Spatial orientation in virtual environments: Background considerations and experiments

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Abstract. Spatial orientation strongly relies on visual and whole-body information available while moving through space. As virtual environments allow to isolate the contribution of visual information from the contribution of whole-body information, they are an attractive methodological means to investigate the role of visual information for spatial orientation. Using an elementary spatial orientation task (triangle completion) in a simple virtual environment we studied the effect of amount of simultaneously available visual information (geometric field of view) and triangle layout on the integration and uptake of directional (turn) and distance information under visual simulation conditions. While the amount of simultaneously available visual information had no effect on homing errors, triangle layout substantially affected homing errors. Further analysis of the observed homing errors by means of an Encoding Error Model revealed that subjects navigating under visual simulation conditions had problems in accurately taking up and representing directional (turn) information, an effect which was not observed in experiments reported in the literature from similar whole-body conditions. Implications and prospects for investigating spatial orientation by means of virtual environments are discussed considering the present experiments as well as other work on spatial cognition using virtual environments.

1 Introduction

Virtual environments (VEs) introduce new methodological possibilities to carry out research on spatial cognition (Cutting, 1997; Ellis, 1991; Wickens & Baker, 1995). Compared to the standard inventory of methods used in research on spatial orientation and learning, methodological advantages result from the high degree of freedom in constructing spaces and in controlling and varying environmental variables, straightforward methods of variation and control of perceptual-motor factors during

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navigation, and convenient methods of online-measurement of spatial behavior. Up to now there is a comparatively small number of empirical studies using navigations in VEs for purposes of basic research in spatial cognition, but with the ongoing rapid development in VE-technology this picture is likely to change in the near future (Brauer, Freksa, Habel, & Wender, 1995; Durlach & Mavor, 1995).

One of the central open questions in using VEs for research on spatial cognition is whether spatial performances and achievements (e.g., building up survey knowledge) observed in virtual and real world environments are comparable. While a navigator in a VE has to almost exclusively rely on the visually simulated information supplied by the VE-system (e.g., depth cues, optical flow), a navigator in a real world environment can make use of multisensory information from the outer world (i.e., visual, auditory, tactile, etc.) as well as different internal sources of information generated by the whole-body movements through space (i.e., motor efferent commands, proprioceptive and vestibular signals). Whole-body motion information is known to be of central importance for spatial orientation and learning in animals (Gallistel, 1990a) and humans (Klatzky, Loomis, & Golledge, 1997). How the lack of whole-body information affects spatial orientation and learning performances in VEs is not known yet (Durlach & Mavor, 1995).

After giving some background information on the role of vision and whole-body motion in coding spatial information and the potentials of VEs as a tool for research on spatial cognition, this chapter will report research on spatial orientation in VEs. In the empirical part, two experiments on triangle completion (i.e., homing to the starting point after navigating two legs of a triangle) conducted in a VE (only visual information available) will be presented. The resulting error patterns will be compared to those of experiments on non-visual triangle completion (only whole-body information available) reported in the literature (Loomis, Klatzky, Golledge, Cicinelli, Pellegrino, & Fry, 1993). On the basis of this comparison, we will discuss how visual information typically present in VEs contributes to spatial orientation.

2 Actor-centered coding of spatial information

By actor-centered coding we refer to the sensory and memory mechanisms of picking up, preserving and integrating spatial information (e.g., distances and directions to objects) during locomotion through space. Vision and whole-body motion provide the two most important spatial coding mechanisms in humans and most animal species (Nadel, 1990; Rieser & Garing, 1994).

Visual coding of spatial information

Vision provides a rich source of spatial information which is assumed to dominate spatial orientation and the development of spatial knowledge in humans (Gibson, 1979/1986; Sholl, 1996; Thinus-Blanc & Gaunet, 1997). For the stationary observer visual information contains a multitude of spatial cues such as relative size of objects,

density gradients, occlusion, binocular disparity, surface slants, height in the visual field to name a few. The moving observer obtains further spatial information from optical flow, motion parallax, dynamic occlusion and disocclusion of objects and surfaces, etc. A prominent view of visual spatial orientation and learning is that the navigator extracts the spatial structure of the environment ('invariant structure') from the spatial information contained in the continually changing flow of retinal information (Gibson, 1979/1986). There is no doubt that vision (among the different sensory modalities) plays a predominant role in guidance problems such as following a trail or avoiding collisions, in identifying and localizing objects in the surrounding, or in perceiving spatial relations between simultaneously available landmarks. Much more controversial is the dominant role ascribed to vision (for instance by Gibson) for more complex spatial orientation problems such as knowing about object locations momentarily occluded from sight or building up spatial knowledge of large-scale space (for a critical discussion see Strelow, 1985).

Most empirical research on the role of vision in human spatial orientation has concentrated on questions of perceiving spatial layouts or events from the perspective of a stationary observer (Sedgwick, 1982, 1986; Cutting, 1986). In the last years, research has started to examine the contribution of visual mechanisms to solving more complex problems of spatial orientation and learning. Vishton and Cutting (1995) examined the ability of subjects to correctly determine their visually defined direction of self-movement using computer simulated motion sequences through virtual 'forests' composed of multisegment lines ('trees'). Their experiments show that the displacements of identifiable objects (displacement fields) and not the continuous flow of optical information as such (velocity fields) are used as input for determining heading direction, which the authors consider to be a simple mode of wayfinding.

