# Gender Differences in Cue Preference During Path Integration in Virtual Environments

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Three studies were conducted to examine whether men and women differ in how they recalibrate their path-integration systems when walking without vision in virtual environments. Distance cues provided by a scene and a tone, which ended each trial, were placed in conflict. Participants briefly viewed a room with a target, which was offset from their midlines and hung inside a doorframe on the far wall. After viewing, participants walked to the target's position until a tone sounded, ending the trial. In two experiments the doorframe was placed at 6 m and the tone sounded at 4 or 8 m. The rooms had minimal or photorealistic texturing applied. The third experiment used photorealistic texturing, but here the tone sounded at 6 m and the doorframe was presented at 4 or 8 m. Path angles were recorded to estimate perceived distance to the target. In all conditions tested, the women failed to scale their path angles. The men, however, scaled their path-angles with the auditory cue in the minimal-texture condition, but with the visual cue in the photorealistic-texture conditions. These results suggest that gender differences exist in the way that humans recalibrate their path-integration systems when walking without vision in virtual environments.

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## 1. INTRODUCTION

While vision is the dominant sense that humans use to learn about their environments, it is not the only means through which humans are able to determine where they are and where they have been. Humans, like many animals and insects, also have the ability to integrate idiothetic information (e.g., proprioceptive and vestibular cues) obtained from self-motion with stored spatial representations to update their perceived locations in space [Mittelstaedt and Mittelstaedt 2001]. This process has been called *path integration* or *dead reckoning*. Traditionally, researchers have studied human path-integration ability by removing all external visual information while participants walk to previously seen targets

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or return to a starting position after being led around two legs of a triangle [Loomis et al. 1993, 1999; Philbeck and Loomis 1997; Rieser et al. 1990]. While results from these studies suggest that humans can perform such tasks reasonably well, one question that has not received a lot of attention is whether or not gender differences exist in human path-integration ability and the types of cues that men and women use to reach their destinations.

The current study was designed to begin looking at this question by examining whether or not men and women use different information to calibrate their path-integration systems when walking without vision to previously viewed targets in virtual environments (VE). The importance of understanding whether these types of differences exist, stems from the growing trend of researchers in the behavioral sciences to use immersive virtual reality (VR) systems for the study of human navigation and spatially oriented behavior. While there are many advantages to using VE over real-world settings, system limitations can cause changes in the way that participants perceive distances [Messing and Durgin 2005; Thompson et al. 2004] and these changes, in turn, can lead to changes in behavior. In particular, a review of studies on path integration by Loomis and Knapp [2003] reports that substantial differences in path-integration ability are seen when one compares results from studies in virtual and real environments. Whereas humans are able to accurately walk without vision to targets as far as 20 m away in real environments, researchers have found significant compression for targets as close as 2 m away when humans perform the same task in VE. In order for VR to be useful in the study of human navigation, participants must be able to overcome these compressed perceptions of space and recalibrate their path-integration systems with the visual scenes presented to them. Therefore, it is important for researchers to understand whether or not men and women tend to rely on different cues for recalibration, as gender differences in cue utilization could lead to gender effects based on extraneous variables rather than those being studied.

Given that gender differences have been found with regard to the types of strategies men and women use when performing spatial and navigation tasks in the real world [Dabbs et al. 1998; Grön et al. 2000; Linn and Peterson 1985; Maguire et al. 1999; Voyer et al. 1995], it is possible that gender differences also exist in the types of cues men and women use to recalibrate their path-integration systems when walking in virtual environments. In fact, evidence for such a difference has already been suggested by the results of two previous studies [Chaudhury et al. 2004; Turano and Chaudhury 2005] examining the induced Roelofs effect, although the paradigm used was not designed to directly examine what cues participants relied on to complete the task. In these studies, an immersive VE was created in which participants viewed a room for 1 s with a doorframe located 4 m away on the opposite wall and a ball suspended inside the doorframe. Both the ball and doorframe were offset by $3^\circ$ to the right or left or centered on the participant's midline. The task required the participants to walk to the ball once the scene disappeared and a tone was sounded when the participants had walked the appropriate distance, ending each trial. In this case, the appropriate distance corresponded to the point at which the participant crossed the frontoparallel plane where the doorframe and target were located (4 m in one experiment and 5 m in the other). Results from these two studies showed that the women in the studies were more susceptible to the induced Roelofs effect than the men. That is, when the doorframe, but not the target ball, was shifted to the right or left, most of the women offset their paths as if the ball had shifted in the opposite direction. To explain this gender difference, the authors suggest that the women used the doorframe as a landmark, assuming it to be fixed in space, to create an external reference frame and define their location in space. As a result of this, small changes in the position of the doorframe led to changes in the women's perceived midlines as if they, instead of the doorframe, had moved. This explanation for the mechanism behind the induced Roelof's effect has been called the biased-midline theory [Dassonville et al. 2004]. Recent studies [Dassonville and Bala 2004a, 2004b; Dassonville et al. 2004] have found evidence to support its existence across a variety of experimental settings. Assuming that the women did, in fact, use the doorframe as a landmark with which to orient themselves in space, the question then becomes how one can explain the men's performance. As there were only three available sources of information about the environment (the visual presentation of the room for 1 s at the beginning of the trial, the idiothetic information participants received while walking to the target, and a distance cue provided by the tone sounded at the end of each trial), the authors suggest that the men in the study may have decreased their susceptibility to the induced Roelofs effect by relying on something else to determine their midline. For example, the men may have relied on an egocentric reference frame (or frame of headset) and used the tone as a distance cue to recalibrate their path integration systems. However, as noted above, it is not possible to determine whether this explanation holds from the results of this study, because the distance at which the tone sounded was never manipulated.

Therefore, in order to test this theory directly, the present study was designed where the distance cue provided by the tone was placed in conflict with the distance cues provided by the scene. Using a simplified version of the environment of Chaudhury et al. [2004], a room was constructed with a doorframe located in a wall 6 m from the starting position, *always centered* on the participants' midlines (unlike in the previous study where the doorframe was offset and the focus was on the induced Roelofs effect). A ball was placed inside of the doorframe, displaced to the right or left of the participants' midlines. Each participant was shown the room for exactly 1 s and, after this time, they were to walk to the ball. However, in contrast to the previous experiments, the tone signifying the end of each trial was sounded when participants crossed the frontoparallel planes corresponding to either 4 or 8 m from the starting position. As in the previous study, trials completed in both conditions were grouped into "epochs" of multiple trials so that changes in performance over time could be assessed. Based on the principle of size constancy, perceptions of how far offset to the right or left the target is from midline should depend on how far away participants believe the doorframe and target are from the starting position. If the participants only rely on the visual information received at the beginning of each trial to indicate how far away the target is from the starting position, there should be no significant difference in their path angles for the 4 and 8 m walking conditions as the distance of the doorframe and target does not change. On the other hand, if the participants integrate the distance cue provided by the tone with self-motion cues to recalibrate their path-integration systems, their path angles should adjust across epochs to changes in perceived distance and their path angles should be significantly smaller for the final epoch in the 8 m walking condition than for the final epoch in the 4 m walking condition (see Figure 1 for an illustration of this). Based on the gender differences in the previous experiments, it was hypothesized that a walking distance × epoch interaction should be seen for the men, but not the women, with the men adjusting their path offsets to the distance cue provided by the tone over the course of the block of trials completed for each condition. Given that the path angles in the last epoch of trials should be different for the men, but not the women, in the 4 and 8 m walking conditions, it was also hypothesized that a comparison of mean path angles in the last epoch of trials would show a gender × walking distance interaction.

