walk between their first and second sets of estimates.

Results

The analyses were carried out in two steps. We first conducted an overall analysis that included all factors in the design of the experiment to test for overall effects of trial and distance. We chose the real-real and virtual-virtual conditions for this analysis because there was no change in environment from the first set to the second set of estimates. We then conducted planned *t*-tests to test specific hypotheses.[1] We addressed two questions: 1) were distance estimates more accurate in the real than in the virtual environment? and 2) How did experience with making distance estimates in our virtual environment affect subsequent estimates in the real environment, and vice versa?

Our measure of accuracy was the percentage of the actual distance participants estimated for each distance. We calculated this percentage by dividing the time-to-walk estimate by the actual time-to-walk for each distance. Thus, each participant received 12 accuracy scores – six for each of the two test trials. We estimated the amount of time actually required to walk the six distances for each participant by dividing each actual distance (i.e., 20, 40, 60, 80, 100, and 120 ft) by the participant's baseline walking speed. Each participant's walking speed was determined by dividing the baseline-walking distance by the average baseline-walking time.

Overall Analyses—Figure 2 shows the mean percentage of the actual distances estimated by participants in the four conditions during first (left panel) and second (right panel) trials. To test for overall effects of trial and distance, we entered the percentage of actual distance estimated into a Condition (real-real, virtual-virtual) $\times$ Trial (first, second) $\times$ Distance (20, 40, 60, 80, 100, 120 ft) repeated measures ANOVA with the first factor as a between-subjects variable and the second and third factors as within-subjects variables. There was a significant overall effect of distance, $F(5, 125) = 8.60$, $p < .001$, $\eta_p^2 = .26$, but no effect of trial, $F(1, 25) = 1.21$, *ns*. As shown in Figure 3, follow-up tests indicated that estimates made at the 20 and 40 ft distances were significantly more accurate than estimates made at all other distances. There was also an effect of condition, $F(1, 25) = 5.96$, $p < .05$, $\eta_p^2 = .19$,

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[1]We collapsed over distance when conducting the planned comparisons in both experiments because we had no specific hypotheses for interactions of distance and condition.

indicating estimates in the real-real condition ($M = 79\%$, $SD = 31.7$) were more accurate than those in the virtual-virtual condition ($M = 56\%$, $SD = 23.6$).

Planned Comparisons

<u>Were distance estimates more accurate in the real than in the virtual environment?:</u> As shown in Figure 4, first estimates in the real-real and real-virtual conditions appeared to be more accurate than first estimates in the virtual-virtual and virtual-real conditions. Planned comparisons revealed that first estimates were significantly more accurate in the real-real than in the virtual-virtual and virtual-real conditions, $t(25) = 2.41$, $p < .05$, Cohen's $d = .92$, and $t(24) = 2.30$, $p < .05$, $d = .90$, respectively. However, the difference between first estimates in the real-virtual condition and the virtual-virtual and virtual-real conditions did not reach significance, $t(24) = 1.30$, *ns, d = .50*, and $t(23) = 1.18$, *ns, d = .47*, respectively. As would be expected, first estimates in the real-real and real-virtual conditions did not differ significantly, $t(23) = .83$, *ns, d = .33*, nor did first estimates in the virtual-virtual and virtual-real conditions, all $t(25) = .18$, *ns, d = .07*. To provide an even stronger test of differences across real and virtual environments, we compared the combined performance of participants in the two real environment conditions (real-real and real-virtual) to that of participants in the two virtual environment conditions (virtual-virtual and virtual-real). This analysis revealed that first estimates made in the real environment ($M = 74\%$, $SD = 30.2$) were significantly more accurate than those made in the virtual environment, ($M = 55\%$, $SD = 19.9$), $t(50) = 2.58$, $p < .05$, $d = .71$. Together, these results clearly show that distance estimates made first were more accurate in the real than the virtual environment.