Alfano and Michel (1990) examined the effects of restrictions of horizontal field of view on the construction of spatial knowledge. Subjects had to explore an unfamiliar room while wearing goggles with different fields of view (9°, 14°, 22°, 60°) or no goggles (natural field of view ca. 200°). An immediate memory test using a miniature model reconstruction task showed that the accuracy of object placements decreased as a function of restrictions in field of view. Width of field of view seems to be an important factor in integrating spatial information over successively perceived parts of space. In a similar vein, Rieser, Hill, Talor, Bradfield and Rosen (1992) found decrements in distance and direction judgments between landmarks in a city for subjects with early-onset losses of visual field as compared to subjects with a normal size of the visual field, even when the latter subjects had suffered from early- or late-onset acuity losses.

Whole-body coding of spatial information

A second important source of information underlying spatial orientation and learning are internal signals generated by whole-body movements through space. Three different information sources can be distinguished: (a) motor efferent commands in control of body movements, (b) proprioceptive signals from mechanical forces exerted on joints,

muscles and tendons, and (c) vestibular signals informing about translational and rotational accelerations of the body. There is a long tradition of research on the role of whole-body motion information in animal spatial cognition (O'Keefe & Nadel, 1978; Poucet, 1993). Gallistel (1990b) proposed a model for various animal species based on path integration (or dead reckoning) mechanisms which allow animals to return to the starting point of a trip even in the absence of exteroceptive (esp. visual) spatial information (for a review of path integration models see Maurer & Séguinot, 1995). In an unfamiliar terrain, path integration mechanisms function to construct a representation of the environment ('cognitive map'). Limitations in the precision of path integration result from the cumulation of errors over time- or space-extended movements, which can make intermittent correction by exteroceptive information sources (e.g., perceived distances and direction to landmarks) necessary. Animal models of spatial cognition stress the interplay of whole-body and exteroceptive information and often consider exteroceptive information to enrich whole-body information and not vice versa.

Research on the role of whole-body movement information in human spatial orientation and learning has intensified in the last years. This research shows that whole-body motion provides effective mechanisms for picking up, preserving and retrieving spatial information as well as integrating it to spatial knowledge. Loomis, DaSilva, Fujita and Fukusima (1992) found that blindfolded locomotor judgments (walking to a target location) following a short visual preview are more accurate than perceptual judgments (numerical estimates) manifesting the characteristic psychophysic distortions of visual space (Wagner 1985). Haber, Haber, Penningroth, Novak and Radgowski (1993) found that bodily performed direction judgments are more accurate than numerical or symbolical judgments. Other work shows that people reach a high degree of accuracy in dynamically updating distances and directions to objects while locomoting in the absence of vision (Loomis et al. 1992; Rieser, Guth, & Hill, 1986) and that whole-body information can exert facilitating as well as interfering effects on imaginal retrieval of object locations in the actual or a remote spatial surrounding (Rieser, 1989; Presson & Montello, 1994; May, 1996; Rieser, Garing, & Young, 1994).

Klatzky, Loomis, Golledge and coworkers have taken up the study of path integration abilities in humans using tasks of nonvisual path completion and path reproduction (Klatzky, Loomis, Golledge, Cicinelli, Doherty, & Pellegrino, 1990; Loomis et al. 1993; Klatzky et al., 1997). In a typical task blindfolded subjects are led along two legs of a triangle and have to return to the assumed starting point on a direct route ('homing'). Homing performances turn out to be quite accurate with systematic errors observed for different geometrical triangle layouts (angles and leg lengths). Fujita, Klatzky, Loomis, and Golledge (1993) have reported an Encoding Error Model for path completion tasks that accounts for these systematic errors by assuming erratic subjective distance and turn coding while moving along the path.

Up to now, comparatively little is known about the relative contribution and the mutual interplay of visual and whole-body coding mechanisms in more complex problems of human spatial orientation and learning (e.g., cognitive mapping on the basis of navigational experience). One way to approach this question is to isolate the

contribution of one of the information sources, as is done in research on nonvisual path integration or research comparing spatial abilities of sighted and blind people (Golledge, Klatzky, & Loomis, 1996; Sholl, 1996). While it is relatively easy to isolate the contribution of whole-body information by blindfolding subjects and depriving them of auditory and other exteroceptive information, it is much more difficult to examine the contribution of visual information in isolation. The problem is one of isolating visual sources of spatial information without bringing the navigator into the role of a passive recipient of visually displayed information (e.g., as induced by slide shows or video displays). Here, the study of behavior in interactive VEs could open up new ways of examining the separate contribution of visual coding mechanisms to spatial orientation and learning.