## 2. EXPERIMENT ONE

### 2.1 Methodology

2.1.1 *Participants.* Ten participants (5 women), ages 22–41, participated in the experiment. All participants were naïve with respect to the purpose of the experiment. All participants gave written consent and were compensated for their time. This research followed the tenets of the Declaration of Helsinki.

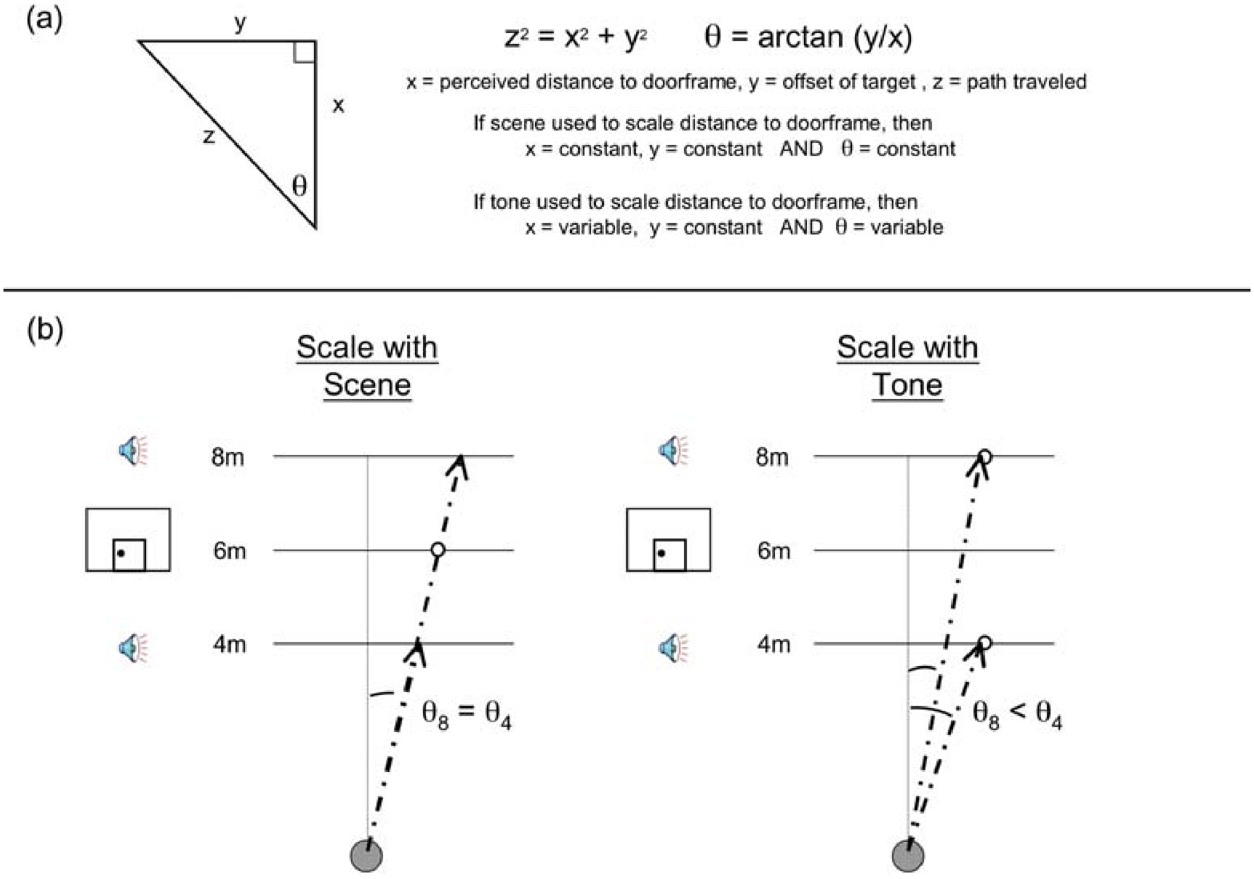

Fig. 1. Schematic display of hypothesis. (a) Mathematical description of path angle's dependence on perceived distance to target and target offset. (b) Illustration of change in path angle expected if participants rely on distance cue from the scene presented at 6 m in both blocks of trials or the tone that is sounded at 4 m in one block and 8 m in the other. The large shaded circle represents the starting position and the gray vertical line represents the starting orientation. The three horizontal lines represent the distances at which the tone and scene are presented and the small white circles on these lines represent the perceived location of the target. The black dotted lines represent the expected paths of the participants.

To assure that all participants had normal vision, visual function was tested binocularly with participants wearing their normal corrective lenses. Visual acuity was tested using an ETDRS eye chart and contrast sensitivity was tested using a Pelli–Robson letter chart. The pupillary distance of each participant was measured and used to adjust the position of the displays in the headset to obtain a stereo view of the environment.

2.1.2 *Stimulus Description and Generation.* The scene was a room, 4.2 m wide × 2.28 m high × 6.4 m long. The target was a ball, 14.5 cm in diameter, suspended at eye-height within a doorframe that was 1.74 m wide × 2.03 m high. The doorframe was positioned at a distance of 6 m from the participant's starting position and the lateral position of the doorframe was centered on the participant's midline (see Figure 2). The target was positioned at ±3° relative to the participant's midline, with a negative offset indicating that the target was to the left of the participant's midline. There were four conditions

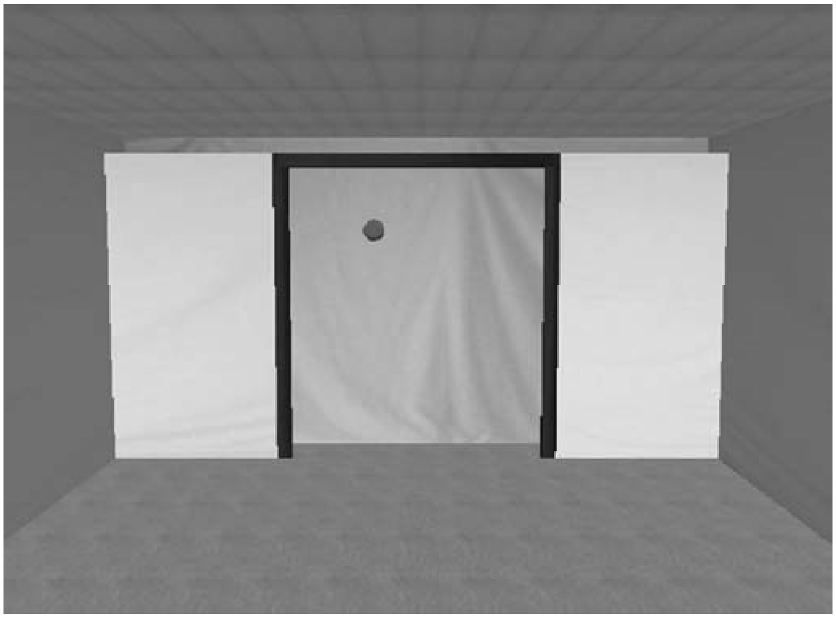

Fig. 2. First-person view of the virtual environment used in Experiment 1 as seen by the participants.