<u>How did experience in the real or virtual environment affect subsequent distance estimates?:</u> As shown in Figure 4, experience in the real or virtual environment appeared to affect the accuracy of subsequent estimates, particularly when moving from the real environment to the virtual environment. We tested these effects by comparing distance estimates made second across the four conditions. First, second estimates were significantly more accurate in the real-real ($M = 80\%$, $SD = 30.9$) than in the virtual-virtual condition ($M = 58\%$, $SD = 23.0$), $t(25) = 2.36$, $p < .05$, $d = .90$, showing that the difference between real and virtual environments seen above persisted with repeated experience with the task. However, there was no significant difference between second estimates in the real-virtual and virtual-real conditions, $t(23) = .41$, *ns, d = .16*, indicating that experience with making distance estimates in one environment affected estimates in the other environment. Second, there was no significant difference between the combined second estimates of participants in the two real environment conditions (real-real and virtual-real; $M = 74\%$, $SD = 29.8$) and that of participants in the two virtual environment conditions (virtual-virtual and real-virtual; $M = 65\%$, $SD = 30.2$), $t(50) = 1.10$, *ns, d = .30*. This stands in contrast to the first estimates in the two environments reported above. However, second estimates were not significantly different in either the real-real and the virtual-real conditions, $t(24) = 1.03$, *ns, d = .40*, or in the real-virtual and virtual-virtual conditions, $t(24) = 1.39$, *ns, d = .53*.

Discussion

The analyses above show that participants' first estimates were more accurate in the real than in the virtual environment. This was particularly evident when we combined the two groups of real environment first and virtual environment first participants. Second estimates remained significantly different when there was no change in environment from the first to the second set of estimates (i.e., the real-real and virtual-virtual conditions). However, second estimates were no longer significantly more accurate in the real than in the virtual environment when there was a change in environment. There was a trend for virtual environment estimates to become more accurate after experience in the real environment than in the virtual environment, and for real environment estimates to become less accurate

after experience in the virtual environment than in the real environment. Together, these trends were enough to wipe out the advantage of the real environment over the virtual environment observed in participants' first estimates.

These findings clarify and extend the results reported in Plumert et al. (2005). As noted earlier, this study relied on within-subject comparisons of distance estimates in real-virtual and virtual-real conditions. Estimates did not differ across environments in the real-virtual condition, but virtual environment estimates were significantly less accurate than real environment estimates in the virtual-real condition. The full factorial design used in the present investigation showed that real environment estimates were significantly more accurate than virtual environment estimates when there was no change in environment from the first to the second set of estimates. This finding adds to other research in this area showing that people underestimate distance in virtual environments relative to the real environment (e.g., Creem-Regehr et al., 2005; Loomis & Knapp, 2003; Sahm et al., 2005; Thompson et al., 2004; Willemsen & Gooch, 2002; Witmer & Sadowski, 1998).

One issue left unaddressed is the underlying cause of the observed order effect. Are people merely remembering the amount of time they held down the stopwatch in the real environment and carrying this timing over to subsequent estimates in the virtual environment (and vice versa)? Or does experience in the real or virtual environment really influence how people perceive those same distances in the opposite environment? We carried out a second experiment to examine the robustness of the order effects found in Experiment 1. More specifically, we examined whether the environment order effect generalizes from imagined walking in the virtual environment to blindfolded walking in the real environment, and vice versa. Everything was the same as in Experiment 1 except that all estimates made in the real environment were made via a blindfolded walking task rather than the imagined walking task. Note that previous work has shown that blindfolded walking estimates and imagined walking estimates are virtually identical, making direct comparisons between the two valid (Plumert et al., 2005). As in Experiment 1, we expected that first estimates would be more accurate in the real than in the virtual environment. We also expected that there would be no difference between second estimates in the real-virtual and virtual-real conditions, indicating that previous experience in real and virtual environments influences people's subsequent perception of distance even when the distance estimation task changes.

EXPERIMENT 2

Method

Participants—Fifty-four undergraduates (27 females) participated for course credit.

Apparatus and Materials—As in Experiment 1, participants used a handheld stopwatch to make time estimates in the virtual environment. During real environment trials, participants performed a blindfolded walking task to the target. Target distances were marked with colored golf tees (not visible to participants) and a tape measure was used to measure how far participants walked while blindfolded. During both virtual environment time-to-walk estimates and real environment blindfolded walking estimates, participants wore a blindfold in order to prevent them from viewing targets while making their estimates. Participants also wore noise-canceling headphones that played white noise while making estimations of distance in both the virtual and real environments. Experimenters were able to communicate with participants through the use of a microphone that would interrupt the white noise in order for the experimenter to give instructions. The use of white noise headphones was important in Experiment 2 since participants would be walking blindfolded

to targets outside and we did not want them to use auditory cues (such as street traffic) when deciding how far to walk to reach a target.

Experimental Settings—Both the real environment and the virtual environment were the same as Experiment 1.

