

Sarah S. Chance*
Department of Psychology
University of California
Santa Barbara, CA 93106-9660

Florence Gaunet
Laboratoire de Physiologie de la
Perception et de l'Action
CNRS-College de France
11 place M. Berthelot
75005 Paris, France

Andrew C. Beall
Man Vehicle Laboratory
Massachusetts Institute of
Technology
70 Vassar Street
Cambridge, MA 02139

Jack M. Loomis
Department of Psychology
University of California
Santa Barbara, CA 93106-9660

Locomotion Mode Affects the Updating of Objects Encountered During Travel:

The Contribution of Vestibular and Proprioceptive Inputs to Path Integration

Abstract

In two experiments, subjects traveled through virtual mazes, encountering target objects along the way. Their task was to indicate the direction to these target objects from a terminal location in the maze (from which the objects could no longer be seen). Subjects controlled their motion through the mazes using three locomotion modes. In the Walk mode, subjects walked normally in the experimental room. For each subject, body position and heading were tracked, and the tracking information was used to continuously update the visual imagery presented to the subjects on a head-mounted display. This process created the impression of immersion in the experimental maze. In the Visual Turn mode subjects moved through the environment using a joystick to control their turning. The only sensory information subjects received about rotation and translation was that provided by the computer-generated imagery. The Real Turn mode was midway between the other two modes, in that subjects physically turned in place to steer while translating in the virtual maze; thus translation through the maze was signaled only by the computer-generated imagery, whereas rotations were signaled by the imagery as well as by proprioceptive and vestibular information. The dependent measure in the experiment was the absolute error of the subject's directional estimate to each target from the terminal location. Performance in the Walk mode was significantly better than in the Visual Turn mode but other trends were not significant. A secondary finding was that the degree of motion sickness depended upon locomotion mode, with the lowest incidence occurring in the Walk mode. Both findings suggest the advisability of having subjects explore virtual environments using real rotations and translations in tasks involving spatial orientation.

1 Introduction

One of the primary bases for navigation is *path integration*, the continuous updating of one's position and orientation using information about self-velocity and self-acceleration over time (Gallistel, 1990; Mittelstaedt & Mittelstaedt, 1980). (The other important basis for navigation is *piloting*, a term that refers to navigation based on the sensing of distinctive locations in conjunction

with an external or cognitive map.) Unlike piloting, path integration does not require a map of the environment being traveled; indeed, it is path integration that promotes the integration of disjoint environmental features into a coherent representation of an environment (Gallistel, 1990; Poucet, 1993; Thinus-Blanc, 1988). To develop such a map of real or virtual environments, travelers must have the sensory information available to perform path integration. This research is concerned with learning more about the sensory inputs to path integration as assessed in a task in which participants imaginably update objects encountered along the route of travel.

There are several potential sources of information available to the path-integration process. An important distinction in the literature on animal navigation is that between allothetic and idiothetic sources of information (Mittelstaedt, 1985). Allothetic information derives from external sensing of the environment and includes optic flow and acoustic flow. Idiothetic information is internally generated during movement and includes vestibular signals, afferent proprioceptive signals, and efference copy of the commands issued to the musculature. Many experimental studies of animals have addressed the contribution of these various inputs to path integration (e.g., Beritoff, 1965; Etienne, 1992; Mittelstaedt, 1985; Mittelstaedt and Mittelstaedt, 1980; von St. Paul, 1982).

In contrast to the many investigations of animal path integration, the studies on human path integration are quite limited in number (see review by Loomis et al., in press). Of these, some have attempted to evaluate the informational inputs to the path integration process, most of which have been concerned with path integration in the absence of vision (e.g., Beritoff, 1965; Glasauer et al., 1994; Juurmaa and Suonio, 1975; Mittelstaedt and Glasauer, 1991; Sholl, 1989; Worchel, 1952). Two studies that did manipulate the availability of visual information made use of a virtual visual display to provide optic flow information about self-motion while eliminating landmark information in a triangle completion task. The first of these (Loomis et al., 1995) employed five conditions for evaluating optic flow, vestibular, and proprioceptive stimulation as inputs to the path

integration process. Two conditions involved walking (both with and without vision), two involved wheelchair transport (with and without vision), and the fifth was a stationary condition with vision (optic flow). The main finding was a difference in performance between the stationary condition and the other conditions—the directional response toward the origin was much poorer when optic flow alone specified the outbound path. The second of these experiments (Klatzky et al., in press) included a comparison of real turning accompanied by optic flow and simulated turning (specified only by optic flow). The results indicate that optic flow alone might be a poor stimulus for the updating of heading (facing direction).

