Spatial Cognition and Computation **2:** 333–354, 2000.

Place learning in humans: The role of distance and direction information

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Received 5 July 2001; accepted 29 January 2002

Abstract. Although the process of establishing a memory of a location is necessary for navigation, relatively little is known about the information that humans use when forming place memories. We examined the relative importance of distance and angular information about landmarks in place learning. Participants repeatedly learned a target location in relation to three distinct landmarks in an immersive computer-generated (virtual) environment. Later, during testing, they attempted to return to that location. The configurations of landmarks used during testing were altered from those participants learned in order to separate the effects of metric distance information and information about inter-landmark angles. In general, participants showed greater reliance on distance information than angular information. This reliance was affected by nonmetric relationships present during learning, as well as by the degree to which the learned environment contained right or straight angles.

Key words: landmarks, landmark-based navigation, place learning, virtual environments, virtual reality

1. Introduction

Many common spatial tasks in large-scale environments require people to use landmarks in order to establish a memory of their location (a place memory). For example, a new visitor to a city may establish a place memory of her hotel by learning the spatial relationships between it and several prominent nearby landmarks. This place memory will allow her to recognize her hotel when she is in its vicinity, and it can be used to guide navigation back to it from distant places (a process known as *piloting* or *landmark-based navigation*). In this paper, we investigate human place learning, focusing on the relative importance of distance and angular information in remembering locations. For instance, in the example given above, our traveler can remember her hotel's location in terms of its distances to nearby landmarks or in terms of the relative directions in which those landmarks lie (we often refer to these relative directions as *bearing differences*), or both. We are concerned with understanding the degree to which – and the circumstances under which – these two kinds of information are typically used.

The study of place learning and landmark-based navigation in animals has received a great deal of attention in the psychological and biological literature. It has long been observed, for example, that birds such as Clark's nutcrackers are able to find thousands of seed caches months after having buried seeds in them. The birds' ability to do this likely requires them to store spatial information that is provided by distant landmarks visible at each burial site (Gallistel 1990). Experimental evidence has shown that these birds are sensitive to the geometric properties of landmark arrangements and are able to use both distance and directional information effectively in finding hidden seeds (Kamil and Jones 2000). In these experimental settings, it is common for investigators to manipulate properties of landmarks or their geometrical relationships in order to determine those elements of the landmark array that exert stimulus control over performance and, by assumption, are encoded in memory. For example, Morris (1981) developed a place learning paradigm for rodents that requires rats to find a previously learned location in a pool of opaque water. By manipulating the degree to which the rats were allowed landmark information, Morris found that rats are able to use distal landmarks to guide navigation to an unseen target location. Subsequent research has gone on to show that while rodents are able to use information about landmark identity, they may principally rely on information about the geometric properties of the landmark arrangement (Benhamou and Poucet 1998; Collett et al. 1986; Greene and Cook 1997; Maurer and Derivaz 2001).

Recently, several experiments on humans using a computer-simulation of Morris' paradigm have begun to examine place learning and landmark use in humans. These experiments have examined the validity of predictions derived from theories of cognitive mapping (Hamilton and Sutherland 1999; Jacobs et al. 1997; Jacobs et al. 1998; see also Thomas et al. 2001) and have begun to address the influence of distance information on place learning (Gaunet and Loomis 1999). Recent experiments have also examined the influence of gender on place learning ability (Astur et al. 1998) and on cue usage (Sandstrom et al. 1998). Collectively, these experiments have shown that place learning in humans can occur readily in computer-simulated environments and that such learning follows many of the principles of place learning in animals. Computer-simulated, or "virtual" environments (VE's) offer a valuable tool for research of this type because they allow investigators much greater control over stimulus characteristics than they might have in the real world. Repositioning real-world landmarks can be difficult or impossible; however, it is very simple in VE's. VE's also allow investigators interested in human piloting to control or eliminate information acquired by other navigational mechanisms, such as path integration (i.e., keeping track of one's position and orientation based on sensed self-motion).

1.1. *Information available from an array of landmarks*

An array of landmarks provides several distinct sources of information that can aid a person in forming a mental representation of a place. Consider the type of place to be learned that we use in the present paper: an environment consisting of three distinct, radially symmetric landmarks, and a target location within the triangle formed by the three landmarks (see Figure 1). What information is available to a ground-based observer positioned at the target location? Because the landmarks are distinct (in our case they have different colors), non-spatial information about landmark identity is available. In general, we assume that people remember and use this information. More interesting for our purposes are the two classes of spatial information – nonmetric and metric – which we now briefly discuss.