Design and Procedure—Participants were tested individually in a single session. As in Experiment 1, we first obtained an estimate of each participant's typical walking speed by timing how long it took each participant to walk between two points in a hallway. Participants completed this walking task twice and experimenters calculated the average between these two trials to obtain each participant's baseline walking speed. Following the baseline-walking task, participants completed two sets of distance estimates in one of the same four conditions as Experiment 1: real-real ($N = 14$), virtual-virtual ($N = 14$), real-virtual ($N = 13$), or virtual-real ($N = 13$).

Participants who made estimates in the real environment were taken outside to a place at one end of the lawn facing the university building. The first experimenter informed participants that the second experimenter would stand at different places on the lawn in front of them and that their task was to walk to the location of the second experimenter while wearing the blindfold and headphones. Participants were told that the second experimenter would move out of the way so that they wouldn't have to worry about running into them. After they finished making each blindfolded walking estimate, an experimenter would lead participants back to the starting position while still blindfolded in order to avoid giving participants any feedback about the accuracy of their estimates. Participants completed two practice trials without feedback (randomly ordered at distances of 35 and 55 ft) to make them feel more comfortable walking without vision and to make sure that they understood the task. Previous researchers (e.g. Interrante et al., 2006; Mohler et al., 2006) have utilized a period of familiarization with blindfolded walking to help participants feel more comfortable walking without vision. After the two practice trials, participants completed test trials for six randomly ordered distances (20, 30, 40, 50, 60, and 70 ft).[2] In between trials, participants kept the blindfold over their eyes so that they could not see the second experimenter moving into position. At the start of each trial, the second experimenter used the colored golf tee markers to stand at the target distance. When the second experimenter was in position, participants were instructed by the first experimenter to lift up the blindfold and look at the target (second experimenter). The first experimenter counted silently for four seconds and then instructed participants to lower the blindfold. Participants were instructed that once they were wearing the blindfold they should walk forward until they thought they had reached the target location. After participants stopped walking, the experimenters measured the distance the participant had walked using a tape measure.

Participants who made estimates in the virtual environment completed time-to-walk estimates using a stopwatch. The experimenter informed participants that they would see a person standing at different places on the lawn in front of them and that their task was to imagine walking to the person and to start the stopwatch when the imagined starting to walk and stop the stopwatch when they imagined reaching the target location. The procedure for the virtual environment trials was the same as Experiment 1 except that the new distances were used (20, 30, 40, 50, 60, and 70ft) and participants were given two practice trials without feedback at 35 and 55 ft. Participants also wore both the blindfold and the white noise headphones while making distances estimates in the virtual environment. Thus, all

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[2]We truncated the range of distances in this experiment because most participants are uncomfortable walking with their eyes closed for long distances.

aspects of the experiment were the same in the real and virtual environments except for the task used to assess distance perception.

After completing their first set of estimates in either the real or the virtual environment, participants were taken to the location of their second set of estimates. As in Experiment 1, it took approximately 3- to 4 minutes to go from the real to the virtual environment, or vice versa. As before, experimenters took participants in the real-real and virtual-virtual conditions on an approximately 3- to 4-minute walk between their first and second test trials.

Results

The analyses again were carried out in two steps. We first conducted an overall analysis that included all factors in the design of the experiment to test for overall effects of trial and distance. We chose the real-real and virtual-virtual conditions for this analysis because there was no change in task or environment from the first set to the second set of estimates. We then conducted planned comparisons to test the specific hypotheses. As in Experiment 1, our measure of accuracy was the percentage of the actual distance participants estimated for each distance. For blindfolded walking estimates, we calculated this percentage by dividing the distance walked by the actual distance for each target distance. For time-to-walk estimates, we calculated this percentage by dividing the time-to-walk estimate by the actual time-to-walk for each distance. Thus, each participant received 12 accuracy scores – six for each of the two sets of test trials.

Overall Analyses—Figure 5 shows the mean percentage of the actual distances estimated by participants in the four conditions during first (right panel) and second (left panel) trials. To test for overall effects of distance and trial, we entered the percentage of actual distance estimated into a Condition (real-real, virtual-virtual) × Trial (first, second) × Distance (20, 30, 40, 50, 60, 70 ft) repeated measures ANOVA with the first factor as a between-subjects variable and the second and third factors as within-subjects variables. There was a significant Distance × Condition interaction, $F(5, 130) = 3.37$, $p < .01$, $\eta_p^2 = .11$, but no effect of trial, $F(1, 25) = .01$, ns. There was also an effect of condition, $F(1, 26) = 6.47$, $p < .05$, $\eta_p^2 = .20$, indicating estimates in the real-real condition ($M = 84\%$, $SD = 13.7$) were more accurate than those in the virtual-virtual condition ($M = 69\%$, $SD = 24.4$). Simple effects tests of the Distance × Condition interaction yielded a significant effect of distance for the real-real condition, $F(5, 65) = 5.12$, $p < .001$, $\eta_p^2 = .28$, but not for the virtual-virtual condition, $F(5, 65) = 1.05$, ns. As shown in Figure 6, estimates in the real-real condition for 60 and 70 ft were significantly more accurate than those for 20, 30, 40, and 50 ft.