3 Virtual environments as a tool for research on spatial cognition

VEs are a new type of human-computer interface which allow users to interact with an egocentrically defined graphic simulation of a 3D spatial environment (for technical descriptions cf. Ellis, 1994; Kalawsky, 1993; Pimentel & Teixeira, 1993). Actor and computer system are coupled in form of a perception-action cycle, in which actions (via hand or head movements) lead to a spatiotemporally realistic updating of the actor's viewpoint in the simulated environment (via monitor or other types of displays) forming the basis for further viewpoint-dependent actions. Techniques used to display VEs are desktop monitors, projection screens or head-mounted stereoscopic displays (HMDs); actions of the navigator are realized by recording inputs to keyboards, 2- or 3-D mice, joysticks, data-gloves, or head-trackers. These input devices constitute abstract interfaces, which do not convey the whole-body motion information accompanying navigations in real world environments (Durlach & Mavor, 1995). Head-tracking techniques are a first step to convey body locomotion information, but at the current state of VE-technology usually only allow to record head- or whole-body rotations, and have to be combined with one of the other input devices to realize translational movements through simulated space.

Whole-body interfaces such as motion platforms, treadmills or bicycles are still in the phase of prototype development and testing, but could lead to interesting research perspectives in the future (Distler & Bülthoff, 1996). The lack of ready-to-use whole-body motion interfaces suggests to employ VE-technology for examining visual modes of spatial orientation and learning. Furthermore, the lack of whole-body information requires to be careful with generalizations beyond the predominantly visual definition of spatial cognition set by the current state of the technology.[2]

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[2] Limitations in the visual display of spatial information in current VE-technology go back to restrictions in horizontal field of view (mostly below 90°), reduced fidelity of displaying visual scenes, and time lags between user actions and display updating (esp. when using high-resolution displays with large fields of view). It is difficult to discuss implications of these limitations for research on spatial cognition as they will very

VEs bring different methodological advantages to the field of spatial cognition. As researchers in the field know, experiments in real world settings are very often troublesome (e.g., problems in controlling spatial pre-knowledge of the participants, problems in manipulating environmental features, problems in experimental replications or interexperimental comparisons because of differences in experimental settings). VEs can help to avoid such problems. Methodological advantages result for instance from the higher degree of freedom in constructing spaces as well as manipulating environmental variables (e.g., one can freely define scene properties, landmark positioning or the geometry of the environmental layout). There are straight-forward methods of controlling and varying the perceptual-motor factors during navigation at hand (e.g., one can define visual parameters such as field of view or movement parameters such as speed). Furthermore, there are convenient methods of online-measurement of spatial behavior (e.g., one can record trajectories during exploratory behavior or keep track of movement decisions and latencies during wayfinding).

So far, only a small number of experimental studies have used VEs to examine questions of spatial orientation and learning. Henry and Furness (1993) reported an experiment indicating deficits in building up spatial knowledge while navigating a virtual museum as compared to navigations in the corresponding real-world museum. Subjects in the simulation conditions underestimated the spatial dimensions of the rooms navigated through and were less precise (increased variable errors) in pointing to unseen object locations in other rooms. Results revealed no significant performance differences between three different display techniques used (desk-top monitor, HMD without and HMD with head-tracking).

May, Péruch and Savoyant (1995) examined goal-oriented navigations in a VE on the basis of routes learned from topographic maps. The maps depicted routes that were either aligned or 90°- or 180° misaligned; alignment refers to the spatial correspondence of upward direction in the map and goal direction in navigation space (Levine, 1982). The greater the degree of misalignment the more time was needed to find the goal and the more deviations from the requested route were observed. An analysis of the spatial distribution of stops subjects made while traveling from start to goal indicated systematic differences in memory retrieval between the different alignment conditions.

Péruch, Vercher and Gauthier (1995) examined spatial orientation performances between conditions of active exploration of space (interactive mode; self-performed movements through a VE) and two conditions of passive exploration (video and slide presentation modes; presenting the same sequences as the active conditions either unsampled 18 frames per second or sampled 1 frame each 4 seconds). Following exploration, subjects had to find target locations obstructed from sight by using the shortest possible path. Results showed that subjects in the condition of active exploration performed significantly better (higher scores and shorter completion

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much depend on the concrete context of research. Constraints set by visual display limitations are likely to relax with further technological developments in VE-technology.

times); differences between the two passive conditions were not found (similar results were obtained by Tong, Marlin, & Frost, 1995; Williams, Hutchinson, & Wickens, 1996).

Gillner and Mallot (1997) used a high-fidelity simulation of a virtual town with a hexagonal layout of streets to evaluate a view-based approach to spatial navigation. The underlying model (Schölkopf & Mallot, 1995) assumes a view-graph spatial representation, where nodes representing local views are connected by edges representing movement decisions. Subjects had to perform different online- and off-line tasks reflecting the quality of the route and survey knowledge they had acquired during navigations in the virtual town. Results partially support the local representation assumptions of their model, although their data do not entirely differentiate whether the nodes in the graph represent local scenic views or local place information. An interesting variation in Gillner and Mallot's experiment concerned the use of different viewing conditions such as navigating under day or night conditions with different degrees of occlusions by trees along the routes; degree of occlusion revealed strong impacts on wayfinding performances, but no differences between the comparable night and day conditions were found.