Related studies in imaginal updating of previewed targets suggest a difference in the way subjects process translations and rotations (Presson and Montello, 1994; Rieser, 1989). In these studies, subjects first viewed an array of targets and then with eyes closed rotated through an angle or walked a short distance forward, after which they indicated the directions to the targets. Under these conditions subjects performed accurately. If, instead, subjects *imagined* rotating or translating, a different pattern of results emerged—while subjects were still accurate in updating the targets after an imagined translation, updating after an imagined rotation resulted in large systematic error. Related findings have been reported by May (1996). It would appear that when the vestibular and proprioceptive signals specify stationarity of the body, they are more easily countermanded by imagined movement in the case of translation than in the case of rotation. The work mentioned above (Klatzky et al., in press; Loomis et al., 1995) suggests that the same pattern may hold when it is optic flow, rather than imagination, that is opposed to the vestibular and proprioceptive inputs.

The aim of the two experiments we report here is to assess the effects of three locomotion modes, differing in their idiothetic components, on the imaginal updating of objects encountered during travel. In these experiments, subjects performed a variant of a task commonly used to assess environmental knowledge (e.g., Lindberg and Gärling, 1982; Montello and Pick, 1993). Here subjects traveled through a virtual (visually simulated)

maze and encountered target objects, the locations of which they were required to remember. Subjects indicated the direction to the targets from a terminus from which the objects could no longer be seen, so their direction had to be inferred through path integration. The primary manipulation in both experiments was the locomotion mode during exploration. In the Walk mode, subjects walked normally in the experimental room. Their body position and heading were tracked, and this tracking information was used to continuously update the visual imagery presented to the subjects on a head-mounted display (HMD). In this mode information about the subject's translations and rotations were conveyed by the computer-generated imagery as well as by vestibular and proprioceptive information (including efference copy). In the Visual Turn mode subjects moved through the environment using a joystick to control their turning. Thus the subject's heading and course (travel direction) in the virtual environment were controlled solely by the joystick. Forward speed was held constant by the simulation program. The only sensory information subjects received about rotation and translation was that provided by the computer-generated imagery. The Real Turn mode was midway between the other two modes, in that subjects physically turned in place to steer while translating through the virtual maze. Thus the subject's heading and course in the virtual environment were controlled by the subject's physical heading while forward speed was maintained constant by the simulation program. In this mode, translation through the maze was signaled only by the computer-generated imagery, whereas rotations were signaled by the imagery as well as by proprioceptive and vestibular information. Using these locomotion modes, subjects traveled to a terminus from which the targets were not visible and indicated the direction to each target.

If optic flow alone is sufficient to allow a user to update his or her position in space, subjects should perform equally well in these three modes. If it is true that subjects can update their positions in space equally well after real or simulated translations, but need to actually *perform* a rotation to update their heading, then we should see equal performance in the Walk and Real Turn modes and poorer performance in the Visual Turn mode.

Of secondary interest is whether motion sickness (simulator sickness) depended on mode of locomotion. This question was evaluated using self-reports.

2 Experiment 1

2.1 Method

2.1.1 Subjects. The subjects in the experiment were 17 undergraduate students and 5 graduate students. Three felt ill during the first session and did not complete the experiment. One additional subject failed to return for all three sessions. Consequently, 18 subjects (6 male, 12 female) completed the experiment. Each participated in all three locomotion modes. The undergraduate students received credit in a course in introductory psychology; the graduate students were paid for their participation.

2.1.2 Apparatus. The experiment was conducted using a custom-built virtual display system developed by two of the authors (Beall and Loomis). There are three basic subsystems: the 3D graphics computer, the HMD, and the head tracker.

The graphics computer is a Silicon Graphics (SGI) Indigo2, High-Impact computer with an ICO multi-channel output board. This computer generates a stream of shaded, texture-mapped images for each eye.

The HMD in our system is the Virtual Research FS5 display consisting of two CRTs, one for each eye. The ICO output board converts the SGI graphic images to the 800 (horizontal) \times 486 (vertical) resolution of the FS5. Each display in the FS5 is refreshed in full color at 60 Hz in field-sequential mode (60 Hz for each of red, green, and blue fields). The maximum graphics update rate for each eye is 30 Hz, but the update rate can be considerably lower depending upon the complexity of the graphics imagery. The field of view of each display is 44 deg (horizontal) \times 33 deg (vertical) with 100% binocular overlap. With an angular resolution of just over 3 arcmin, the display allows visual resolution on the order of 20/70 with excellent rendering of stereoscopic depth.

The third subsystem is the hybrid head tracker, which continually determines the position and orientation of

the user's head. This information is used to update the user's binocular imagery as he/she moves around in space. The head tracker consists of two components, the video tracker and a goniometer.

The video tracker (Beall, 1997) is a second-generation implementation of one used in earlier research (Loomis, Hebert, and Cicinelli, 1990). The new implementation consists of the following components: two small lights mounted on the backpack worn by the user, two CCD cameras, two digitizing boards, and a video tracking computer. The two 6 v flashlight bulbs are mounted on vertical stalks attached to the backpack and are used to determine the location and heading of the user's torso; they are at different elevations for easy differentiation by the tracking software. The video signals from the two CCD cameras (Sony model CCD-V701/NTSC camcorders) are received by the two Matrox Meteor digitizing boards installed in the 120 MHz Pentium computer. Custom-designed software running on the PC determines the image location of each bulb within the coordinates of the digitizing board with subpixel accuracy; thence, triangulation software determines the location of each bulb within the room (with an accuracy of several millimeters). These two locations are then used to compute the position and heading of the torso.