(2 walking distances × 2 target positions) and each participant performed 9 trials per condition for a total of 36 trials per subject.

The virtual room was constructed using 3D Studio Max software (Discreet, Montreal, CA) and exported to a graphics program engine developed in-house with C++ and Microsoft's DirectX. The graphics program used the output from the HiBall Optical Tracker (3rd Tech, Chapel Hill, NC) together with the imported scene to determine the participant's current point of view in the environment.

### 2.1.3 *Apparatus*

2.1.3.1 *Head Tracking System.* Head position and orientation were sampled every 7 ms using a HiBall-3000 Optical Tracker (3rd Tech, Chapel Hill, NC). Infrared LEDs were housed on the ceiling tiles of the testing room and their signals were detected by optical sensors mounted in a holder that was attached to the top of the headset. Tracker resolution is reported to be 0.2 mm with an angular precision of less than 0.03°. The output of the head tracker was filtered using an exponential smoothing function with an 80-ms time constant. Point of view was calculated from the head position and orientation data collected. Daubechies wavelet transform of the 6th order, Db6 [Ismail and Asfour 1999], was applied to the data from the head tracker to filter out the oscillations associated with gait and to determine walking path. This type of transformation is commonly used when paths are determined from head-tracking devices and has been shown to give an accurate estimate of a participant's midline while walking.

2.1.3.2 *Head-Mounted Display* (*HMD*). The HMD was a modified Low-Vision Enhancement System developed by Robert Massof at the Wilmer Eye Institute. The headset contained two color microdisplays (SVGA, 800 × 600 3D OLED Microdisplay, Emagin Corp). Spatial resolution was 0.1°/pixel and the refresh rate was 60 Hz. The field of view for each display was 49° H × 38° V. Spatially offset images were generated for each display producing a stereo view.

2.1.4 *General Procedure.* Prior to beginning the experiment, the participants were given specific instructions regarding the task. All participants were told that they would be shown a room for exactly 1 s. On the far side of that room, participants were told that there would be a doorframe with a ball hanging inside of the doorframe. Participants were instructed that once the scene disappeared they should walk to the ball until they heard a tone ending the trial, at which time they should turn around and return to the starting position for the next trial. Participants were not told anything about where the ball would be positioned inside of the doorframe (i.e., offset to the right or left).

Each trial began with an alignment phase, during which time the experimenter ensured that the participant's head was in the proper starting position and orientation. To do so, the experimenter viewed a monitor displaying two sets of four crosses, one set fixed to the center of the subject's head and the other fixed in real space. With proper alignment, the two sets of crosses overlapped. If the two sets of crosses were offset, the experimenter instructed the subject how to move in order to achieve proper alignment. Once the participant was aligned, a tone sounded and the scene was displayed for 1 s. At the end of the 1 s, another tone sounded and the scene was replaced with a black screen. After the scene disappeared, the participants were allowed to begin walking at their normal pace to the ball. When the participant had reached the 4 or 8 m mark (i.e., the frontoparallel planes 4 and 8 m away from the starting position and orientation, parallel to the plane that the doorframe and target were located), a third tone sounded, indicating the end of the trial. After the final tone sounded, the participants turned around and walked back to the starting position with the aid of the experimenter. The experimenter walked next to the participants throughout the experiment to ensure their safety.

The trials were divided into two blocks of 18 trials, with each block corresponding to one walking distance (i.e., 4 or 8 m). This was done in order to give participants time to extract distance information from the final auditory cue and adjust their path angles accordingly. Within each block of trials, the target was offset to the right on one-half of the trials and offset to the left on the remaining one-half. The order in which the target was offset to the right or left was randomly assigned. The order in which the participants completed the two blocks of trials alternated such that three of the women and two of the men completed the 8-m walking condition first, while two of the women and three of the men completed the 4 m walking condition first. (For simplicity, these will be called the 4- and 8-m walking conditions from now on although actual path lengths were longer because of path offsets and idiosyncratic walking patterns.)

2.1.5 *Data Analysis.* Walking paths were determined from the data obtained from the HiBall head tracking system (sample paths shown in Figure 3). Path angle was calculated from the smoothed X, Z position reached when the final tone was sounded. In order to follow the same methodology as the previous studies, trials were grouped into three epochs with three trials per epoch for the left and right offset trials (i.e., total of six trials per epoch). The median path angle for each epoch (left and right) was determined. The difference of the median values for the left and right offsets was then halved, providing a single average path angle value for each epoch. This method was used in place of averaging the absolute values of the path offsets to control for any deviations in the participants' midlines that may have occurred resulting from the headset not being completely centered in front of their eyes. If the headset was not centered in front of a participant's eyes, the center of the room would be shifted to the right or left and cause the participant's paths to veer in that direction. Because path angle was determined by information received from the head tracker, a shift in midline because of the headset being off center would lead to an overestimation of the mean path angles if the absolute values for the right and left target conditions were averaged.

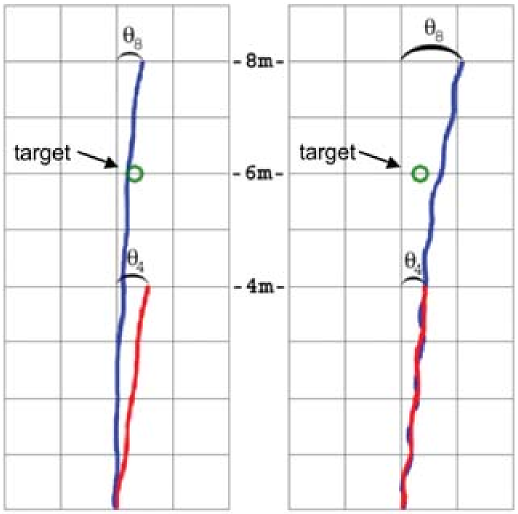

Fig. 3. Top-down view of sample paths from a male participant (left panel) and a female participant (right panel).