Recently, Ruddle, Payne and Jones (1997) reported a series of experiments on the development of spatial knowledge on the basis of navigations in a complex virtual building. One experiment aimed at replicating the experimental findings of Thorndyke & Hayes-Roth (1982) obtained in a real-world building. The overall pattern of results was quite similar between the two studies with subjects learning the environments from maps showing better Euclidean knowledge of distances and directions to unseen landmarks than subjects learning the environments from navigational exploration. Although not statistically substantiated by the authors, interexperimental comparisons revealed clear decreases in accuracy of Euclidean distance and direction knowledge of the VE navigators as compared to the real-world navigators in the Thorndyke and Hayes-Roth's study. Other experiments examined the impact of landmark availability (landmarks present vs. not) and landmark familiarity (abstract paintings vs. everyday objects) on the development of route (wayfinding errors) and survey knowledge (Euclidean estimates errors) over nine consecutive navigation sessions. Results showed that landmark availability only influenced the development of route knowledge and this only when landmarks were distinguishable everyday objects. Analysis of the development of route and survey knowledge over consecutive sessions indicated that both types of knowledge improved very much in parallel from an early stage of learning (third session) on.

In summary, this short review of recent VE studies shows that very different aspects of spatial cognition can be examined using visually simulated environments. The two studies relevant to the question of effects of missing whole-body information (Henry and Furness, 1993; Ruddle et al., 1997) hint at deficits in building up spatial knowledge on the basis of navigations in virtual as compared to real world environments. Examining spatial performances in relatively complex environments (i.e., virtual buildings) makes it difficult to determine the exact causes of such deficits. Furthermore, studies comparing real and virtual environments generally reveal similarities as well as differences. In particular, the conditions of transfer of spatial

information between real and virtual environments (or vice-versa) may vary from one experiment to the other (Bliss, Tidwell, & Guest, 1997; Kozack, Hancock, Arthur, & Chrysler, 1993; Wilson & Foreman, 1993).

The experiments reported below aim at investigating spatial knowledge acquisition in VEs. For this end we used simple VEs, which allowed to present and test well defined spatial parameters (distances and directions) and compare performances between real and virtual environments. The experiments can be considered as a first step in evaluating potential deficits in picking up and using spatial information in VEs.

4 Triangle completion experiments

The experiments to be reported here used VEs to examine triangle completion on the basis of purely visual information and compare the results to performances obtained by Loomis et al. (1993) under whole-body motion conditions (subjects blindfolded).[3] When navigating in a VE portions of the spatial environment are successively laid open; rotational movements of the virtual camera let elements appear on one side of the screen while elements on the opposite side vanish from sight. The portion of the environment seen during a time-extended journey is considerably larger than the portion visible in any of the still scenes. This raises the question of how observers are able to integrate the spatial information perceived during navigations in a visually simulated environment (Beer, 1993). The triangle completion task allows to examine this question with a behavior-based approach, letting the observer become a situatively embedded actor in a well-defined spatial task.

The central aim of our experiments was to examine the characteristics of spatial knowledge acquired during purely visual navigations in VEs. For this purpose we remodeled the nonvisual triangle completion experiment of Loomis et al. (1993, Experiment 1) in a simple VE with no task-relevant landmark information. The Encoding Error Model of Fujita et al. (1993) was used to systematically compare homing performances between visual simulation and whole-body conditions. The question was whether visually simulated navigations through space result in any systematic deficits in coding distance and direction information while moving along the pathway.

A second question asked in our experiments was whether the navigator's field of view would influence the accuracy of homing performances. Research in real world environments shows that the size of field of view can influence spatial orientation and learning performance, either due to the amount of spatial information available at a time or due to the participation of peripheral visual mechanisms (Alfano & Michel, 1990; Johansson & Börjesson, 1989; Rieser et al., 1992). Virtual environments allow to make a distinction between the absolute field of view (FOV) and the geometric field of view (FOVg). While FOV is defined by the visual angle subtended at the observer's eye, FOVg describes the portion of the entire 360° surrounding of a world model projected onto the screen at a time. Our experiments varied the FOVg and kept the

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[3] These experiments have been reported in Péruch, May, & Wartenberg (1997).

FOV constant. By this manipulation only the amount of simultaneously available spatial information was varied. The question was whether a larger amount of simultaneously available spatial information during navigation leads to improved homing performances.

4.1 Experiment 1

Method

Subjects. 10 subjects (4 male, 6 female) participated in the experiment. Ages ranged from 23 to 42 years. All subjects had normal or corrected-to-normal vision.

Experimental room. The experiment took place in a completely darkened room. The subject sat in front of a projection screen (2.05 m wide, 1.65 m high). The distance to the projection screen was 2.5 m resulting in a FOV of approximately 45° horizontal by 37° vertical. The joystick was fixed on a table in front of the subject.

Virtual environments. The rendering of VEs was based on a three-dimensional world model. The VE was made up by an arena formed by 16 homogeneous white cylinders evenly spaced on a circle. In relation to the simulated eye height of the observer (1.7 m) the circular arena appeared to have a diameter of about 60 meters. The white cylinders had a radius of 0.4 m and a height of 2 m. Inside the arena two colored cylinders were placed (r = 0.4 m, h = 1.0 m) which together with the non-marked starting point defined the triangle to be navigated (see Fig. 1). The first leg (a) of the triangle was defined by the starting point (C) and a red cylinder (A). The length of the first leg always corresponded to 20 m (2 distance units). The second leg (b) was defined by the red cylinder and a second, blue cylinder (B) while the third leg (c) was defined by the blue cylinder (B) and the non-marked starting point (C; equal to origin). The location and orientation of the triangle inside the arena were randomly chosen for each trial. Triangle geometries used (length of legs a and b and α-angle) were a subset of the triangle geometries used by Loomis et al. (1993). The variation of the geometric field of view (FOVg = 40°, 60°, 80°, see Fig. 2) was realized by the rendering software.