The other component of the head tracker is the 6-df goniometer (Shooting Star model ADL-1), which uses rotary potentiometers to signal the joint angles of the goniometer. Its base containing the electronics is mounted on the backpack, and its free end is attached to the top of the FS5 HMD. Software running on the PC is used to determine the position and orientation of the HMD relative to the backpack. Combining the goniometer and video tracker information, the PC software determines the position and orientation of the head within the workspace. For the scale of the workspaces used, positional accuracy was on the order of 2 cm. Angular accuracy about all axes is better than 1 deg.

The PC communicates the position and orientation of the HMD to the SGI computer over an RS232 serial line running at 38,400 baud. The total system lag (from translation or rotation of the head to change in imagery within the HMD) ranges from 60 to 80 msec for graphics update rates of 30 and 60 Hz. (System lag was mea-

sured as the interval between a step voltage coming from one of the input devices and a change in the graphics imagery as sensed using a photodiode placed against the CRT.) When the update rate is 30 Hz in each eye and the system lag is 60 msec, there is no noticeable lag unless the head is rotated very quickly. In this experiment, the graphics update rate per eye ranged between 6 and 18 Hz (mean = 12 Hz). Even at the rates used here, movement through the virtual environment resulted in smooth and natural optic flow. Combined with the full-color binocular imagery, which resulted in relatively high spatial resolution and stereopsis, the "presence" experienced by the observers was very compelling.

The joystick used in the Visual Turn mode of the experiment is a standard position-control device. Its left-right deflection by the subject was transduced to produce left-right virtual rotation. A "dead-zone" in the center of the joystick's range of motion produced no virtual rotation in order to allow the users to travel forward in a straight line; otherwise, turn rate was proportional to joystick deflection, with minimum turn rate equal to approximately 60 deg/sec and maximum turn rate equal to 360 deg/sec.

2.1.3 Stimuli. The six mazes used in the experiment were created using the 3D modeling program Strata StudioPro Blitz on a Macintosh and were then exported to the SGI. The simulated dimensions of the mazes were approximately 3 m by 4 m (corresponding to the dimensions of the workspace used for the walking mode); the walls of the maze were composed of textured bricks and were 3 m high. The average path length through the mazes was about 10 meters. Twelve objects were created and positioned within the mazes to serve as targets. The targets were all easily recognizable objects (e.g., a television on a table, a chair, a coatrack); they were 1.72 m high and approximately 40 cm on a side. Subject eyeheight was set at 1.7 m. Three of the mazes had only one object and three had three objects. Figure 1 shows a diagram of one of the three-object mazes. The solid squares represent the target locations. The image on the front cover (upper left) shows a typical view from within the virtual maze.

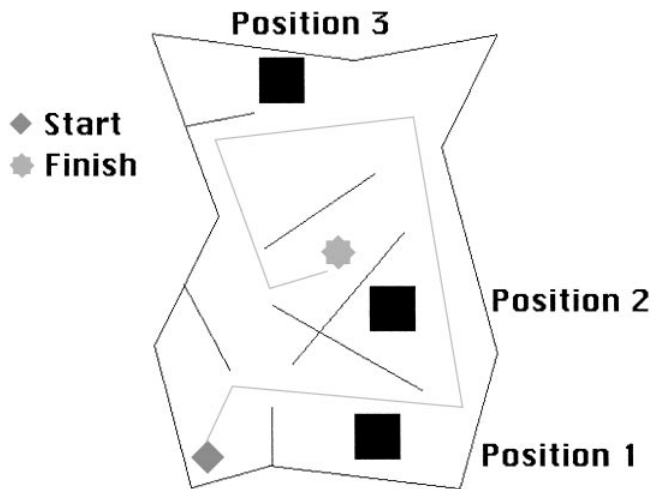


Figure 1. A maze used in Experiment 1. The solid squares represent the locations of the targets. The diamond signifies the starting point and the star signifies the response point. The subjects faced virtual North at both the starting point and at the response point. The mazes were 3 m by 5 m.

2.1.4 Design. The experiment employed a within-subject design using one factor, locomotion mode (Walk, Real Turn, Visual Turn). The subjects participated in three sessions, one for each mode of locomotion. The order of modes was counterbalanced across sessions, there being three subjects in each of the six possible orderings of the modes. All mazes appeared equally often in all modes. During a given session, a subject explored three one-target mazes and three three-target mazes in alternating order, and thus saw all 12 objects. To avoid memory interference for objects, sessions were separated by one week and objects were used only once within a session. The 12 objects were randomly assigned to positions in the mazes.