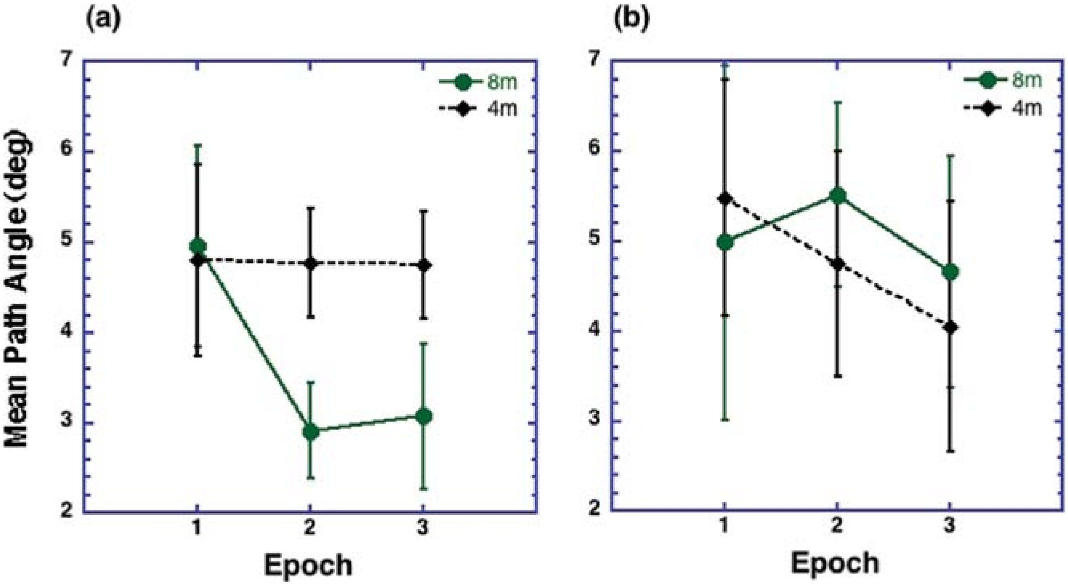

Fig. 4. (a) Men's and (b) women's mean path angles for the 8- (circles) and 4-m (diamonds) walking conditions as a function of epoch. Error bars represent ±1 SE.

## 2.2 Results and Discussion

Figures 4a and b show mean path angle as a function of epoch and walking distance for the women and men, respectively. As can be seen in Figure 4a, mean path angle for the women in the study did not systematically change across trials. Results of a repeated-measures ANOVA confirmed this, showing no effect of epoch, $F(2, 3) = 2.09$, $p = 0.27$, or walking distance, $F(1.4) = 0.02$, $p = 0.79$. There was also no interaction between the two factors, $F(2, 3) = 0.39$, $p = 0.71$. A different pattern was seen for the men

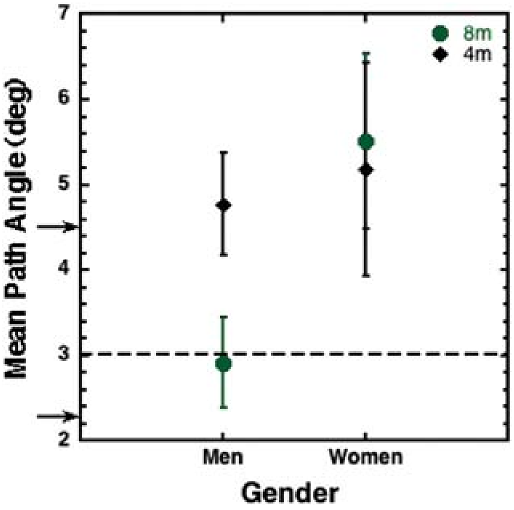

Fig. 5. Mean path angles for the 8- (circles) and 4-m (diamonds) walking conditions as a function of gender. The dashed line shows the true angular offsets of the target and the arrows indicate the angular offsets predicted if the tone was used to scale the distance to the doorframe and target. Error bars represent ±1 SE.

in the study. The men's mean path angles in the 8-m walking condition decreased in the second epoch, while mean path angles in the 4-m walking condition remained stable. A second repeated-measures ANOVA was calculated that showed a significant effect of walking distance, $F(1,4) = 34.68$, $p < 0.01$, but no effect of epoch, $F(2,3) = 0.98$, $p = 0.47$. While the walking distance × epoch interaction did not reach significance, $F(2,3) = 6.30$, $p = 0.08$, planned post-hoc comparisons showed significant walking distance × epoch interactions when the first and second epochs were compared, $F(1,4) = 8.91$, $p = 0.04$, and when the first and third epochs were compared, $F(1,4) = 16.79$, $p = 0.01$. Comparison of the second and third epochs did not show a significant interaction, $F(1,4) = 0.15$, $p = 0.72$. This pattern of results is highly suggestive of a learning effect, with the men's path angles decreasing from the first epoch to the second, then remaining stable across the second and third epochs.

Figure 5 shows the men and women's mean path angles for the last epoch of trials completed in the 4- and 8-m walking conditions. In order to compare the men and women's behavior, a repeated-measures ANOVA was calculated with walking distance as a within-subjects factor and gender as a between-subjects factor. As predicted, a significant interaction was found between gender and walking distance, $F(1,8) = 38.26$, $p < 0.01$. While no main effect of gender was found, $F(1,8) = 0.09$, $p = 0.78$, mean path angles in the last epoch were smaller in the 8-m walking condition than the 4-m walking condition, $F(1,8) = 8.49$, $p = 0.02$.

The finding that only the men in the present study systematically changed their path angles in response to changes in the tone ending each trial supports Turano and Chaudhury's [2005] suggestion that the men in their study performed the task differently than the women by integrating the distance cue provided by the tone with idiothetic information obtained from self-motion to determine the distance to the target. However, the present study alone cannot explain why the men in these studies would use the tone to recalibrate their path integration systems when they were never told that the tone signified that they had walked to the target location. One possible explanation has to do with cue preference. In particular, given a very brief visual cue followed by an auditory cue, it may be that men prefer to utilize the distance cue provided by the tone because it is more effective for calibrating their path-integration systems. If this were the case, both the men and women would have derived the offset of the target relative to their midlines from the scene that was presented to them at the beginning of the trial. However, while the women would have also relied on the scene to tell them the distance to the target, the men would have integrated the distance information obtained from the tone ending the trial to tell them the distance to the target and, thus, how far to the left or right their path should veer.