Subjects moved in the VE by operating a self-centering joystick, providing left/right rotation, forward (but no backward) translation, combinations of both movements, and immobilization. Translational and rotational speed were linearly coupled to joystick movement, maximum values were 3.3 m/sec (translation) and 33°/sec (rotation), respectively. Movement parameters (speed in relation to the triangle dimensions) were defined to obtain triangle completion times comparable to those in the Loomis et al. (1993) experiment. For facilitating interexperimental comparisons all distances below will be specified in terms of distance units (DU).
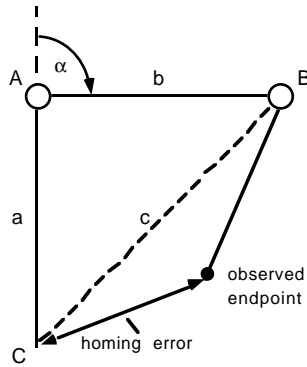
Figure 1. Triangle completion task. Starting at (C), subjects move along leg (a) until reaching the red cylinder (A). After turning an angle α they move along leg (b) until they reach the blue cylinder (B). From this point they have to return to the non-marked starting point (C). Homing error is measured as the Euclidean distance between the observed homing endpoint and the origin (equal to starting point).

Apparatus. Virtual environments were generated using a PC equipped with a 3D-vector-graphics card (Matrox SM 1281, 256 colors, 1280 x 1024 pixels). The hardware allowed for the rendering of about 10.000 Gouraud-shaded z-buffered polygons per second yielding a frame rate of about 15 frames per second. Scenes were displayed by a video-projector offering a screen resolution of 640 x 480 pixels. Joystick-data were gathered by the PC via a 12-bit analog-to-digital converter. The trajectories were recorded by the PC with a temporal resolution of approximately 10 Hz.

Procedure. Before starting the experiment the triangle completion task was explained to the subjects and they were allowed to practice on the device for about 15 minutes. The environments used for practice were not used in the experimental trials.

The experiment consisted of 27 different triangle completion tasks (3 FOVg x 9 triangle layouts) presented in random order. At the beginning of each experimental trial the subject was positioned at the starting point facing the red cylinder. Depending on FOVg-condition and the position of the triangle in the arena, a variable number of white cylinders could be visible from the starting point (see Fig. 2). The blue cylinder was always positioned to the right of the red cylinder. If it was not visible from the starting position (outside the field of view) subjects were instructed to just turn (without translation) to the right until the blue cylinder appeared and then turn back again so that they were facing the red cylinder before starting to proceed along the triangle. Subjects then first moved along the first leg a (length always 2 DU) to the position of the red cylinder (it temporarily disappeared when reached), turned to the right, and then moved to the position of the blue cylinder until it disappeared. Reaching this point, the s's task was to turn towards the assumed direction of the non-marked starting point and home to it as accurately as possible. No feedback with respect to homing accuracy was given. The next trial followed after a short pause. The entire experiment lasted about one hour.
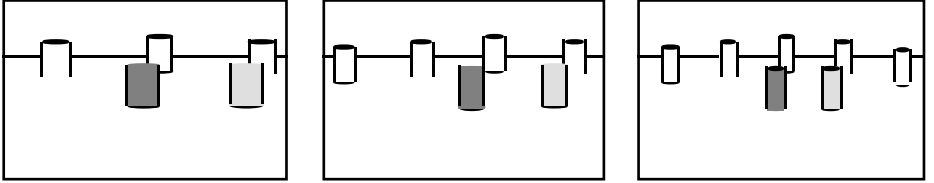
Figure 2. Geometric field of view (FOVg). Schematic drawings of spatial scenes as seen by a subject located at the starting point under different conditions of FOVg: 40° (left), 60° (center), 80° (right).

Design. The experiment made up for a 9 (triangle layout[4]) x 3 (FOVg = 40°, 60°, or 80°) within-subject design. Homing errors were defined by the Euclidean distance between observed homing endpoint and origin (see Fig. 1).

Results

Homing errors were analyzed by a repeated measures ANOVA (9 triangle layouts x 3 FOVg). A significant main effect of triangle layout was found ($p < .001$). Neither the FOVg effect ($p = .06$) nor the interaction between triangle layout and FOVg ($p = .36$) were significant. Analysis of turning angles revealed that the effect of triangle layout was mainly due to subjects generally underestimating the final turn in B (overall average = - 24° ± 1.5 (SEM)).

Discussion

The results show that triangle layout determines homing performances to a high degree. With respect to the pronounced misjudgment of the origin's direction under visual simulation conditions it could be possible that an answering bias (i.e., s's stop turning too early while making the final directional judgment) was at work. A second experiment was run in order to control for this possible answering bias.

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[4] Three angles a (60°, 90°, or 120°) crossed with three lengths of the second leg b (1, 2, or 3 DU).

4.2 Experiment 2

Method

Subjects. A new group of 8 female and 8 male subjects participated in this experiment. Ages ranged from 20 to 26 years. All subjects had normal or corrected-to-normal vision.

Experimental room, apparatus, VEs and experimental design were the same as in Experiment 1.