2.1.5 Procedure. When subjects arrived at the experimental site for the first session, they filled out a questionnaire that asked them to rate their sense of direction on a scale of 1 (“terrible”) to 5 (“excellent”) (Kozlowski and Bryant, 1977) and their tendency to experience motion sickness on a scale of 1 (“never”) to 5 (“often”). Interpupillary separation was measured and entered into the graphics program so that the geometri-

cally correct images would be generated. The procedure for the experimental trials for that session was described. Subjects were to move through the six mazes following as closely as possible a guide object that traveled through each maze along a defined path. The guide led subjects past the targets and then to a terminal marker, which was located at a place in the maze from which the targets were not visible. When subjects arrived at the marker, their forward translation stopped; the guide continued 0.3 meters beyond the marker in the direction of virtual North (the subject’s facing direction at the start of the trial). Subjects were told to face the guide. They were then asked to indicate the direction to the targets. The method used to indicate direction was a verbal report of the “minute hand” position of each object. That is, given that the guide was straight ahead (0 min.), an object directly to the right would be at 15 min., and one directly behind would be at 30 min., and so on.

Before the trials began, subjects were shown 2D representations of the targets and then practiced the verbal response mode until they demonstrated proficiency and indicated that they were comfortable with the response method. Subjects then put on the HMD and backpack and were placed in a practice maze to familiarize themselves with the operation of the system. They were encouraged to look around using head movements and to note the stability of the environment despite their head movements. After this initial orientation, the practice maze was removed, and the subject saw a blank screen. The experimenter then inertially disoriented the subject by turning him or her in place through large angles for approximately 15 sec.; the purpose of this was to cause the subject to lose orientation with respect to the frame of reference of the room (May, 1996). In addition, opaque fabric was attached to the sides of the HMD to block extraneous light from the room, and subjects wore earphones through which they heard white noise of a sufficient level to block sound cues from the room. If subjects were to actually walk through the room (Walk mode), they were told that the guide object would never lead them into the walls of the physical room, and that the experimenter would accompany them to ensure that they would not collide with the walls.

On each of the six experimental trials, the subject stood at the starting point in the virtual maze and was told which target objects would be present on that trial; the subject then repeated the target names back to the experimenter. After about 10 seconds, the guide appeared in front of the subject at eye level, and moved forward at about 17 cm/sec (taking about a minute to complete a pathway). The subject followed the guide through the maze in the locomotion mode being used for that session, either by walking (Walk mode), making real turns in place to steer the constant forward motion (Real Turn mode), or deflecting the joystick left or right to steer the constant forward motion (Visual Turn mode). After completion of the six trials, the subject indicated how motion sick he/she felt on a scale of 1 (“no symptoms”) to 5 (“very sick”).

2.2 Results

The actual direction to each target was computed from the terminal location in each maze. The dependent measure was the absolute difference, in degrees, between this direction and the direction indicated by the subject (after converting the subject’s verbal report in minutes into degrees). The data for the one-target mazes were not analyzed because of an error that came to light after the experiment (the position of the target was confounded with session). Figure 2 shows mean absolute error, averaged across subjects (six per session per mode) and targets (three in each of the three-target mazes), as a function of session and locomotion mode. The error bars represent one standard error of the mean. Overall, performance error was high, approaching chance (90 deg) in some cases. It is apparent from the figure that locomotion mode had no effect in the first two sessions, but appeared to by the third session. In the one-way-between-subjects ANOVA on the data from Session 3, the effect of mode was just short of significance $F(2, 15) = 3.648, p = 0.051$. A post hoc Tukey test revealed only a significant difference between the Walk and Visual Turn modes ($p = 0.041$).

Further examination of the data indicated an effect of the position of the target (see Figure 3). A two-way ANOVA of position and mode of locomotion produced

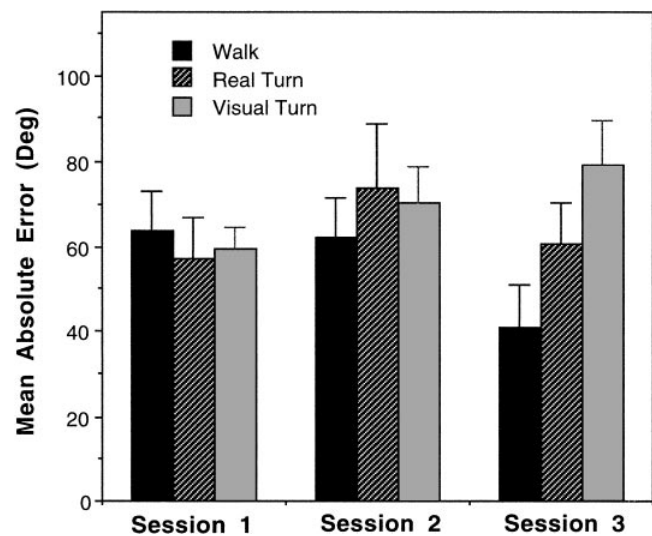


Figure 2. The performance data of Experiment 1 is given for all three experimental sessions. Mean absolute error, averaged over subjects, is given as a function of session and locomotion mode. Error bars represent one standard error of the mean.

the following results. There was an effect of position $F = (2, 30) p = 0.002$ such that performance improved for targets closer (in terms of order) to the response point. The effect of locomotion mode was marginally significant as reported above. A post hoc Tukey test of the two-way ANOVA revealed that the Walk mode differed significantly from the Visual Turn mode ($p = 0.036$).