Planned Comparisons

Were distance estimates more accurate in the real than in the virtual environment?: As shown in Figure 7, first estimates in the real-real and real-virtual conditions appeared to be more accurate than first estimates in the virtual-virtual and virtual-real conditions. Planned comparisons revealed that first estimates were significantly more accurate in the real-real than in the virtual-virtual and virtual-real conditions, $t(26) = 2.79$, $p < .05$, Cohen's $d = 1.05$, and $t(25) = 2.86$, $p < .01$, $d = 1.09$, respectively. In addition, first estimates were significantly more accurate in the real-virtual than in the virtual-virtual and virtual-real conditions, $t(24) = 2.00$, $p = .056$, $d = .78$, and $t(24) = 2.05$, $p = .051$, $d = .81$, respectively. As would be expected, first estimates in the real-real and real-virtual conditions did not differ significantly, $t(25) = .44$, ns, $d = .17$, nor did first estimates in the virtual-virtual and virtual-real conditions, all $t(25) = .07$, ns, $d = .03$. To provide an even stronger test of differences across real and virtual environments, we again compared the combined performance of participants in the two real environment conditions (real-real and real-virtual) to that of participants in the two virtual environment conditions (virtual-virtual and

virtual-real). As expected, first estimates made in the real environment ($M = 84\%$, $SD = 13.58$) were significantly more accurate than those made in the virtual environment, ($M = 67\%$, $SD = 22.76$), $t (52) = 3.44$, $p < .01$, $d = .94$. Together, these results clearly show that distance estimates were more accurate in the real than the virtual environment.

How did experience in the real or virtual environment affect subsequent distance estimates?: As shown in Figure 7, experience in the real or virtual environment again appeared to affect the accuracy of subsequent estimates, particularly when moving from the real environment to the virtual environment. As would be expected, planned comparisons revealed that second estimates were more accurate in the real-real ($M = 83\%$, $SD = 9.79$) than in the virtual-virtual ($M = 71\%$, $SD = 20.40$) condition, $t (26) = 1.94$, $p = .06$, $d = .73$. However, we also found that second estimates were marginally *more* accurate in the real-virtual condition than in the virtual-real condition, $t (24) = 1.87$, $p = .07$, $d = .73$. Furthermore, second estimates in the real-virtual condition were significantly more accurate than those in the virtual-virtual condition, $t (25) = 2.36$, $p < .05$, $d = .90$, and did not differ significantly from those in the real-real condition, $t (25) = 1.29$, *ns, d = .49*. Second estimates in the virtual-real condition did not differ from the virtual-virtual condition, $t (25) = 1.20$, *ns, d = .47*, or from the real-real condition, $t (26) = 1.38$, *ns, d = .53*.

Discussion

Once again, planned comparisons revealed that real environment estimates were more accurate than virtual environment estimates when there was no change in environment from the first to the second set of estimates. Most importantly, comparisons of second estimates showed the same effects of environment order observed in Experiment 1. In this case, however, virtual environment estimates made after experience in the real environment were *more* accurate than real environment estimates made after experience in the virtual environment. In addition, second estimates in the real-virtual condition were also more accurate than second estimates in the virtual-virtual condition and did not differ from second estimates in the real-real condition. These results support the idea that experience with making distance estimates in the real environment supports subsequent distance estimates in virtual environments. Experience with making distance estimates in the virtual environment also affected subsequent estimates in the real environment, though the effects were less dramatic.

One potential concern about the design of Experiment 2 is that both the task and the environment changed when moving from the real to the virtual environment and vice versa. This opens up the possibility that something about the *blindfolded walking task* rather than experience in the real environment influenced subsequent distance estimates in the virtual environment, and that something about the *imagined walking task* rather than experience in the virtual environment influenced subsequent distance estimates in the real environment. However, Experiment 2 was designed to build upon the design of Experiment 1. In Experiment 1, only the environment changed when moving from one environment to the other (the imagined walking task was used in both environments). This experiment established that when the second environment was the same as the first environment (real-real and virtual-virtual), participants' second estimates were more accurate in the real than in the virtual environment, but when the second environment differed from the first environment (real-virtual and virtual-real), participants' second estimates did not differ significantly across the two environments. In Experiment 2, the distance estimation task also changed when moving from one environment to the other, and yet the pattern of results remained the same. This suggests that the effects of experience in the real or virtual environment on subsequent distance estimates generalizes from imagined to blindfolded walking, and vice versa. Additional research with HMDs could be used to determine

whether this pattern of results also holds when people perform blindfolded walking in a virtual environment after imagined walking in the real environment.