Procedure. The procedure was essentially the same as in Experiment 1. The only difference concerned instructions given to s's when reaching the blue cylinder (point B). Before homing to the assumed origin they were requested to turn right until the red cylinder (point A) appeared on the right side of the projection screen. From here subjects could turn back to the left again until they assumed to be facing towards the origin and subsequently move to it. This manipulation intended to exclude any systematic misjudgment of homing direction due to an answering bias as described above.

Results

A 9 (triangle layout) x 3 (FOVg) repeated measures ANOVA on homing error revealed a significant main effect of triangle layout ($p < .001$). As in Experiment 1, neither the FOVg effect ($p = .36$) nor the interaction between triangle layout and FOVg ($p = .24$) turned out to be significant. Once again subjects exhibited a clear tendency to underestimate the angle of the final turn (overall average $= -19° \pm 1.5$ (SEM)). For testing whether errors observed in the two experiments differed systematically a 2 (Experiment 1 vs. 2) x 9 (triangle layout) x 3 (FOVg) ANOVA with goal error as dependent variable was performed. The main effect of experiment was not significant ($p = 0.35$). The interaction between experiment and triangle layout was significant ($p < 0.001$) due to the fact that for $\alpha = 120°$ deviations between the experiments were smaller than for $\alpha = 60°$ or $\alpha = 90°$.

Discussion

The larger systematic homing errors under visual simulation conditions apparently do not result from an answering bias for the final directional judgment. The comparison between Experiment 1 and 2 showed that homing errors did not differ due to s's performing the final directional judgment coming from a rightward (Experiment 1) or a leftward (Experiment 2) turn. In our experiments, triangle layout seems to be the

main factor determining the observed homing behavior under visual simulation conditions.

5 Applying the Encoding-Error Model

As a first step for comparing homing performances under visual simulation and whole-body conditions the observed homing endpoints were plotted for Experiments 1 and 2 (Fig. 3, solid lines, the data were combined as no substantial differences showed up) and for whole-body conditions (Fig. 3, dashed lines, data from Loomis et al. 1993, Experiment 1), respectively. In both conditions, a systematic influence of triangle geometry on homing performance could be observed: homing errors increased with decreases in turning angle α and increases in length of leg b. However, the homing performance differed significantly between whole-body and visual simulation conditions, which is revealed by confidence ellipses overlapping only in one of the nine cases (leg b = 3 and α = 90°).
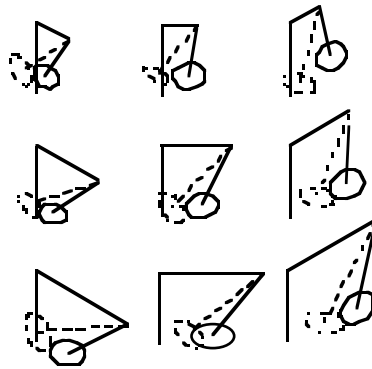
Figure 3. Two-dimensional plot of homing performances. Centroid and 95%-confidence ellipses for homing endpoints under whole-body motion conditions (dashed lines, reanalysis of data from Loomis et al. 1993) and visual simulation conditions (solid lines, data from Experiments 1 and 2 combined). Rows correspond to lengths of leg b (upper: b = 1 DU, middle: b = 2 DU, lower b = 3 DU); columns correspond to different turning angles (left: α = 120°, middle: α = 90°, right: α = 60°). Non-overlapping confidence intervals indicate significant differences between experiments (Batschelet, 1981).

Systematic homing errors observed under visual simulation conditions (solid lines) were considerably larger than those observed by Loomis et al. (1993) under whole-body conditions (dotted lines): in 8 of 9 cases the homing endpoints under visual simulation conditions were farther away from the origin than under whole-body conditions (exception: leg b = 1 DU and α = 120°). The systematic differences go back

to the s's tendency to underestimate the final turning angle in the visual simulation condition, an effect which was not observed under whole-body conditions.

To determine the potential causes of the systematic differences in homing errors observed between whole-body and visual simulation conditions, we used the Encoding Error Model (EEM) formulated by Fujita et al. (1993). The EEM was developed in order to theoretically account for systematic errors in homing during path completion tasks. The model assumes four component processes to underlie pathway completion: (i) sensing the pathway, (ii) building up a route representation, (iii) computing (and representing) the desired trajectory back to the origin, and (iv) executing the homeward trajectory. According to the EEM, sensing the pathway (i.e., coding distance and turn information while moving along the pathway) is the only determinant of homing errors. While homing in a triangle, navigators have the impression of correctly completing it, as they do not notice errors arising from erratic coding of distance and turn information during locomotion. Mathematically the EEM is specified by four axioms. (1) The internal representation satisfies the Euclidean axioms. (2) The length of a straight line segment is internally coded by a function $d_{subj} = f(d_{obj})$. (3) The value of a turning angle is internally coded by a function $t_{subj} = g(t_{obj})$. (4) There is no systematic error in either computing nor executing the homeward trajectory. Calculating back from the observed homing performances, the model leads to separate distance and turn coding functions. Thus, the EEM allows to reduce the observed complex pattern of homing behavior to two psychophysical coding functions, one for distance and one for turn information.