Nonmetric spatial information relates to those spatial relationships that do not require the concept of congruence for their definition (see Gallistel 1990). Such relationships include topological or projective relationships such as concurrence, betweeness, and adjacency, as well as "sense" relationships such as left/right or clockwise/counterclockwise. Several experiments have investigated the role of nonmetric relationships such as adjacency in human place learning. For example, Hermer and Spelke (1996) adapted an animal learning paradigm from Cheng (1986) and asked people to search for a target that had been hidden in a one corner of an empty rectangular room. The room had either three or four walls uniformly colored white. Hermer and Spelke found that adults were consistently able to find the target if one wall of the room was distinguished from the others in color. Presumably, people used the adjacency relationship between two differently colored walls to remember the position of the target. Similarly, Jacobs et al. (1998) used a computer-simulation of the Morris (1981) paradigm and found that altering the adjacency relationships between landmarks (walls) from those that were learned severely impaired landmark-based navigation performance in adults. In the present paper we look at a similar nonmetric relationship that we call *enclosure*, and examine its influence on place learning in relation to the metric properties discussed below. We define enclosure as the state of being surrounded or contained within a number of landmarks (Note that, although one could consider various degrees of enclosure, here we treat it as an "all-or-none" concept). For example, in Figure 1, the target location is enclosed by the three landmarks. More formally, a location is enclosed by a set of landmarks if and only if it lies within their convex hull. In our experiment,

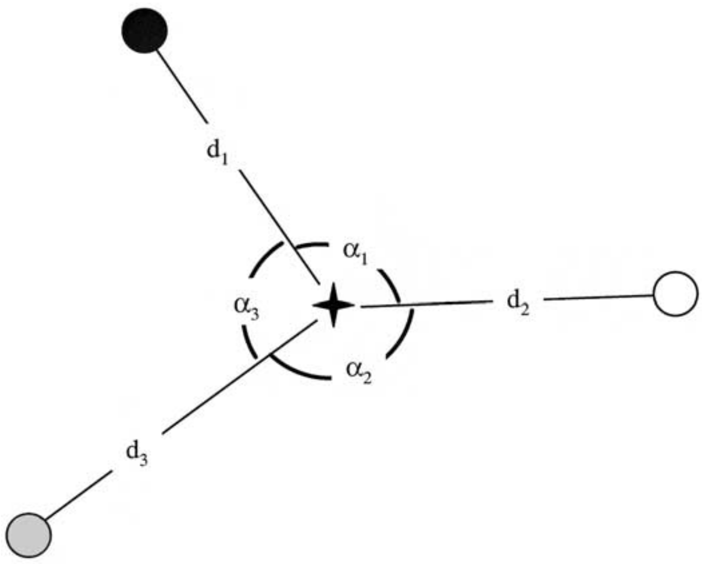

Figure 1. A schematic bird's-eye view of the environments learned in the present experiment. Participants walked to a target location (star) and learned their location relative to three distinctive landmarks (circles). Metric information available to the participants at the target location includes information about the distances between the target and the landmarks (d_1, d_2, and d_3) and information about the bearing differences to each of the landmarks (α_1, α_2, α_3).

following Morris' (1981) paradigm, participants learn the position of a target location that is enclosed by a configuration of distal landmarks. They are then tested by seeing the (slightly-altered) configuration from another point of view and then being asked to return to the location of the now-missing target. On some of these test trials, information about the target's enclosure by the landmark array conflicts with information about metric distances. Participants' behavior during these trials can inform us about the degree to which the memory of being enclosed by the landmark array dominates the metric relationships discussed below.

The second class of information available from a landmark array is metric information, which concerns those quantitative spatial relationships that require the concept of congruence for their definition. These relationships include the relative distances from the viewing location to the other landmarks, and the angles (bearing differences) formed by the viewing location and pairs of landmarks (see Figure 1). The relative use of these two information sources in human place learning is unknown, and is the major focus of the present investigation. Most of the literature on the subject seems to suggest that distance information is less important or reliable. Computer and animal models of piloting behavior typically neglect distance information, and focus exclusively on the use of absolute bearings or bearing differences (Benhamou and Poucet 1996; Cartwright and Collett 1983; Thompson et al. 2000). The justification for doing so may be based on the limited empirical results. For example, Cartwright and Collett (1983) trained bees to learn the location of a food source in relation to three surrounding landmarks. By varying the size of the landmarks or their geometrical arrangement, the authors were able to show that bees use primarily the bearing differences between landmarks – as opposed to the distances from the target to the landmarks – to guide their navigation. While there is evidence that animals can use distance information from landmarks, it is generally thought to be of secondary importance and used, for example, when other information sources provide ambiguous information (Kamil and Jones 2000; Spetch et al. 1997).

In humans, however, it is possible that distance information is more critical to place learning. Spetch et al. (1997) provided an illustration that humans may be sensitive to relative metric distances when they learn locations. These researchers asked people to find an object in a large grassy field that had been hidden near the center of an array of four landmarks. During learning, these four landmarks formed a square. After learning the location of the object, people were tested in a variation of the array that had been expanded in only one dimension to twice its original extent, having now become an elongated rectangle. Rather than search in locations that preserved the absolute distances to some of the landmarks, people (unlike pigeons) uniformly searched in the center of the new array. Although the center of the rectangular array was further from each of the landmarks than the target had been during learning, it was, as in the square array, equidistant from them. The center of the rectangle was thus the location that preserved relative distances to the landmarks. Note that choosing the center of a rectangle as the target location did not preserve the bearing differences to the landmarks that were present during learning. One hypothesis that explains participants' behavior in this experiment is that they were able to disregard the information about bearing differences and respond on the basis of relative distances. However, given Spetch et al.'s stimuli, it was not possible for participants to preserve angular information even if they had wanted to. In the present study, we offer a more direct test of the degree to which distance and angular information is used in place learning.