GENERAL DISCUSSION

Together, the results of this investigation add to a growing body of research comparing distance estimates in real and virtual environments. First, both experiments consistently showed that estimates made in the real environment first were significantly more accurate than those made in the virtual environment first. This difference was even more apparent when we increased statistical power by comparing the combined real environment first conditions to the combined virtual environment first conditions. Higher accuracy in the real environment was also apparent when comparing the second set of estimates in the real-real condition to the virtual-virtual condition. These findings indicate that underestimation of distance in virtual environments relative to the real environment is not limited to HMDs. Even with the wide field of view afforded by our LSID system, participants underestimated distance in the imagined walking task. On average, virtual environment distance estimates made first were 55% and 67% of the actual distance, and real environment distance estimates made first were 74% and 85% of the actual distance in Experiment 1 and Experiment 2, respectively. Note, however, that the distances we used (20 to 120 ft and 20 to 70 ft) were longer than those typically used to compare real and virtual environment distance perception. Further work is still needed to determine whether the degree of underestimation differs across systems. This will require direct comparisons of distance estimation in HMD and LSID systems using the same environment, the same rendering software, and the same task.

Second, our results also confirm the presence of subtle, yet persistent order effects in estimating distances in real and virtual environments. In essence, the difference between the real and the virtual environment was wiped out by previous experience in the other environment. In Experiment 1, distance estimates made second were *not* significantly more accurate in the real environment than in the virtual environment. In Experiment 2, distance estimates made second were actually *more* accurate in the virtual than in the real environment. Although all participants consistently underestimated distances in both environments in both imagined and blindfolded walking tasks, when participants experienced the virtual environment first they underestimated *more* than they normally would in the real environment. Likewise, when participants experienced the real environment first they underestimated *less* than they normally would in the virtual environment. Consistent with Witmer and Sadowski (1998), the order effect was stronger when going from the real environment to the virtual environment than vice versa.

The fact that we found the same effect of experience for both imagined walking and blindfolded walking tasks suggests that the order effects are not simply due to a residual memory for how long to hold down the stopwatch button. But do these experiences actually affect visual perception? At this point, we believe the answer is no. Although we cannot completely rule out changes in visual perception, we propose that these effects result from the interaction of longer and shorter term memories of the larger environment and the target locations. During their initial experience with estimating distances in either the real or the virtual environment, people undoubtedly built up spatial representations of the entire environment and the target locations. We propose that these longer term spatial memory representations exert an influence when people make subsequent distance estimates in the other environment. We think this is especially likely to happen given the nature of the imagined and blindfolded walking tasks. More specifically, both of these tasks involve having people look at a target for 4–5 s and then close their eyes while they walk or imagine to walk to the target. When people have their eyes closed, they must rely on their immediate

memory for the target location within the larger environment. At this juncture, it seems likely that longer-term memory for the entire environment and the target locations can exert an influence. Specifically, when people have experience the real environment first, their less compressed memory for the environment and target locations merges with their more compressed immediate memory for visual distances in the virtual environment, leading to less underestimation of distance than normal. Conversely, when people have experience in the virtual environment first, their more compressed memory for the environment and target locations merges with the less compressed immediate memory for visual distances in the real environment, leading to greater underestimation of distance than normal. This general account also explains why the effect is stronger going from the real to the virtual environment, than vice versa. Specifically, people have a long history of experience in the real environment in general and with the environment we used in particular. These stronger memory representations are likely to exert greater influence on subsequent estimates in the virtual environment than vice versa.

How might we think about the interaction of longer and shorter term spatial memory on a more specific level? One possibility is that longer term memory influences may occur at the global level (i.e., memory for the spatial relations in the entire environment) or at a more local level (i.e., memory for each target location or distance).[3] Influences at the global level are likely to affect the spatial updating processes that are engaged in imagined or blindfolded walking (see Rieser & Pick, 2007 for a discussion of spatial updating). That is, if people represent the spatial relations in the entire environment as more compressed due to previous experience in the virtual environment or as less compressed due to previous experience in the real environment, then the relation between imagined movement of the self through the environment and imagined changes in the optic flow field may shift. So, for example, participants may undershoot more in the real environment after experiencing the virtual environment because their spatial updating is still partially calibrated to the compressed-appearing virtual environment (and vice-versa).