We applied the model to the combined data from Experiment 1 and 2 and reanalyzed the raw data of Loomis et al. (1993) on the basis of the subset of the nine triangle layouts we chose from their total set of 27 triangles. In applying the model to the triangle completion data three steps can be distinguished: (1) Calculating the subjective coding of the three distances (b = 1, 2, 3 DU) and turning angles (α = 60°, 90°, 120°) by fitting hypothetical coded values to the observed data using the least squares method. (2) Determining the goodness of fit (R^2) between actual and model fitted data over the total set of triangles. (3) Describing hypothetical distance and turn coding functions underlying the observed homing behavior.[5]

Step 1. The subjectively coded values for the three lengths of leg b (b=1, 2, 3 DU) and the three turning angles (α = 60°, 90°, 120°) are plotted in Figures 4 (a) and (b). For the visual simulation data (Experiment 1 and 2) the subjective distance coding values obtained by least squares fitting were 1.2 DU, 1.9 DU, and 2.4 DU, while the coded turning angle values were 113°, 120°, and 132°. The reanalysis of Loomis et al. (1993) data yielded values of 1.1 DU, 1.6 DU, and 2.3 DU for distance coding and 75°, 89°, and 102° for turn coding, respectively.

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[5] We used the EEM only as a tool to describe the observed homing performances. It was not our intention to test any of the theoretical assumptions formulated by the model.
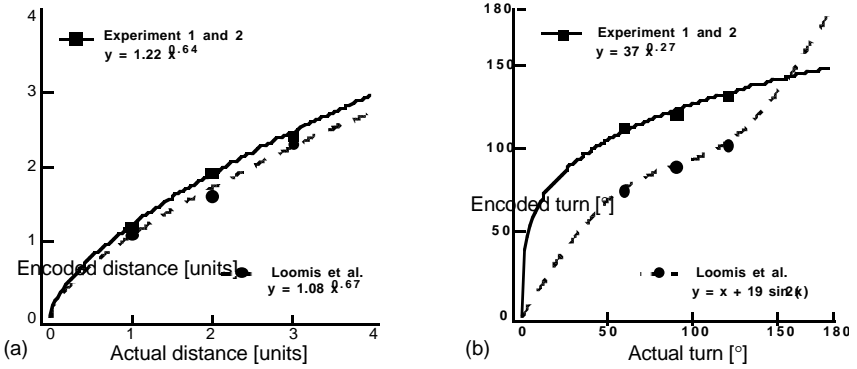
Figure 4. Hypothetical coding functions for (a) distances and (b) turns under conditions of whole-body motion (dashed lines; data from Loomis et al.) and visual simulation (solid lines; combined data from Experiment 1 and 2) (from Péruch, May, & Wartenberg, 1997).

Step 2. Figure 5 shows the homing performances as predicted by the EEM and the observed values for visual simulation and whole-body conditions. The small deviations between predicted and observed values indicate a good fit of the model-derived subjective distance and turn codings for all nine triangles. Correlations between observed and predicted homing errors reveal that the model fit in case of distance coding accounts for 89% of the variance (R2) under visual simulation conditions and for 94% under whole-body conditions. In the case of turn coding the respective values are 93% for visual simulation conditions and 95% for whole-body conditions. These values are comparable in size to those reported by Fujita et al. (1993) on the basis of the total set of 27 triangles.
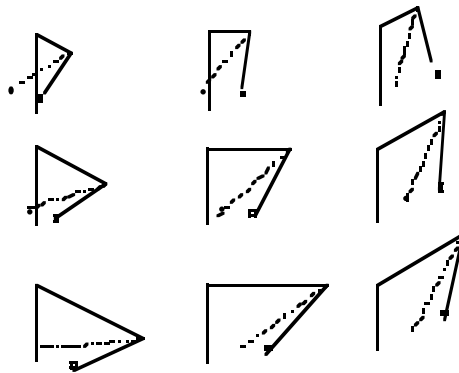
Figure 5. Observed and EEM-predicted homing endpoints. Whole-body motion endpoints (data from Loomis et al., 1993) are shown as dashed lines, model predictions as circles. Visual simulation endpoints (data from Experiment 1 and 2) are shown as solid lines, model predictions as squares.

Step 3. In order to achieve a more general description of the subjects' homing behavior under visual simulation and whole-body conditions we additionally assumed that objective nil movements (zero translations and rotations) are subjectively coded as nil movements.[6] On the basis of this additional assumption and the subjective values obtained in step 1 the coding of distance information under visual simulation and whole-body conditions can be adequately described by power-functions; i.e., relatively small distances are slightly overestimated and the larger distances become, the more they tend to be underestimated. As can be seen in Figure 4a, the coding functions for visual simulation ($y = 1.2 x^{0.64}$) and whole-body conditions ($y = 1.1 x^{0.67}$) only show marginal differences.