While this explanation is plausible, it is also possible that the quality of the cues influenced the men and women differently and that given a higher quality visual cue, the men would have also ignored the depth information provided by the auditory cue. The room shown in this study had white walls with little texture and the floor and ceiling of the room may have offered little information about depth. Because of this, the men may have seen any depth cues from the scene as unhelpful. Given the small discrepancy between the distance at which the doorframe was actually placed (6 m) and the distance at which the tone sounded (4 or 8 m), it could also be that if the men were more sensitive to changes in the walking distances than the women, the poor quality of the visual cue in combination with the distance cue from the tone led the men to perceive that the doorframe and target moved across the two blocks of trials. These explanations differ from the idea of an innate cue preference in that they suggest that cue preference is a function of cue quality for men. In addition, because cue quality would then affect men to a greater extent than women, these explanations further suggest that gender differences in cue preference are also dependent upon cue quality.

## 3. EXPERIMENT TWO

The second experiment sought to examine the validity of the explanations proposed above by repeating the first experiment while adding photorealistic texturing to the environment, thus increasing the level of detail available from the visual cues. If an innate difference in cue preference exists between men and women in tasks such as this one, the men in this experiment should not switch strategies and rely on the distance cue provided by the scene at the beginning of each trial. Rather, the men should continue to attend to the distance cue provided by the tone and their path angles should continue to scale with distance at which the tone sounds. Given that the previous experiment did not find any evidence that the women in the study used the tone to calibrate their path integration systems, it was not expected that the women in this experiment would scale their path offsets with the tone either. Thus, another gender × walking distance was predicted for the last epoch of trials.

### 3.1 Methodology

3.1.1 *Participants.* Nine participants (5 women), ages 25–56, who had not participated in the first experiment participate, were recruited. All participants were naïve with respect to the purpose of the experiment and all had normal or corrected-to-normal vision. Informed consent was obtained from the participants before beginning the experiment and all participants were compensated for their time.

3.1.2 *Stimulus Description and Generation.* To obtain high levels of detail via photorealistic texturing, a real-world facsimile of the virtual environment used in the previous experiment was constructed. White sheets were hung from the ceiling and weighted at the bottom to create walls off to the right and left of the starting position. At the far end, another wall with a doorframe in the center was created using Styrofoam insulation boards (1.2 m × 2.4 m × 3 cm) covered in white sheets with black construction paper along the edges of the doorframe. Collectively, this created a rectangular room roughly 4 m wide × 2.3 m high × 9 m long. The doorframe was centered on the participant's midline and located on the wall at the opposite end of the starting position. The doorframe was 2 m wide × 2.02 m high. The target was a Styrofoam sphere (14 cm in diameter) that was hung in the doorframe using fishing wire attached to hooks in the ceiling. The target was offset from the center of the doorframe by $\pm 3^\circ$, or $\pm 0.47$ m.

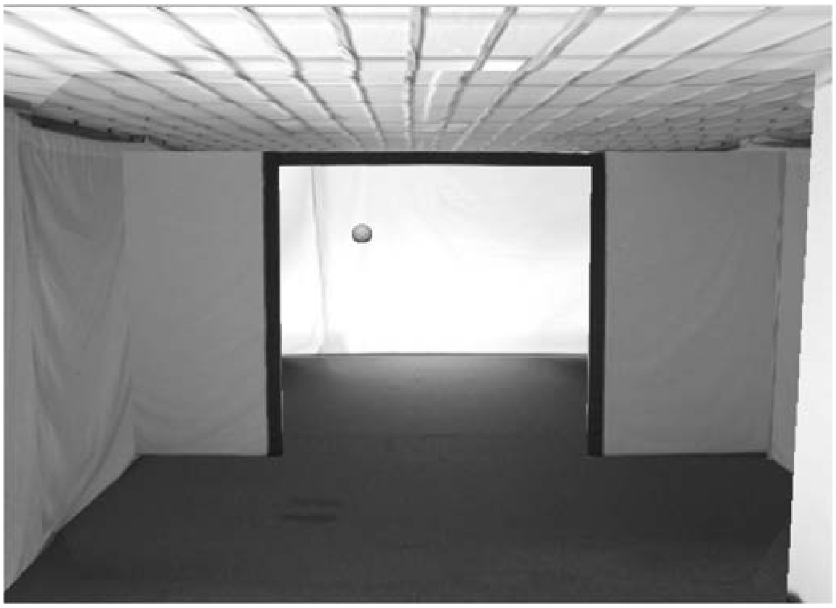

Fig. 6. First-person view of the virtual environment used in Experiment 2 as seen by the participants.

The virtual room was constructed in 3D Studio Max in the approximate shape of the real room. To achieve a suitably realistic level of detail, a digital camera was used to take photographs of the real room. These images were used as texture maps on the walls and other surfaces of the virtual room, using a technique called "camera mapping" in 3DSMax. The effect is as if a slide projector were set in the virtual room corresponding with the location of the camera in the real room, projecting the photograph onto the otherwise white walls and surfaces. Most of the visible surfaces were textured with photographs taken from the expected point of view of the observer so that the textures would appear most realistic from that position. However, since the exact point of view of the observer varies slightly, multiple photographs from multiple angles were needed to cover the entire room, and minor alterations to the textures were made using Photoshop to minimize the appearance of seams in the final scene. The target was again a ball suspended at eye height within a doorframe, 2 m wide × 2.03 m high. The doorframe was positioned at a distance of 6 m from the participant's starting position and the lateral position of the doorframe was centered on the participant's midline (see Figure 6). The target was positioned 0.47 m to the right or left of the center of the doorframe. This created offset angles of ±4.5° relative to the participant's midline.

3.1.3 *Apparatus.* The same equipment from Experiment 1 was used here.

3.1.4 *General Procedure.* The procedure for the second experiment followed that of the first. However, since the men in the previous study had already scaled their path angles by the second epoch of trials in the first experiment and no difference was seen in performance between the second and third epochs of trials, participants only completed 12 trials (i.e., two epochs) for each of the two blocks completed. Again, each epoch consisted of three right and three left offset trials for a total of 24 trials per subject.

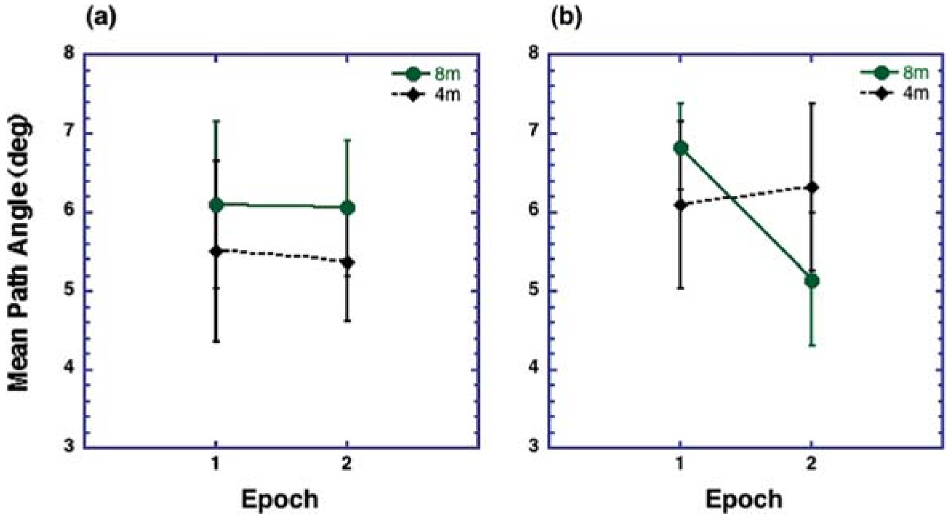

Fig. 7. (a) Men's and (b) women's mean path angles for the 8- (circles) and 4-m (diamonds) walking conditions as a function of epoch. Error bars represent ±1 SE.