1.2. *Constraints on viewpoint location provided by various types of spatial information*

To provide a further basis for the experiment that follows, we undertake a geometrical analysis of the relative influence of distance and angular information for determining the accuracy with which an observer can determine his or her location. We do this by examining the constraints that different kinds of spatial information place on the location of the viewpoint. The question we address is “Where could a person’s viewpoint be if his or her coding of either distance or angular information is imprecise?” In other words, how much do different sources of information contribute to defining the location of the viewpoint? For example, nonmetric information about the order and adjacency relations between a pair of landmarks is useful for place learning, because it constrains the possible locations of the viewpoint to lie on one side of the line that connects the landmarks (Levitt and Lawton 1990; Thompson et al. 2000). Similarly, knowledge about enclosure constrains the viewpoint to lie within the area so enclosed. In the remainder of this introduction, we analyze the constraints placed on viewpoint locations by metric distance and angular information. We do this by examining the effect of locational uncertainty as a joint function of error in encoding relative distances and bearing differences (angles).

Before considering the joint effects of angular and distance encoding error, it is instructive to consider the effect of each independently. We start with distance. The locus of points on a plane that are a constant distance from a landmark define a circle around the landmark. Thus, error or imprecision in the coding of the distance to a single landmark results in possible viewpoint locations that lie within an annulus centered on the landmark (see Figure 2). If there are several landmarks in the environment, each will imply its own annulus of locational uncertainty. Intersections of annuli thus describe locational uncertainty due to errors in representing distances to more than one landmark.[1] A large body of empirical evidence has shown that imprecision in distance estimation increases (roughly linearly) with the distance to be estimated (for a review, see Wiest and Bell 1985). Thus, in what follows, we express distance estimation errors as percentages of the distance to be estimated.

Consider now the effects on locational uncertainty of error in the coding of bearing differences. The locus of points on a plane that maintain a constant bearing difference between two landmark locations define an arc with endpoints that approach each landmark location. Thus, error or imprecision in the coding of the angle between two landmarks results in location estimations that lie within a crescent having the landmarks at its cusps (see Figure 2).[2] Intersections of crescents thus describe locational uncertainty due to errors in representing bearing differences between more than two landmarks. Sutherland (1994) provided a detailed account of many of the variables (e.g., number of landmarks, enclosure of the viewpoint by the landmarks, geometrical arrangement of landmarks) that influence the degree

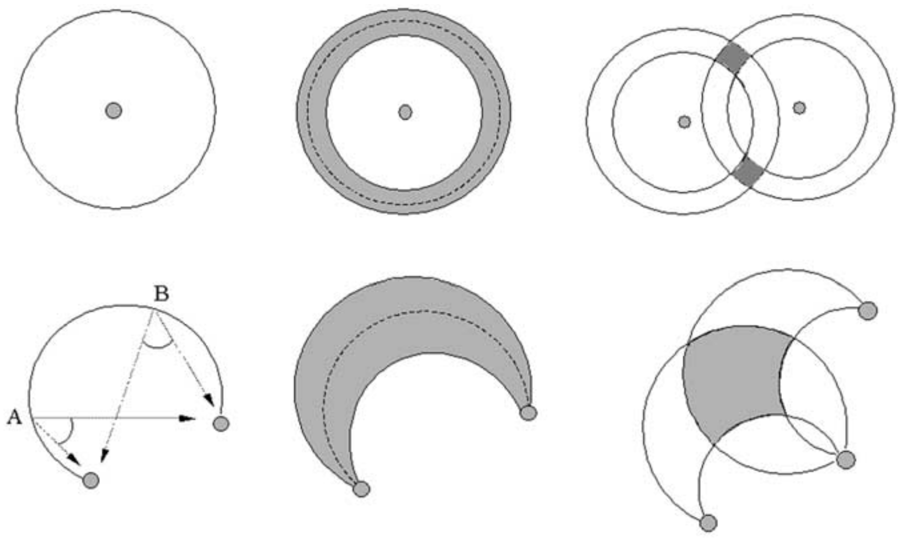

Figure 2. Constraints placed on the two-dimensional location of the viewpoint based on distance information and angular information. Top: If distance from a landmark (small circle) is known, then the viewpoint must lie somewhere on a circle centered on the landmark (top left). If distance is uncertain (top center) the viewpoint lies somewhere within an annulus. When distance to two landmarks is uncertain (top right), the viewpoint must lie within the gray space defined by the intersection of two annuli. Recalling the left-right ordering of the landmarks further constrains the viewpoint to lie within only one of the shaded regions. Bottom: If relative bearings to two landmarks are known (and their left-right order is recalled), then the viewpoint must lie somewhere on an arc (bottom left). Any two points on this arc (e.g., A and B) thus have the same bearing difference to the landmarks. Uncertainty in relative bearings thus constrains the viewpoint to lie within a crescent (bottom center). When bearing differences to two landmarks are uncertain (bottom right), the viewpoint must lie within the gray space defined by the intersection of two crescents.

to which imprecision in determining relative bearings affects uncertainty in location.