With respect to turn coding under whole-body conditions results reported in the literature indicate that people are quite accurate at judging the amount of whole-body turns over a wide range of angles (Klatzky et al., 1990). Assuming an additional value ($180°$ is coded as $180°$) the subjective turn codings obtained in step 1 (see Fig. 4b) can be described by a function ($y = x + 19 \sin 2x$) oscillating around the function for perfectly correct coding ($y = x$). For the visual simulation experiments the coded values are well described by a power-function ($y = 37 x^{0.27}$).[7]

The complex pattern of systematic homing errors found in the different experiments can be consistently accounted for by applying the EEM (Fujita et al., 1993). Coding of distance information under visual simulation as well as under whole-body conditions could be described by similar power functions indicating that differences in distance coding between both modes of navigation were negligible. The observed systematic differences in homing behavior between visual simulation and whole-body conditions seem to go back to pronounced differences in coding turns during locomotion. That these differences indeed are of a systematic nature is indicated by the EEM accounting for about 90% of the variance for whole-body as well as for visual simulation data. Whereas the whole-body movement data (Loomis et al., 1993) can be adequately described by a function oscillating around the correct values (with subjective values in the middle range distorted towards $90°$; $60°$ is coded as $72°$; $120°$ is coded as $102°$), visual simulation data appear to be best described by a power function. Participants under visual simulation conditions showed a strong overestimation of the small turns ($60°$ is coded as $112°$) which diminishes for larger turns ($120°$ is coded as $132°$) and might change to underestimations for larger angles as data from a further experiment suggest (see footnote 7).

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[6] In contrast to Fujita et al. (1993), we assume nonlinear distance and direction coding functions. Reasons for our preference of nonlinear coding functions lie in the additional assumptions made here.

[7] Independent support for such a function comes from a third experiment not reported here. Using the same VE, subjects were requested to turn into the direction of the assumed starting point after completing the first leg (i.e., reaching the red cylinder). While the required turn was $180°$, averaging the observed turns yielded $150.4° \pm 0.9°$ (SE), corresponding to an underestimation of about $30°$; this is what is to be expected according to the described power function (see Fig. 4 b; dashed line).

6 General Discussion

The experiments reported here aimed at examining triangle completion on the basis of purely visual information and comparing the observed performances to triangle completion under whole-body conditions. It was found that errors in triangle completion were systematically larger for navigators in the VE than for subjects performing the task under whole-body motion conditions (Loomis et al., 1993). Applying the EEM (Fujita et al., 1993) to the data of the different experiments leads to a consistent picture, according to which differences in homing accuracy between whole-body and visual simulation conditions go back to systematic deficits in picking up information about turns under conditions of visually simulated navigations; differences in distance coding between both modes of navigation were negligible. This pattern of results was independent of the final turning direction before homing (Experiment 1 vs. 2) as well as independent of the FOVg (40°, 60°, 80°) realized.

That amount of simultaneously available spatial information during navigation (FOVg) had no substantial influence on the accuracy of homing behavior could be due to the fact that our VEs did not provide enough distinctive visual features (e.g., landmarks) for the variation of FOVg to become effective. A recent study of Neale (1996), in which subjects navigated in a visually richer VE (an office building) than the one used here, indicates that FOVg can indeed exert effects on perception (judging room sizes) and memory (distance estimates) of spatial environments. Research in real world environments leaves open the question whether the amount of simultaneously available spatial information or the exclusion of peripheral visual mechanisms is the determining factor causing decreases in spatial learning performances when the field of view is restricted (Alfano & Michel, 1990; Rieser et al., 1992). Virtual environments could be used for further examinations of this question as they allow for independent variation of FOV and FOVg.

The most important result of the experiments reported here are the systematic deficits found in coding directional information while moving along a path. Research on path-integration has shown that elementary errors in turn coding accumulate over multisegment paths when corrective azimuthal cues (e.g., sun) are missing (Benhamou, Sauvé, & Bovet, 1990). Errors in coding of turns of the magnitudes found in our visual simulation experiments are likely to lead to problems of disorientation and deficits in developing spatial knowledge over extended journeys in more complex environments. The turn coding functions reported here imply that navigators who can make use of whole-body movement information (real-world environment) should be at a considerable advantage compared to navigators who have to exclusively rely on visually simulated information as given in our realization.

7 Conclusions

Taken together, the experimental results reported here indicate that whole-body movement information (vestibular and proprioceptive signals, motor efferent

commands) could be a decisive factor in picking up directional information correctly while navigating through space. This does not mean that spatial orientation on the basis of purely visual information is impossible, as for instance the experimental work reviewed earlier in this chapter shows. It rather points to the fact that different sources of information (visual and whole-body) contribute to spatial orientation. VEs have an interesting potential to disentangle the relative contributions of these different information sources, not only as VEs allow to completely isolate visual information from whole-body information - as was the case in our experiments - but also as they allow to vary the amount of whole-body information available by comparing spatial performances in VEs using different interfaces to body movements, as Henry & Furness (1993) for instance do when comparing spatial performance in VEs with head tracking vs. spaceball control. Furthermore, VE technology offers the possibility to investigate the contribution of the various types of visual information to spatial orientation by controlled variation of visual spatial information like FOVg - as done in our experiments - , binocular disparity, or richness of spatial structure (Liu, Tharp, French, Lai, & Stark, 1993; Ruddle et al., 1997; Gillner & Mallot, 1997). The triangle completion paradigm has proved to be well suited to analyze and disentangle the uptake of elementary spatial information about distances and directions. However, for research focusing on more complex forms of spatial knowledge, experiments with more complex pathways in visually enriched, cluttered environments will be needed. In the context of the questions discussed above such research could help to clarify how the structure of more complex spatial knowledge is affected by the interplay of whole-body and visual information.

Acknowledgments

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