### 3.2 Results and Discussion

Figures 7a and b show mean path angle as a function of epoch and walking distance for the men and women, respectively. Two repeated-measures ANOVAs were calculated to determine whether the men or women scaled their path angles with changes in walking distance. No main effects of epoch or walking distance were seen in either case ($p > 0.2$ for all). No interaction between walking distance and epoch was found for the men or the women ($p > 0.1$).

A third repeated-measure ANOVA was then calculated comparing the path angles of the men and women in the second epoch of trials across the 4- and 8-m walking conditions. As can be seen in Figure 8, there was no main effect of gender, $F(1, 7) < 0.01$, $p = 0.98$, or walking distance, $F(1.7) = 0.26$, $p = 0.62$. There was also no interaction found between gender and walking distance, $F(1, 7) = 3.8$, $p = 0.09$. Interestingly, the small trends observed were in the opposite direction of that predicted with the path angles of the men showing a slight increase from the 4- condition to the 8-m condition, while the path angles of the women decreased with increasing walking distance. Given that the offset angle remained constant across both conditions, it is unlikely that the increase in the target offset from ±3 to $\pm 4.5^\circ$ in this experiment can explain the change in the men's performance. As the only other difference between this experiment and the first was the texture used, the lack of a significant gender × walking distance interaction suggests that the amount of detail provided in the visual cue played a significant role in determining whether the men participating in these experiments utilized the distance cues from the scene or the tone. Thus, given a salient visual cue, men are able to ignore the misleading distance cue provided by the tone in support of the hypothesis that the type of cues men use to recalibrate their path-integration systems when walking in virtual environments depends on the quality of the cues presented.

## 4. EXPERIMENT THREE

Finally, in order to determine the nature of the gender difference in the first experiment, the strategies employed by the women needs to be addressed. In particular, while the results of the first two experiments are consistent with the hypothesis that the women who participated in these studies relied on the

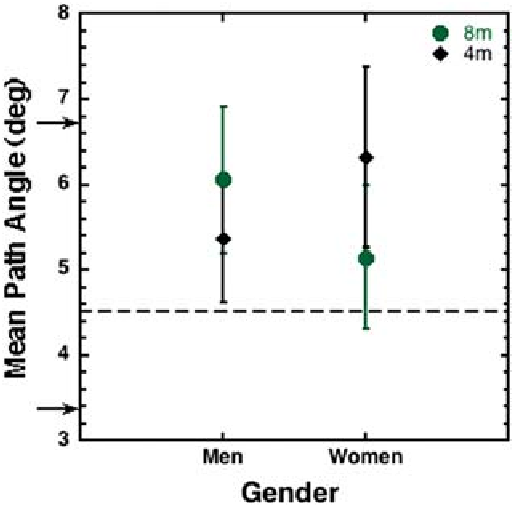

Fig. 8. Mean path angles for the 8- (circles) and 4-m (diamonds) walking conditions as a function of gender. The dashed line shows the true angular offset of the target and the arrows indicate the angular offsets predicted if the tone was used to scale the distance to the doorframe and target. Error bars represent ±1 SE.

scene to both orient themselves in space and determine the distance to the target, the large variability in their data relative to the men (see Figures 5 and 7) and the tendency for the women's path angles to decrease with increasing walking distance in the second experiment, suggests that women's performance may better be described as an inability to effectively calibrate their path-integration systems with either type of distance cue (visual or auditory) than a reliance on visual information to determine the distance to the target. In order to directly test this theory, a third experiment was conducted in which the distance cue provided by the tone remained constant at 6 m while the doorframe and target were presented at 8 or 4 m. If women are able to effectively use the distance cues provided by the scene to recalibrate their path-integration systems and determine the distance to the target, their path angles should systematically scale with changes in the doorframe position. Furthermore, if the results of the last study are indicative of the men switching strategies and relying on the more salient distance cues provided by the scene to determine the distance to the target, the men's path angles should also scale with changes in the distance to the doorframe and target. It was, therefore, predicted that a main effect of doorframe position would be seen for both the men and the women and that no interaction between gender and doorframe position should be observed when comparing the path angles of the men and the women in the last epoch of trials.

## 4.1 Methodology

4.1.1 *Participants.* Ten participants (5 women; aged 20–57), who did not participate in either of the previous experiments, were recruited. All participants were naïve with respect to the purpose of the experiment and all had normal or corrected-to-normal vision as assessed by binocular visual acuity and peak contrast sensitivity. Informed consent was obtained from all participants before beginning the experiment and all participants were compensated for their time.

4.1.2 *Stimulus Description and Generation.* The same environment used in the second experiment was used in this one. However, the back wall and doorframe were placed at 4 or 8 m from the participant's starting position (see Figure 9). With the target positioned 0.47 m to the left or right of the doorframe's

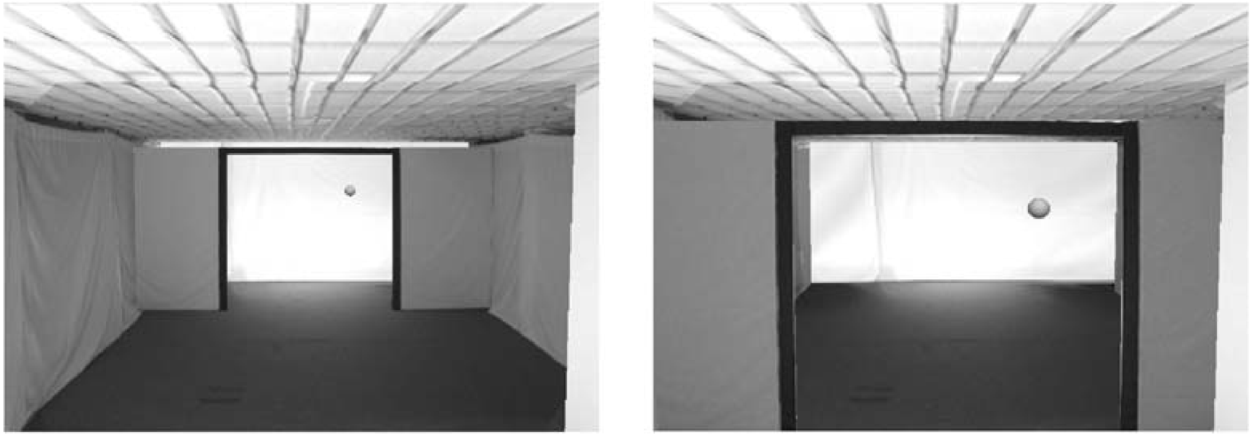

Fig. 9. First-person view of the virtual environments used in Experiment 3 as seen by the participants. The left panel shows the doorframe and target placed 8 m from the starting position and the right panel shows the doorframe and target placed 4 m from the starting position.

center, the target was offset from the participant's midline by ±6.7 or ±3.4° when the doorframe and target were 4 or 8 m away from the starting position, respectively. Throughout the experiment, the final tone sounded when participants crossed the frontoparallel plane 6 m away from the starting position.