Various amounts of distance uncertainty and angular uncertainty together yield location estimations that lie within intersections of various sizes of annuli and crescents. A sample landmark configuration and its associated regions of uncertainty based on relatively low and high distance encoding error and relatively low and high angular encoding error are shown in Figure 3. Clearly, for different landmark configurations, and for different amounts of distance and angular encoding errors, the area and shape of the regions in Figure 3 varies. To begin to assess these relationships, Figure 4 plots the (logarithm of the) area of the region of locational uncertainty as a function of five levels of error in encoding distances and five levels of error with angular encoding. These values are averaged over the 20 landmark configurations used in the present experiment. The levels of distance and angular encoding error were chosen to span a wide range of possible values, almost certainly encompassing those that represent people's ability to learn places. It is clear from Figure 4 that uncertainty about one's location increases as one's ability to remember either distances to landmarks or the angles formed by them decreases. Perhaps more interestingly, the figure suggests that imprecision about distance information may exert a stronger effect on estimations of location than imprecision in coding angular relationships. For example, a person who uses distances relatively accurately, within 5%, will be able to pinpoint his or her location with little uncertainty, regardless of how error-prone his or her angular information is. The converse, however, does not appear to be as true. The use of relatively accurate angular information (within 5 degrees of the true value) may still yield relatively large uncertainty in location if distances are not also used accurately. Statistical analyses on these data confirm this observation. When locational uncertainty is modeled in a 5 (distance) $\times$ 5 (angle) repeated measures random-effects ANOVA model, effect sizes (eta-squared) for distance uncertainty is larger (0.997) than that for angular uncertainty (0.990). We conclude thus that for accurate localization to occur in these environments, it is more beneficial for an agent to code relative distance accurately than bearing differences to landmarks.

Although distance information may be, in general, more helpful for coding one's location in these environments, it is certainly true that angular information may be quite helpful in special cases. Consider the situation when two landmarks are separated by 180 degrees from the to-be-learned location. In this case, the learning location is collinear with two of the landmarks. Such a simple geometric figure – a line – may be particularly easy to encode in memory. Pick et al. (1995) have noted that in natural spaces, people commonly determine their location from an external representation (i.e., a map) by looking for landmarks that are collinear with the viewpoint. Linear landmark arrangements thus seem particularly easy to remember and use. It is also possible that 90-degree angles, which are extremely well-learned and represented by body axes, are similarly easy to represent. For example, Franklin and Tversky (1990) have shown that people's mental models of space can be organized in terms of their three orthogonal body axes. In the same vein, Huttenlocher et al. (1991) have shown that biases in estimations of exocentric locations can be well-described by assuming that people divide the space into four equal quadrants. In the present experiment, we examine the saliency of configurations containing right angles and straight lines, by manipulating the amount of *orthogonality* present in the learning configurations. We define orthogonality as the number of bearing differences between adjacent landmarks that are right or straight angles. If there is a bias to use

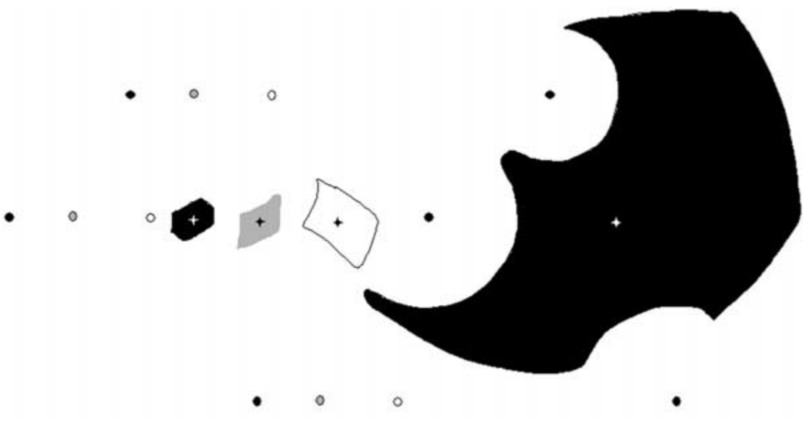

Figure 3. Four regions of uncertainty based on the same configuration of three landmarks (circles), two values of distance uncertainty (10% and 50%) and two values of angular uncertainty (10 degrees and 80 degrees). For each region, the true location of the viewpoint is represented by a star. Because of uncertainty in the knowledge of the distances to the three landmarks and uncertainty in the knowledge of their relative bearings, the viewpoint may lie anywhere within the regions shown. Left: The small black region is the possible location of the viewpoint based on 10% distance uncertainty and 10 degrees of angular uncertainty to the three black landmarks (circles) Center-left: The gray region is the possible location of the viewpoint based on 10% distance uncertainty and 80 degrees of angular uncertainty to the three gray landmarks. Center-right: The white region is based on a distance uncertainty of 50% and 10 degrees of angular uncertainty to the white landmarks. Right: The large black region is based on 50% distance uncertainty and 80 degrees of angular uncertainty.