Influences at the local level may also operate to produce the observed effects of experience on distance estimates. According to the Dynamic Field Theory (DFT) of spatial memory, memory for individual locations is built up over time through the interaction of several interconnected layers or "fields" (Johnson, Spencer & Schöner, 2008; Simmering, Schutte, & Spencer, 2008; Spencer, Simmering, Schutte, & Schoner, 2007). These layers include perceptual, working memory, and long-term memory fields, as well as inhibitory interneurons. The perceptual field forms peaks of activation generated by input from perception of visible reference frames (e.g., the position of the self) and the target's visible location. The perceptual field passes activation about both the reference frame and the target location to the working memory field, forming a peak of activation, which in turn, drives a peak of activation in an associated long-term memory field. This field accumulates traces of activation (i.e., peaks) representing the locations of the previously seen targets. In the current investigation, we assume that over distance estimation trials in the first environment, participants build up peaks of activation for the various target locations based on their perception of the egocentric distances to the targets. When participants experience the second environment, they receive new inputs for the distances to these same target locations. These new inputs are in a sense "averaged in" with the existing peaks representing particular target locations. When going from the real to the virtual environment, participants build up peaks of activation during their real-world experience that are relatively close to the true target locations. When they see these same target locations in the virtual environment, their immediate perception of the compressed distances is merged with existing peaks of

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[3] Note that global and local spatial memory influences are not necessarily mutually exclusive.

activation based on the real environment. This influence of memory from the real environment leads to less compressed distance estimates than normal in the virtual environment. The reverse is true for participants who go from the virtual to the real environment.

The carryover effect of previous experience is not unprecedented. Previous research has shown that the perception of distance can be pushed around under various external or internal influences. Proffitt, Stefanucci, Banton, and Epstein (2003) investigated the role of effort on distance perception by having participants make distance estimations while either wearing a heavy backpack or no backpack. They found that participants who made estimations of distance while wearing the heavy backpack judged targets to be significantly further away than participants who made the same estimations without the backpack. They concluded that egocentric distance is perceived not only in terms of the absolute distance to the target, but also by the amount of anticipated effort required to reach that target. Similarly, Balcetis and Dunning (2007) examined the effect of cognitive dissonance on perception of distance. They asked participants to cross a campus quadrangle wearing a Carmen Miranda costume. Half of the participants were told that they had been randomly assigned to perform this embarrassing task, while the other half of the participants were told that they could perform another task instead of wearing the costume (they all actually chose to wear the costume). Participants who were forced to perform the task experienced lower cognitive dissonance while completing the task since they felt that they had no choice. On the other hand, participants who felt that they had chosen this embarrassing task experienced higher cognitive dissonance while completing this task since they would have to reconcile their discomfort with their belief that they had voluntarily chosen the task. Balcetis and Dunning (2007) found that when participants were asked after completing the task to judge the distance they had walked, participants in the high cognitive dissonance group reported longer distances than did participants in the low cognitive dissonance group. The authors conclude that even internal motivation can influence the perception of distance.

There are some limitations to the current investigation. First, we observed some individual variability in distance estimates. In Experiment 1, for example, we would expect the first set of distance estimations in the real-real and real-virtual condition to be virtually identical since both groups are undergoing the exact same experience (six randomly ordered distance estimation trials in the real environment). However, these two groups diverged to some extent in their first set of judgments. This was largely due to the fact that three participants in the real-virtual condition, but only one participant in the real-real condition made relatively poor distance estimates (estimated the distances at 40% or less of the actual distances). Larger sample sizes in future work would be helpful to better control for such individual differences. We also observed more underestimation in real environment blindfolded walking than that typically seen in past research (e.g., Plumert et al., 2005; Swan et al., 2007). Although the cause of this underestimation is unclear, it may be the result of limited practice with blindfolded walking before test.