Figure 4 gives the mean ratings of motion sickness after the last trial. Error bars represent one standard error of the mean. According to a one-way ANOVA, there was an effect of locomotion mode, $F(2, 34) = 3.29, p = 0.049$.

The correlation between self-reported tendency to experience motion sickness (reported before participating in the experiment) and ratings of motion sickness after the experiment were 0.33 for the Walk mode, -0.19 for the Real Turn mode and 0.10 for the Visual Turn mode. The correlations between self-reported sense of direction and mean absolute error were -0.28 in the Walk mode, -0.33 in the Real Turn mode, and 0.19 in the Visual Turn mode (negative correlation signifies positive relation).

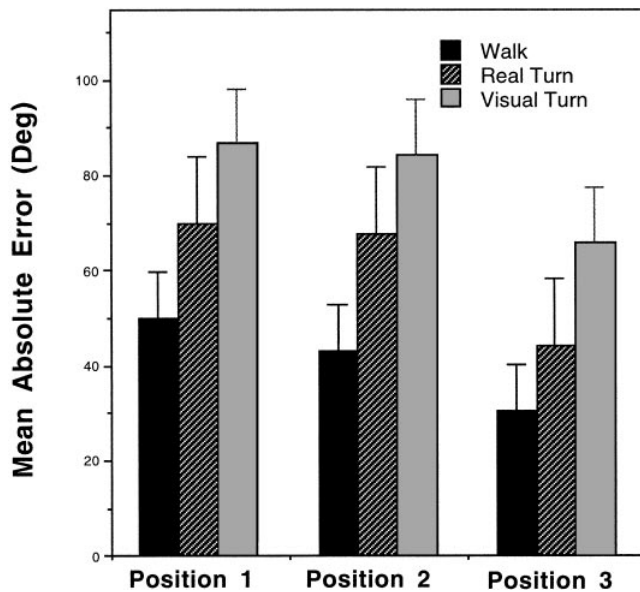


Figure 3. The performance data from the third session of Experiment 1. Mean absolute error, averaged over subjects, is given as a function of locomotion mode and position of the target; the object at position 1 was the first encountered, the object at position 2 was the second encountered, and so on. Error bars represent one standard error of the mean.

There was also a tendency for males to perform better in the experiment, but this effect did not reach statistical significance.

2.3 Discussion

The various analyses suggest that by the third session, there was an effect of locomotion mode on performance. In this session, there was a significant difference in performance between the Walk mode and the Visual Turn mode, but other differences were not reliable. This result implies that there is useful information for target-position updating conveyed in the Walk mode that is not present in the Visual Turn mode. Because performance generally was quite poor in all modes, we conducted a second experiment with some methodological improvements. We hoped these changes would lead to an overall improvement in performance and more clearly reveal whatever effect of locomotion mode exists. In Experiment 1, the guide object moved at a fairly slow speed, resulting in a slow walking speed with unnatural gait in

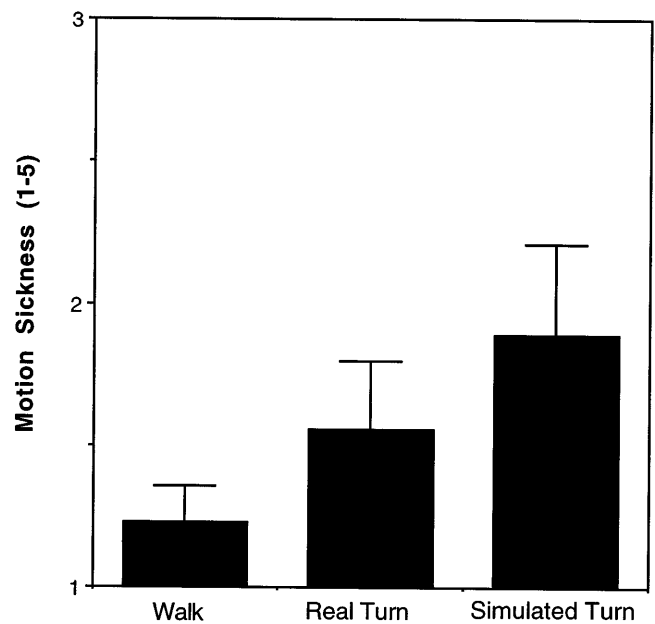


Figure 4. The mean motion sickness ratings in the three locomotion modes of Experiment 1. Error bars represent one standard error of the mean.

the Walk mode. We suspected that this movement did not allow optimal use of vestibular and proprioceptive information. Furthermore, we were concerned that subjects were giving such importance to tracking the guide object that their attention to the targets was diminished. The mazes in the second experiment were constructed so that there were no decision points along the path, meaning that a guide object was no longer necessary. We increased the overall size of the mazes and the widths of the walkways to afford more comfortable travel. Finally, out of a concern that the verbal report in Experiment 1 was too abstract, we opted for a more natural response. In Experiment 2, subjects indicated the target's direction by turning to face what they believed to be its direction.