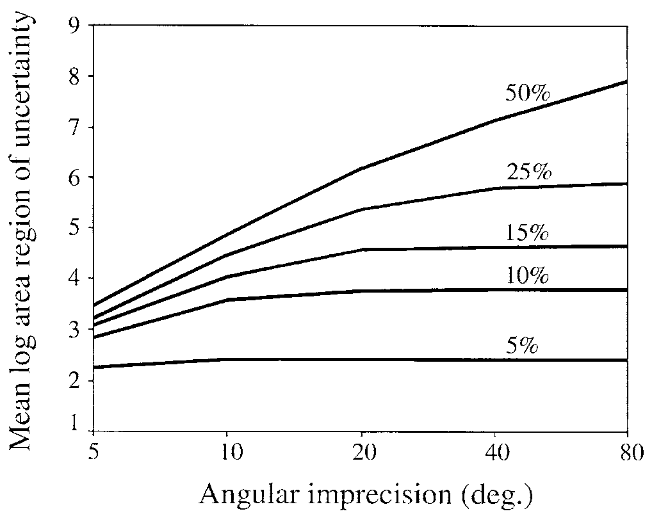

Figure 4. Logarithm of the area of the region of uncertainty for various levels of distance and angular uncertainty, averaged over the 20 landmark configurations used in the present experiment.

either distance or angular information when people form place memories, such a bias may be affected by the orthogonality of the learning environment.

In this experiment, participants learned several locations, each relative to a different configuration of three distinctive landmarks. They were then tested in an altered configuration of the landmarks. Alterations were made such that one location in the testing configuration preserved distance information and one location preserved information about bearing differences (see Figure 5). The participants' behavior in the altered configurations allow us to make inferences about the degree to which distance information is preferentially used over angular information. The design of the stimuli also allow us to draw conclusions about the degree to which orthogonality and the nonmetric relationship of enclosure may affect this preference.

2. Method

2.1. *Participants*

Nineteen undergraduate students (7 men and 12 women) from the University of California in Santa Barbara participated in the experiment in return for course credit in their introductory Psychology class. Mean age of the participants was 18.4 years (SD = 1.1).

2.2. *Materials and apparatus*

Twelve experimental stimuli (inspired by Cartwright and Collett 1983; see also Maurer and Derivaz 2001) were designed to separate the influence of distance and angular information and to examine the effects of orthogonality and the nonmetric relationship of enclosure. Each stimulus consisted of a pair of configurations: a learning configuration, consisting of a target location surrounded by three landmarks, and a testing configuration, that contained only the three landmarks. In each learning configuration, the modeled distance between the target and the three landmarks varied between two and seven meters. Inter-landmark bearing differences ranged from 59 to 180 degrees. Each testing configuration was an altered version of its corresponding learning configuration. Alterations were made such that one location in the testing configuration, D, maintained identical distance relationships as were in the learning configuration. Specifically, the three distances from D to each of the three landmarks were the same as the three distances from the target to the three landmarks in the learning configuration. Another point, A, maintained the same inter-landmark bearing differences that were present during learning (see Figure 5). D and A were also constrained to be equidistant from the center of the explorable space used by the participants.

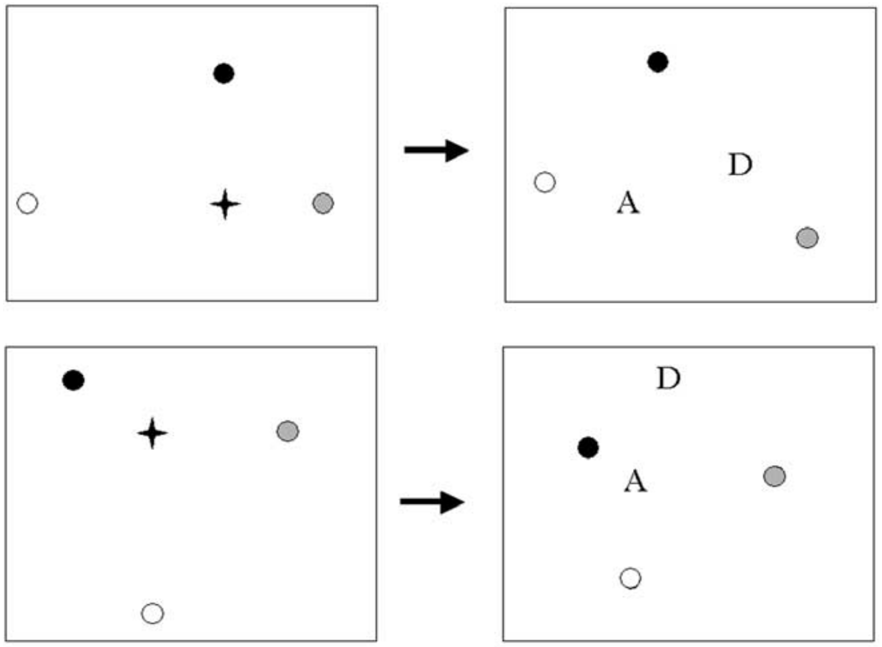

Figure 5. Two sample sets of learning and testing configurations used in the present experiment. Two different learning environments are shown on the left, with their corresponding testing environments on the right. (Unlike in the experiment reported, testing configurations are shown here rotated into alignment with the learning configuration.) Participants learned a target location (star) in relation to three distinct landmarks (circles) and then were tested on an altered version of the landmark configuration (right). Alterations were made such that one location, D, maintained the same target-to-landmark distances as in the learning configuration. Another location, A, preserved the same target-to-landmark bearing differences. Top: The learning environment contains three right or straight angles. Bottom: D is not enclosed by the landmark configuration. The present experiment varied the degree to which right angles were present during learning and the degree to which D was enclosed by the landmark array during testing.