Another limitation to the current study is the use of relatively long distances, especially in Experiment 1. These distances were chosen to allow for direct comparison to Plumert et al. (2005), but they were longer than those typically used in distance estimation research. The majority of distance estimation research conducted to date has utilized distances within the action space of 3–20 meters (e.g., Creem-Regehr et al., 2005; Knapp & Loomis, 2004; Messing & Durgin, 2005; Thompson et al., 2004). According to Cutting and Vishton (1995), action space extends to include the circular area about 30 m around the observer, while the area beyond 30 m of the observer is vista space. We are generally unable to act upon vista space and depth cues such as motion perspective and convergence and accommodation are ineffective at this range causing the observer to rely solely on pictorial cues to depth such as

height in the visual field, relative size and linear perspective. The distances at which we observed greater underestimation in Experiment 1 are perhaps beyond the realm of action space in which participants are able to make relatively accurate distance estimates. In the future, it may be more useful to focus on distances within 90 ft of the observer.

These results also raise several questions for future work. One is how well do these order effects generalize to non-identical environments? In our experiments, the virtual environment was an exact replication of the real environment. If the environments were different, would these order effects still persist? Note, however, that direct comparisons of particular distances across non-identical real and virtual environments can be challenging because other differences between the environments can also affect distances estimates. Lappin, Shelton, and Reiser (2006), for example, found that when participants completed the same bisection task in a hallway, lobby, and open lawn, they overestimated the midpoint by significantly different amounts in each environment. Another question is how much experience is necessary to obtain these order effects and how long do these effects last? Especially when going from the virtual to the real environment, one would expect participants would recalibrate to the real world fairly quickly. A third question that remains is what is the source of these order effects in distance estimation? Two possibilities now stand—changes in visual perception and long-term memory influences. In other words, either the actual distances look more or less compressed due to experience in the other environment or distances are remembered as more or less compressed due to experience in the other environment. In previous research showing that the perceived effort required to reach a target appears to change visual perception of distance, participants made judgments with their eyes open (e.g., Proffitt et al., 2003). In the current investigation, participants made estimates with their eyes closed (either blindfolded or imagined walking), and therefore visual perception was not available at the time of response. Although it is difficult to tease apart the competing explanations, future work involving people making imagined walking estimates with their eyes open may help to shed light on the underlying causes of the observed order effects. Further studies aimed at addressing these questions have both practical implications for using virtual environments as a tool for training new skills and theoretical implications for understanding the role of memory in distance perception.

Acknowledgments

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Figure 1.
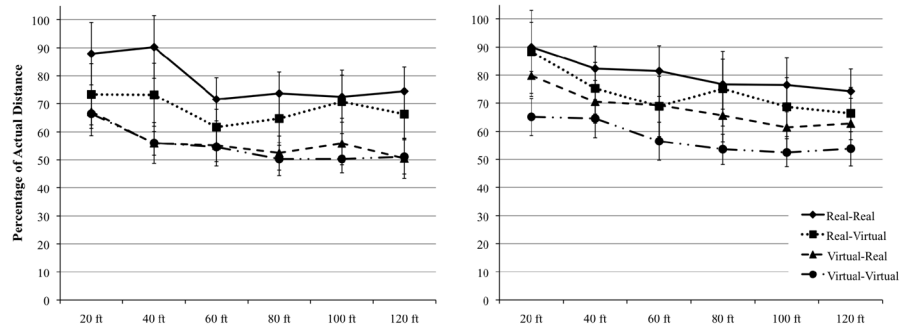Photographs of the real (left panel) and virtual (right panel) environments.

Figure 2.
Mean accuracy of first (left panel) and second (right panel) estimates by condition and distance in Experiment 1.
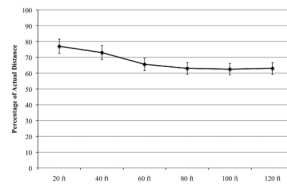
Figure 3.
Mean accuracy of estimates for each distance in Experiment 1 (real-real and virtual-virtual conditions only).
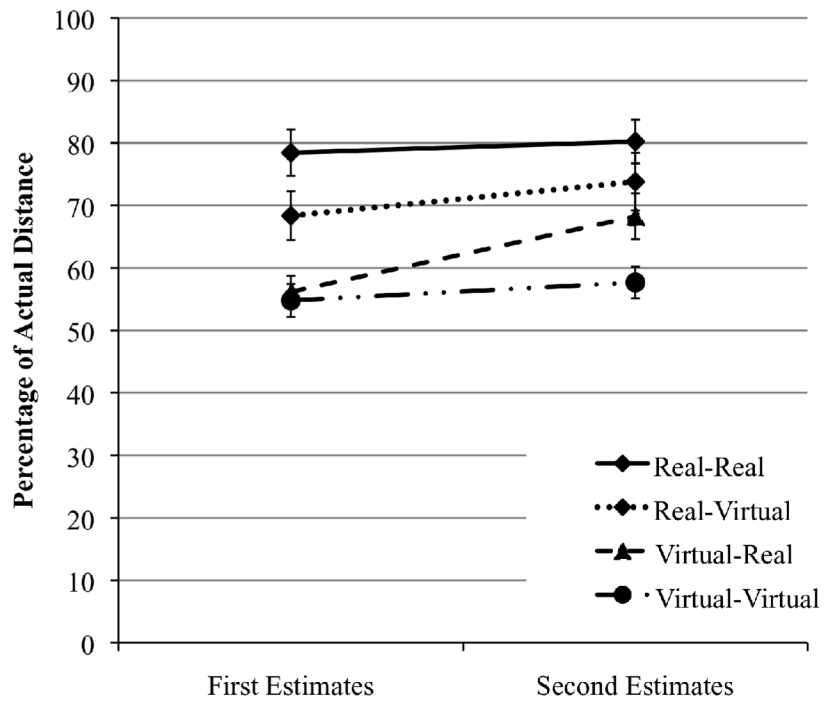
Figure 4.
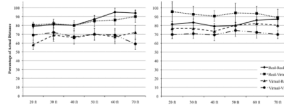Mean accuracy of first and second estimates by condition in Experiment 1.