4.1.3 *Apparatus.* The same equipment from Experiment 1 was used here.

4.1.4 *General Procedure.* As in the second experiment, two epochs of trials (3 right and 3 left offsets per epoch) were completed in each block of trials for a total of 24 trials per subject. Block order (8 and 4 m doorframe/target position) was alternated across participants.

### 4.2 Results and Discussion

Figures 10a and b show mean path angle as a function of epoch and doorframe position for the women and men, respectively. Results of a repeated-measures ANOVA showed that, contrary to the hypothesis, there was no effect of epoch, $F(1,4) = 0.89$, $p = 0.40$, or doorframe position, $F(1,4) = 1.61$, $p = 0.27$, for the women. There was also no interaction between the two factors, $F(1,4) = 0.86$, $p = 0.41$. A different pattern emerged for the men, with the results of a second repeated-measures ANOVA showing a significant effect of doorframe position, $F(1,4) = 110.90$, $p < 0.001$, but no effect of epoch, $F(1,4) = 0.65$, $p = 0.47$. No interaction between doorframe position and epoch was found, $F(1,4) = 0.40$, $p = 0.56$.

Figure 11 shows the mean path angles for the last epoch of trials as a function of gender and doorframe position. Results of a third repeated-measure ANOVA show a significant interaction between gender and doorframe position, $F(1,8) = 6.99$, $p = 0.03$, with the men in the study scaling their path angles to changes in the distance to the doorframe and target while the women did not. A main effect of target distance was also found, $F(1, 8) = 10.54$, $p = 0.01$, with path angles generally decreasing with an increased target distance. No main effect of gender was found, $F(1, 8) = 2.42$, $p = 0.16$. The fact that the men in this study were able to systematically change their path offsets in response to changes in the position of the doorframe and target suggests that the men participating in the last two experiments were able to use distance cues provided by the scene to calibrate the distance to the doorframe and target and, thus, the degree to which their paths should veer to the right or left with changing target positions. Furthermore, the fact that the women in this study did not show any systematic changes

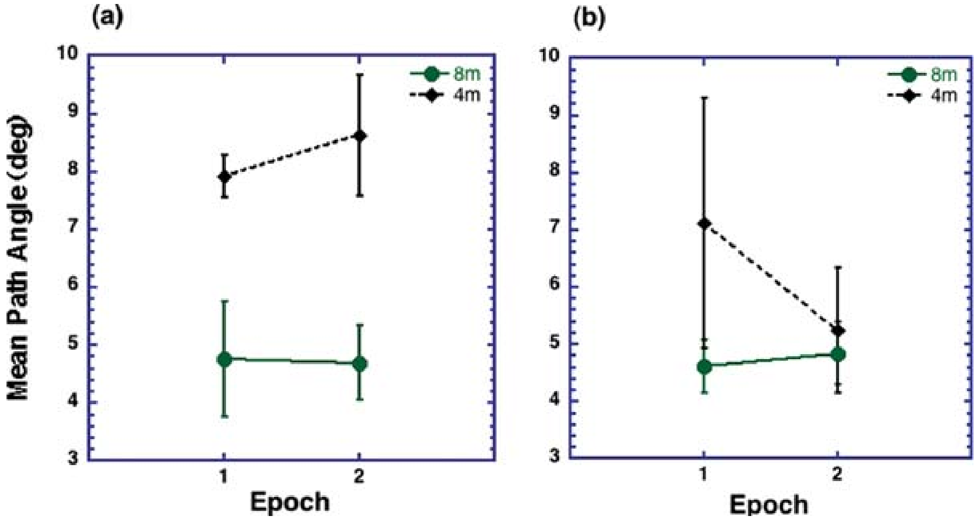

Fig. 10. (a) Men's and (b) women's mean path angles for the 8- (circles) and 4-m (diamonds) doorframe conditions as a function of epoch. Error bars represent ±1 SE.

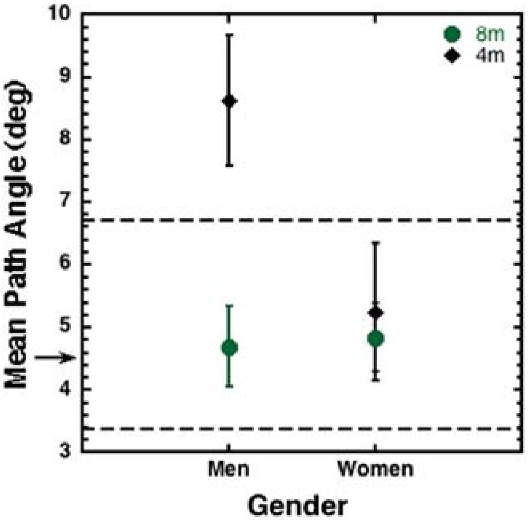

Fig. 11. Mean path angles for the 8- (circles) and 4-m (diamonds) doorframe conditions as a function of gender. The dashed lines show the true angular offsets of the target and the arrow indicates the offset predicted if the tone was used to scale the distance to the doorframe and target. Error bars represent ±1 SE.

in path offsets with changes in the distance to the doorframe and target supports the hypothesis that women are not as effective as men at recalibrating their path-integration systems when walking in virtual environments.

## 5. GENERAL DISCUSSION

Collectively, the results from the present study demonstrate that gender differences exist in the way that men and women recalibrate their path-integration systems when walking without vision to previously seen targets in virtual environments. Furthermore, the results indicate that the difference between men and women is more complicated than an innate difference in cue preference. While the results of the first experiment showed that the men in the study did utilize the distance cue provided by the tone to scale their path angles, the results of the second experiment did not replicate this finding (i.e., men did not scale path angles with walking distance) when photorealistic texturing was applied to the scene. The third experiment then provided support that men can also effectively use distance cues provided by the scene and not the tone by showing that changes in the actual distance to the doorframe and target with photorealistic texturing led to systematic changes in the path angles of the male participants. This overall pattern of results suggests that men are able to use both visual and nonvisual distance cues to recalibrate their path-integration systems in virtual environments and the extent to which visual and nonvisual cues are attended to in tasks such as this depends upon the quality of the cues provided. On the other hand, for the women who participated in these studies, the lack of any systematic changes in path angles in any of the three experiments demonstrates that even if women did tend to rely on visual information to determine the distance to the target, the availability of these distance cues was not sufficient for the women as a group to effectively scale their path offsets with changes in the distance to the doorframe and target. Therefore, the gender differences observed in this study not only resulted from differences in the types of cues the men and women attended to when determining the distance to the target, but also a superior ability on the part of the men to use path integration systems in reaching the target.