Two factors were systematically varied in the construction of these stimuli: orthogonality and enclosure. Orthogonality was defined as the number of right or 180° bearing differences in the learning configuration (0, 1, or 3). Enclosure was defined as whether D was located inside or outside the landmark configuration. The combination of these two factors yields six possible stimulus types, and two such sets of six were created. The appendix presents the coordinates of the landmark and target locations for each of the twelve experimental stimuli.

Eight additional configurations were also constructed and used as foils. In these trials, the testing configuration was a rigid rotation (about the center of the explorable space) of the learning configuration. During the experiment,

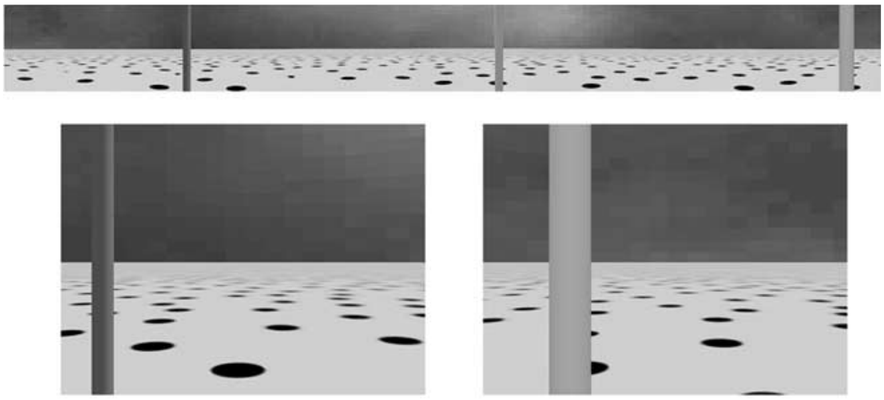

Figure 6. Top: Panoramic 360-degree image of one of the learning environments. Three distinct landmarks are located at various distances and directions from the viewpoint. Bottom: Two views of how this environment appeared to participants in the head-mounted display.

these foils were interspersed with the experimental trials in order to minimize the chance of participants thinking that the learning and testing environments were different.

3-D models of 3.64 m (0.12 m radii) cylinders colored red, green, and blue were constructed and used as landmarks in an immersive VE. A fourth black cylinder was also used during learning to mark the learning location. Each cylinder extended to twice the eyeheight of the simulated viewpoint (1.82 m). The ground and sky of the VE were textured in low-resolution polka-dot and blue bitmaps, respectively (see Figure 6). These textures were randomly rotated between the learning and testing phases of the experiment in order to eliminate any locational or directional information that their patterns might provide. Participants were instructed of this, and advised not to rely on locational information derived from the ground and sky of the VE.

Participants interacted with the VE in a V8 head-mounted display (HMD) from Virtual Research. This HMD provided 640 × 480 stereoscopic images with a 48-degree horizontal field of view. Users moved through the environment by physically walking in a large (6m × 6m) laboratory room. Their 2-D position in this room was tracked with a passive video tracking system, accurate for distances greater than one mm (see Beall et al. 2001). Head orientation (yaw and pitch) was tracked with an Intersense IS-300 inertial tracker mounted to the HMD. Position and orientation information were processed by the rendering computer, a Pentium III using an Evans and Sutherland Tornado 3000 graphics card, which updated the graphics for each eye at a rate of approximately 24 frames per second.

Randomization and presentation of the stimuli as well as the recording of the participants' position and orientation were controlled through a scripting facility in the Python programming language, supplemented with a utility module written specifically for virtual environment applications (see Beall et al. 2001).

2.3. *Procedure*

Participants were run individually through 14 trials (one set of six experimental trials plus the eight foils), each of which presented a different landmark configuration. Each trial began with a learning phase that was followed immediately by a testing phase. Trials 5, 7, 9, 11, 13, and 14 presented one set of the experimental stimuli in an order that was randomized for each participant. On these trials, described above, the testing configuration was an alteration of the learning configuration. The first two trials were practice trials, and no data were collected from them.

At the beginning of the learning phase, the participant entered the environment from a fixed starting point in the laboratory. The participant walked directly to the target black post. When he or she had walked within 0.15m of the target, a tone sounded, and the computer moved the viewpoint to the exact location of the target and disabled viewpoint translation. Participants then spent as much time as they wanted looking around and learning their location. They then pressed a button to clear the screen and begin the testing phase.

For testing, participants again entered the environment from the same fixed starting point in the laboratory. Prior to this, the landmark configuration had been either rotated (foils) or altered and rotated (experimental trials) (Rotating each testing configuration ensured that the target was not in the same physical location in the laboratory as during learning, forcing participants to use the target-to-landmark relationships to perform the task). Participants were told that they were viewing from another place the same configuration of landmarks that they had just learned. They were asked to determine where their previous viewing location had been and were asked to face toward it. The orientation of the participants' head was recorded as they pressed a button while looking in the direction that they believed the target to be. After their initial heading estimation was recorded, participants were asked to move to the location of the missing target. Participants' position and orientation during this task were measured every 250 milliseconds. Participants pressed the button when they felt that they were at the proper location and their position was recorded. They then returned to the starting point to begin a new trial.

At the completion of all of the trials, participants were asked whether they thought that any of the testing configurations had been different from what they had learned.