3 Experiment 2

3.1 Method

3.1.1 Subjects. The subjects were 24 undergraduate students. Each participated in one of the three

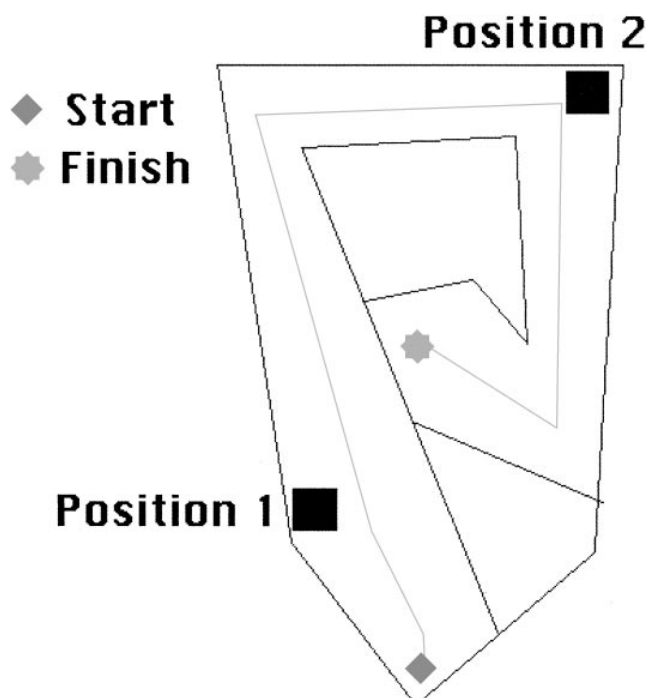


Figure 5. A maze used in Experiment 2. The solid squares represent the locations of the targets. The diamond signifies the starting point and the star signifies the response point. The mazes were 3.2 m by 6 m.

locomotion modes. Subjects received credit toward a course in introductory psychology.

3.1.2 Stimuli. The stimuli used in Experiment 2 were similar to those used in Experiment 1. Six new mazes were constructed; three were used for practice trials, and three for experimental trials. The mazes were constructed so that there were no decision points between the starting point and response point. They were slightly larger than those in Experiment 1, measuring 3.2 meters by 6 meters. The average path length was about 12 meters. Two target objects were present in each maze. Figure 5 shows one of the experimental mazes.

3.1.3 Design. We used a between-subjects design with locomotion mode as the primary experimental manipulation. Seven subjects participated in the Walk mode, seven subjects participated in the Real Turn

mode, and 10 subjects participated in the Visual Turn mode.

3.1.4 Procedure. The procedure for the experiment was the same as in Experiment 1 except for the following changes. First, subjects in the Real Turn and Visual Turn modes did not translate forward at a constant speed; rather, they controlled their forward speed with a joystick. This technique allowed them to pause if desired, as they could in the Walk mode. In the Visual Turn mode, subjects used the same joystick to control translation and rotation, with left-right deflection causing virtual rotation and forward deflection causing forward movement. (These types of movement could be performed simultaneously, producing curved pathways.) Forward speed was proportional to forward joystick deflection, with a maximum speed of 45 cm/sec. These values were chosen so that the mean travel speed was about the same as that in the Walk mode (which was run first). This objective was met; for the total travel time averaged about 27 sec in all three locomotion modes. Second, because subjects did not have any decision points in the mazes, it was not necessary that they follow a guide block. Third, subjects responded by turning to face the targets (with a real turn or a joystick turn, corresponding to the locomotion mode) instead of indicating the direction with a verbal response. The computer tracking system returned a measure of heading that was compared with the actual target direction. Subjects were asked to rate the degree of motion sickness after each trial rather than just at the end of the session. Lastly, subjects were allowed to perform three practice trials before beginning the experimental trials. The practice trials were identical to experimental trials, except that subjects were allowed to ask questions after each. After the questions, all subjects indicated that they understood the task and were comfortable with the mode of locomotion.