In order to understand why these differences occurred, it is helpful to consider the model Loomis and colleagues [Loomis et al. 2002] propose for path integration. According to this theory, successful path integration is a two-step process in which humans first encode the location of a target in space and then complete spatial updating of their position relative to the perceived target location while walking. As a result of this, errors can occur in encoding the location of the target, during spatial updating, or in both steps. The two gender differences discussed above can be thought of as exemplifying both types of errors. First, in order to use the distance cue provided by the tone to scale the magnitude of their path angles, the men in the first experiment must have encoded different locations for the target in the 4- and 8-m walking conditions. While it is true that the distance information provided by the tone would have been extracted during spatial updating, by using this information to adjust their path angles in future trials, the men were, in fact, using this information during the encoding phase and altering their perceptions of where the target was located. Thus, the differences in the ending path angles can be explained, in part, by differences in encoding errors (see Figure 1). This explanation is consistent with other studies [Cutmore et al. 2000; Dabbs et al. 1998; Grön et al. 2000; Linn and Peterson 1985; Sandstrom et al. 1998; Voyer et al. 1995] suggesting that men and women use different strategies during orientation and navigation tasks. In particular, one study [Dabbs et al. 1998] has found evidence that men tend to take a Euclidean approach in navigating to a target, using cardinal directions and absolute distances, while women rely more on visual landmarks and egocentric directions (i.e., left/right). Second, the fact that the women failed to scale their path angles with changes in the doorframe and target location in the third experiment also suggests that differences in encoding strategies is not the whole story. Differences in spatial updating proficiency must have also occurred. Given that studies on path integration in the real-world have not reported gender differences in spatial updating for the short distances tested in this experiment [Ellard and Shaughnessy 2003], the deficit in the women's ability to perform spatial updating must be the result of some aspect of the virtual environment. As noted earlier, there is a significant amount of research suggesting that distances are underrepresented in virtual environments [Loomis and Knapp 2003; Messing and Durgin 2005; Thompson et al. 2004]. It has also been found that gender differences exist in the way that men and women respond to conflicting visual and vestibular information within a virtual environment

[Viaud-Delmon et al. 1998]. The paradigm used manipulated the visual feedback presented to participants while turning in a chair and viewing a virtual room such that participants perceived themselves as turning 90° in the room while actually rotating 180° in the chair. Results of this study showed that men were able to recalibrate their perceived vestibular sensations to a greater extent than women such that, after being presented with the conflicting information, men underestimated how far they turned in the chair when blindfolded. Given that the vestibular system is known to be important for perceived self-motion and orientation [Lackner and DiZio 2005] and the present experiment tested path angles rather than distance traveled, it could be that this paradigm tapped into the same gender difference in recalibrating to visuovestibular conflicts that Viaud-Delmon et al. [1998] observed. Furthermore, as traditional path-integration studies in virtual environments [Loomis et al. 1999; Loomis and Knapp 2003] usually examine straight-line distance errors and have not examined differences under conflicting visual and nonvisual cue conditions, the use of a novel paradigm in the present study may be why a gender difference was observed here but not in previous studies.

While the current findings provide valuable information about how men and women integrate various distance cues with self-motion cues to scale distances and recalibrate their path integration systems, care needs to be taken in generalizing the results of this study to behavior in real-world settings. In particular, the second study conducted by Turano and Chaudhury [2005] found that the gender differences observed in the VE when studying the induced Roelof's effect did not transfer over to the real-world setting. Furthermore, another study [Ellard and Shaughnessy 2003] using a similar cue conflict paradigm as the present study, but in a real-world setting, failed to find a significant gender difference. In the study by Ellard and Shaughnessy, participants were provided with both a visual cue and a proprioceptive cue (blind walking out to target and back to starting point), with the order of presentation counterbalanced across trials. In each trial, one cue indicated that the target was 6 m away, while the other cue indicated that the target was 8 m away. In this case, no gender difference was observed, with both men and women's distance estimations showing a bias toward whatever distance cue (visual or proprioceptive) was provided last. It seems plausible, then, that the behavior of the participants in this study was influenced by factors that are present in a VE and absent in real-world settings. For example, it may be that differences in stereo thresholds influenced behavior. As the use of displays limits resolution capabilities, if the men and women in this study did possess different stereo thresholds, their ability to extract distance cues from the visual scene would differ as well. However, no research was found documenting such a gender difference and it seems unlikely that the men and women differed overall with respect to this visual function. A stronger candidate is the compression of perceived distances in VE noted above [Messing and Durgin 2005; Thompson et al. 2004] and the resulting recalibration that is required to make internally generated self-motion cues (proprioceptive and vestibular) consistent with visual information that is acquired at the beginning of each trial. However, given that the paradigm used in the current study has not been applied in the real-world, it would be useful to construct real-world facsimiles of the first and third experiments where the participants are able to walk beyond the doorframe, as this would allow direct comparison between the two environments while keeping the conflict between the auditory and visual distance cues ambiguous. In order to do so successfully, however, it would be important that all extraneous noises be controlled. In particular, given that the participants' paths sometimes veered farther to the right or left than the extent of the doorframe, it would be necessary to construct the room so that the back wall moved to permit the participants to walk through without the participants hearing any of this movement occurring. Larger sample sizes would also be helpful for increasing external validity.

In conclusion, the current findings have significant implications for researchers who use VR to study human behavior. While VR is becoming a popular tool for researchers in a variety of fields, processing requirements limit the amount of detail that can be used if participants are to walk around inside the

VE [MacKenzie and Ware 1993; Stanney et al. 1998; Wloka 1995]. Because of this, researchers must sacrifice some amount of realism in order for participants to maintain a level of presence within that environment. Furthermore, despite numerous innovations in graphics programs, researchers continue to show that space appears compressed to individuals immersed in a VE [Messing and Durgin 2005; Thompson et al. 2004]. As a result of these limitations, individuals who are expected to walk within a VE will continue to need to recalibrate their path-integration systems in order to effectively integrate visual information with self-motion cues. In order to best accommodate these factors and make VR a useful technique to study human behavior, the present findings suggest that care should be taken to recognize inadvertent cues available to participants, such as a tone ending each trial, as men and women can pick up on and use these cues differently, while adjusting to their new surroundings.

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