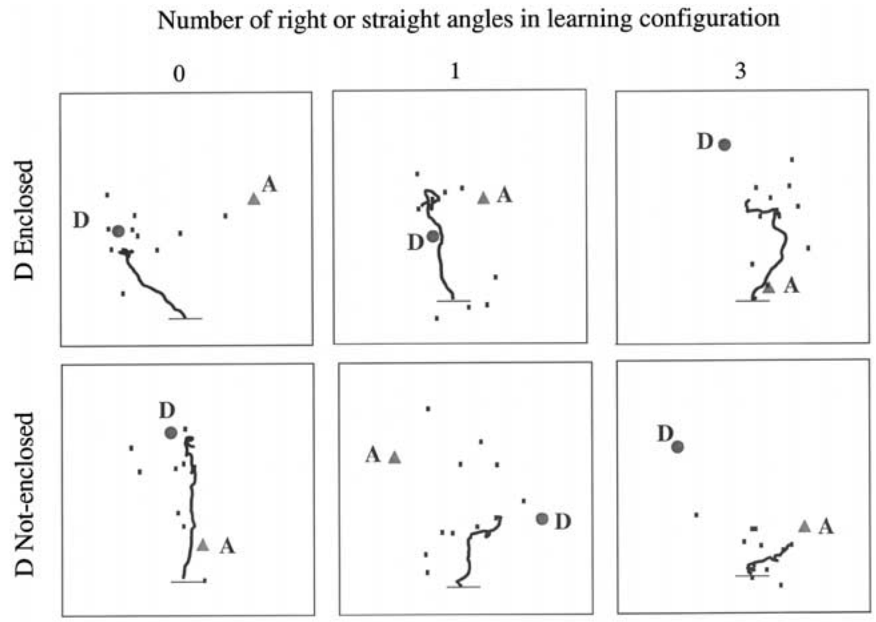

Figure 7. Representative trajectories from one of the participants in each of the orthogonality and enclosure conditions. Stopping points for the other participants who learned these environments are also shown (small squares). The large frames around each panel represent the boundaries of the explorable space, and the solid line represents the participants' starting point. Locations A (triangles) and D (circles) are explained in figure caption 5.

3. Results

Analyses were conducted on only the six experimental trials. Figure 7 illustrates representative paths from one participant in each of the orthogonality and enclosure conditions. As illustrated in the figure, this participant took a fairly direct path to her final choice of the location in nearly all trials. Most of the trajectories from the other participants are also characterized by a relatively direct path to the general vicinity of their location estimation, followed by, occasionally, relatively small adjustments to their position estimation. Figure 7 also illustrates the stopping points for half of the participants – those that received the second set of experimental trials. Despite the variability in stopping places among participants, it can be seen from the figure that certain testing configurations (e.g., D enclosed and no right angles during learning) yield a consistent attraction to D, while others (e.g., D not enclosed and three right angles during learning) yield a strong attraction to A.

For each trial, participants indicated a location (X) during testing that they believed matched the learned target location. We term the principal dependent variable in the following analyses "preference for distance location" (PD) and define it as (DX – AX) / DA, the difference between the distance from X to D and the distance from X to A, normalized by the distance between D and A.[3] This variable can range from –1 to 1, with positive values indicating a location estimation closer to D and negative values indicating a response closer to A. We regard PD as a measure of the degree to which distance information was used relative to angular information. Across all participants, PD ranged between 0.54 and –0.33, and averaged 0.11 (SD = 0.20), indicating an overall preference to choose places closer to D as representing the learned target location. This average is significantly greater than zero (t(18) = 2.36, p = 0.03).

The effects of enclosure and orthogonality on people's preference for the distance location was examined in a 2 (enclosure – D in or out) × 3 (orthogonality – 0, 1, or 3 right angles) × 2 (gender) × 2 (stimulus set) mixed-effects ANOVA with the first two factors examined within subjects, and the last two examined between. There were no significant main effects of gender or stimulus set. Nor did these variables interact with any of the effects of interest. As a result, data are collapsed over stimulus set and gender.

Despite the overall trend for people to choose locations closer to D, this effect is modulated by both enclosure and orthogonality. These effects can be seen in Figure 8. In the case of enclosure, participants' preference for D is attenuated when D does not conform to the enclosure relationship that the learned target location had with the configuration of landmarks. When D lies within the testing configuration, PD averages 0.24 (SD = 0.27). This mean falls to –0.02 (SD = 0.23), a very slight overall attraction to A, when D lies outside the testing configuration. The ANOVA confirmed that this main effect of enclosure was significant (F(1,10) = 8.95; p = 0.01).

The orthogonality of the learning environment also affected peoples' choice of location. The more orthogonal the learning environment, the more likely people were to select a location close to A. Learning configurations with no right angles resulted in a mean PD of 0.39 (SD = 0.38). Those with one right angle resulted in an average PD value of 0.15 (SD = 0.24), while those with three right angles resulted in an average PD of –0.20 (SD = –0.40). The main effect of orthogonality was significant (F(2,9) = 4.83, p = 0.04), as was the contrast testing its linear effect (t(10) = 3.22, p = 0.01).

During testing, none of the participants remarked that the configuration appeared to have changed. In post-experiment interviews, however, 11 of the 19 participants reported that they believed that some trials presented different testing and learning configurations. Most of these people reported (erroneously) that the testing configuration maintained the same shape as the learning configuration, but that it had changed in scale.