3.2 Results

Six estimates of direction to a target were recorded from each of the 24 subjects (two direction estimates from each of the three experimental mazes). Figure 6

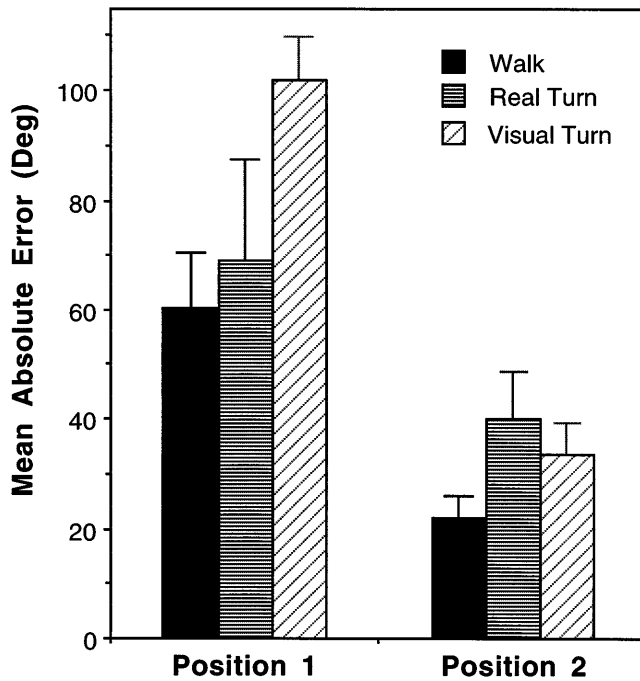


Figure 6. The performance data from Experiment 2. Mean absolute error, averaged over subjects, as a function of locomotion mode and position of the target. Error bars represent one standard error of the mean.

shows the performance data from Experiment 2. Mean absolute error is plotted as a function of locomotion mode and target position. Error bars represent one standard error of the mean. A two-way ANOVA (with locomotion mode a between-subjects variable and position a within-subjects variable) showed an effect of locomotion mode, $F(2, 21) = 3.637$, $p = 0.044$ and an effect of position $F(1, 21) = 33.870$, $p < 0.0001$. There was also an effect of gender in the experiment, with males ($m = 53$) performing with higher accuracy than females ($m = 59$), $F(1, 21) = 6.290$, $p = 0.022$. A post hoc Tukey test on locomotion mode revealed that the difference between the Walk mode and the Visual Turn mode was statistically significant ($p < 0.036$) and the difference between the Walk mode and the Real Turn mode was not statistically significant ($p = 0.443$). The difference between the Real Turn mode and the Visual Turn mode also was not statistically significant ($p = 0.391$).

A between subjects two-way ANOVA was run on mo-

tion sickness using locomotion mode and trial number. Although there was a trend of increasing motion sickness paralleling the result obtained in Experiment 1, there was no effect of locomotion mode. There was a significant effect of trial, $F(5, 105) = 3.8$, $p = 0.003$.

The correlation between self-reported tendency to experience motion sickness and ratings of motion sickness in the experiment were 0.00 for the Walk mode, -0.49 for the Real Turn mode and 0.25 for the Visual Turn mode. The correlation between self-reported sense of direction and mean absolute error was -0.56 in the Walk mode, 0.13 in the Real Turn mode, and -0.13 in the Visual Turn mode (negative correlation signifies positive relation).

3.3 Discussion

Despite the methodological improvements, performance did not significantly improve over that of Experiment 1. Even so, the results of Experiment 2 replicated the main finding of Experiment 1. That is, performance error is lower in the Walk locomotion mode than in the Visual Turn locomotion mode. Performance in the Real Turn locomotion mode was intermediate. The secondary finding of Experiment 1, showing an effect of locomotion mode on motion sickness, was paralleled by a similar trend in Experiment 2, but the trend was not statistically significant. This interesting trend will be pursued in future research, using a more sensitive measure of motion sickness, such as latency to the first reported feelings of motion sickness.

4 General Discussion

The basic finding of this research was a difference in performance between the Walk and Visual Turn locomotion modes, showing that vestibular and proprioceptive information contribute to the ability to perform egocentric spatial updating. A strong prediction was made at the outset that these nonvisual signals would be crucial only for the updating of heading, and, therefore,

that the only performance difference would be between the Visual Turn locomotion mode and the other two locomotion modes. There was a difference between the Visual Turn and the Real Turn modes in the expected direction, but it fell short of statistical significance.

The secondary finding was the effect of locomotion mode on the degree of reported motion sickness; specifically, the Walk mode elicited the lowest ratings of motion sickness. This finding is consistent with the widely held view that one of the causes of motion sickness is a discrepancy between vestibular signals and other informational inputs specifying body motion (see the FORUM section of the special 1992 issue of *Presence*, Vol. 1, devoted to simulator sickness).

We wish to qualify these findings in two ways. First, the effects on performance were obtained with very little time spent in the virtual environments. Given the late emergence of the mode effect in Experiment 1, we might expect larger differences between the modes with more extensive practice in performing the tasks. Second, it is possible that with a larger field of view than that of the HMD we used, optic flow might be sufficient to elicit perceived self-motion (vection) in the Real Turn and Visual Turn modes; see Peruch, May, and Wartenberg (1997) for a discussion of field of view in virtual environments. If so, a large field of view might result in more accurate path integration, such that these modes would show the same performance levels as the Walk mode. On the other hand, the greater sense of self-motion unaccompanied by the appropriate vestibular and proprioceptive information could lead to a greater incidence of sickness in these two modes.