Figure 5.
Mean accuracy of first (left panel) and second (right panel) estimates by condition and distance in Experiment 2.
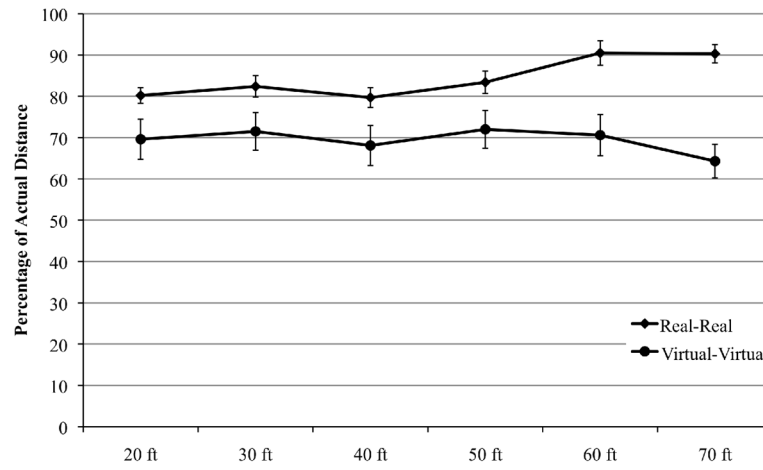
Figure 6.
Mean accuracy of estimates for each distance in Experiment 2 (real-real and virtual-virtual conditions only).
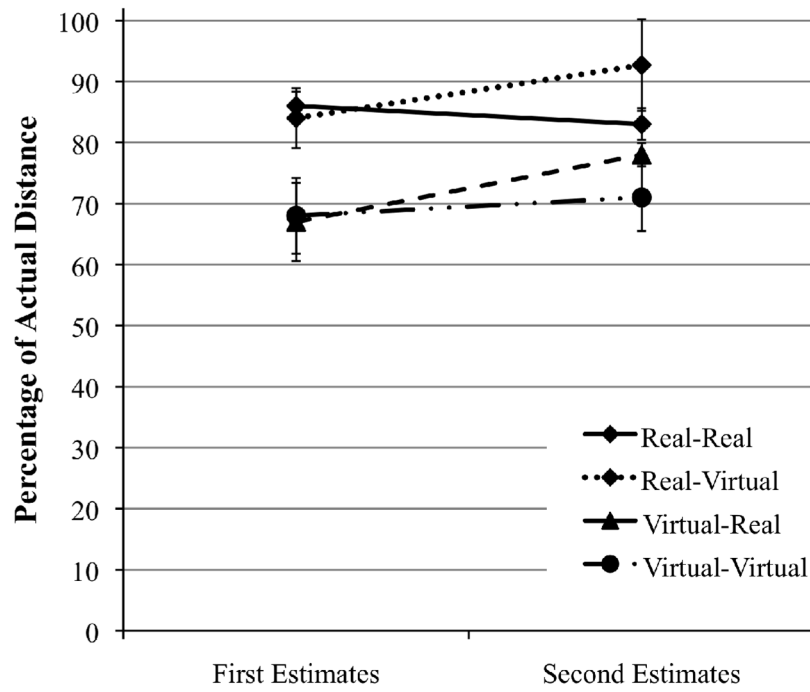
Figure 7.
Mean accuracy of first and second estimates by condition in Experiment 2.