Even with the limited field of view of the HMD used here, these results have implications for the design of virtual environment interfaces. For those applications where spatial orientation is important, our research indicates the possible benefits of using real rotations and translations to control exploration of virtual environments. Consistent with this, Pausch, Proffitt, and Williams (1997) found that head turning proved more effective in a visual search task than control of viewing direction by way of a hand-held pointing device.

Acknowledgments

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References

- Beall, A. C. (1997). Low-cost position and orientation tracking system for small scale environments. Unpublished manuscript, Department of Psychology, the University of California, Santa Barbara.
- Beritoff, J. S. (1965). *Neural mechanisms of higher vertebrate behavior*. W. T. Liberson. (Ed. and Trans.). Boston: Little, Brown.
- Gallistel, C. R. (1990). *The organization of learning*. Cambridge, MA: MIT Press.
- Glasauer, S., Amorim, M. A., Vitte, E., & Berlhoz, A. (1994). Goal-directed linear locomotion in normal and labyrinthine-defective subjects. *Experimental Brain Research*, *98*, 323–335.
- Etienne, A. (1992). Navigation in small mammal by dead reckoning and local cues. *Current Directions in Psychological Science*, *1*, 48–52.
- Juurmaa, J., & Suonio, K. (1975). The role of audition and motion in the spatial orientation of the blind and sighted. *Scandinavian Journal of Psychology*, *16*, 209–216.
- Klatzky, R. L., Loomis, J. M., Beall, A. C., & Chance, S. S., Golledge, R. G. (in press). Spatial updating of self-position and orientation during real, imagined, and virtual locomotion. *Psychological Science*.
- Kozlowski, L. T., & Bryant, K. J. (1977). Sense of direction, spatial orientation and cognitive maps. *Journal of Experimental Psychology: Human Perception and Performance*, *3*(4), 590–598.
- Lindberg, E., & Gärling, T. (1982). Acquisition of locational information about reference points during locomotion: The role of central information processing. *Scandinavian Journal of Psychology*, *23*, 207–218.
- Loomis, J. M., Hebert, C., & Cicinelli, J. G. (1990). Active localization of virtual sounds. *Journal of the Acoustical Society of America*, *88*, 1757–1764.
- Loomis, J. M., Beall, A. C., Klatzky, R. L., Golledge, R. G., & Philbeck, J. W. (1995). Evaluating the sensory inputs to path integration. Paper presented at the Psychonomic Society meeting, Los Angeles, CA, November 10–12, 1995.

- Loomis, J. M., Klatzky, R. L., Golledge, R., & Philbeck, J. W. (in press). Human navigation by path integration. In R. Golledge (Ed.), *Wayfinding: Cognitive mapping and spatial behavior*. Baltimore: Johns Hopkins Press.
- May, M. (1996). Cognitive and embodied modes of spatial imagery. *Psychologische Beiträge*, 38, 418–434.
- Mittelstaedt, H. (1985). Analytical cybernetics of spider navigation. In F. G. Barth (Ed.), *Neurobiology of arachnids* (pp. 298–316). Berlin: Springer-Verlag.
- Mittelstaedt, M. L., & Glasauer, S. (1991). Idiothetic navigation in gerbils and humans. *Zoologische Jahrbucher Abteilungen für allgemeine Zoologie und Physiologie de Tiere*, 95, 427–435.
- Mittelstaedt, M. L., & Mittelstaedt, H. (1980). Homing by path integration in a mammal. *Naturwissenschaften*, 67, 566–567.
- Montello, D. R., & Pick, H. L. (1993). Integrating knowledge of vertically aligned large scale spaces. *Environment and Behavior*, 25, 457–484.
- Pausch, R., Proffitt, D., & Williams, G. (1997). Quantifying immersion in virtual reality. *ACM SIGGRAPH 97 Conference Proceedings, Computer Graphics*, 13–18.
- Peruch, P., May, M., & Wartenberg, F. (1997). Homing in virtual environments: Effects of field of view and path layout. *Perception*, 26, 301–311.
- Poucet, B. (1993). Spatial cognitive maps in animals: New hypotheses on their structure and neural mechanisms. *Psychological Review*, 100(2), 163–182.
- Presson, C. C., & Montello, D. R. (1994). Updating after rotational body movements: Coordinate structure of perspective space. *Perception*, 23, 1447–1455.
- Rieser, J. J. (1989). Access to knowledge of spatial structure at novel points of observation. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 15, 1157–1165.
- Sholl, M. J. (1989). The relation between horizontality and rod-and-frame and vestibular navigational performance. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 15, 110–125.
- Thinus-Blanc, C. (1988). Animal spatial cognition. In L. Weiskrantz (Ed.) *Thought without language* (pp. 371–395). Oxford, UK: Clarendon.
- von Saint Paul, U. (1982). Do geese use path integration for walking home? In F. Papi & H. G. Wallraff (Eds.), *Avian navigation* (pp. 296–307). New York: Springer.
- Worchel, P. (1952). The role of vestibular organs in spatial orientation. *Journal of Experimental Psychology*, 44, 4–10.