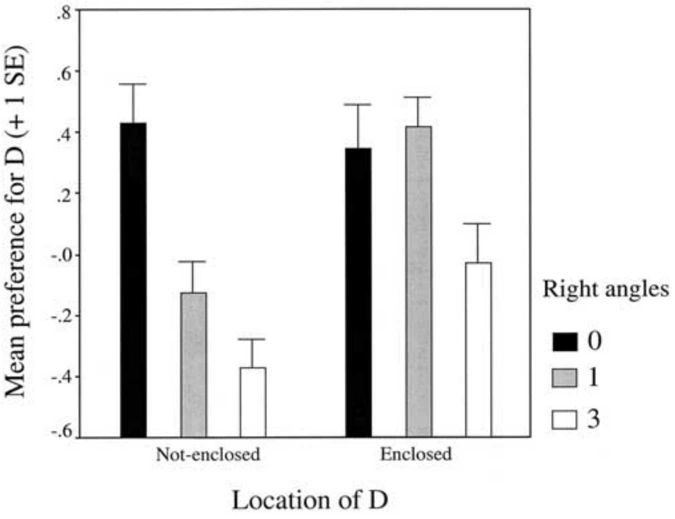

Figure 8. Mean preference for choosing D (explained in figure caption 5) as the correct location by the orthogonality of the learning configuration and by D's adherence to its enclosure relationship during testing.

4. Discussion

In this experiment, people learned their location in relation to three distinct landmarks in a simple computer-generated environment. Their attempts to return to this location during testing indicated that, in general, information available during learning about relative distances to landmarks influenced their answers more than information about bearing differences between the landmarks. In the introduction, we presented evidence that the use of accurate relative distance information in these environments is more critical for determining one's location than the accurate use of bearing differences. It appears, then, that participants in this experiment were behaving adaptively, focusing on the information sources that would help them perform the task the best. However, there are at least two reasons why this is a somewhat surprising result. First, most existing models of landmark-based navigation generally do not regard distance information as making an important contribution to place learning. Perhaps this is because these models have arisen in the context of animal cognition. Although organisms such as bees (Cartwright and Collett 1983) and birds (Kamil and Jones 2000) appear to weight information about relative bearings more heavily than information about distances in place navigation, it is possible that humans rely more than other animals on information about distances when learning where a place is. Models of human place learning and piloting will thus need to account for this finding.

The relative importance of distance information in remembering a location is also surprising when one considers that the visual fidelity of our virtual environment fell short of that of a full-cue real environment. Although the binocular cues of convergence and retinal disparity and perspective cues, like texture gradient and height in the field, were present, other important cues like familiar size and linear perspective were absent. There are now several studies that show underestimation of perceived egocentric distance in virtual environments (Loomis and Knapp, in press; Witmer and Kline 1998), and it seems likely that judgments of absolute distance for our participants would have likewise been similarly biased. Yet, it is important to realize that in the present experiment, successful task performance did not depend on the accurate perception of absolute distances; reliance on relative distances (ratios) to landmarks was sufficient. Any errors in underperceiving the overall scale of the environment would have had no effect on place learning performance.[4]

Although, in general, people in this experiment appeared to rely more on relative distance than on angular information, there were important and informative exceptions to this trend. People tended not to use distance information when it implied a target location that did not conform to the enclosure relationship that they learned. One way to explain this finding is that knowledge about the containment of the target location within the landmark configuration represents a more fundamental level of coding location than that offered by distance information. This hypothesis suggests that certain nonmetric relationships, such as enclosure, may serve as a primary basis for coding information in the environment. Enclosure information may be relatively difficult to override with knowledge about metric relationships. These results are thus principally in agreement with the theories of spatial cognition that posit a multi-level organization of spatial memory. Huttenlocher et al. (1991) for example suggest that two different levels of location coding – a "coarse" and a "fine-grain" level – can interact to create biases in judgments of location. In the present context, enclosure information may have served as one sort of locational coding at the "coarse grain" level with metric coding providing more "fine-grained" information. The degree to which these levels interact to create biases, however, is unclear from the present results. Indeed, it is plausible that, unlike in hierarchical models of spatial memory, nonmetric relationships such as enclosure are coded relatively independently from metric relationships.

Another factor that was associated with decreased reliance on distance information was the degree to which the learned landmark configuration appeared from the target to contain right angles or straight lines. As learning configurations became more and more orthogonal, people tended to move to a location that preserved this orthogonality when they attempted to find their way back to the target location. This finding suggests that right and straight angles are more easily encoded in memory than other kinds of angles. This is probably not surprising. Being between two landmarks or having them at right angles is a very salient cue. Several studies have shown that right angles occupy a privileged role in spatial cognition. For example, estimations of angles are typically biased toward right angles (Chase and Chi 1981; Huttenlocher et al. 1991), and spatial memory is commonly organized about the three orthogonal body axes (Franklin and Tversky 1990).

Our results can be summarized fairly succinctly: in landmark-based place learning in these environments, people tended to rely primarily on information about relative distances except when: 1.) it created nonmetric distortions of target-to-landmark enclosure relationship, or 2.) angular information was very salient during learning (e.g., containing all right angles). This experiment complements recent work on human place learning and landmark-based navigation that have used computer-simulated environments (Astur et al. 1998; Gaunet and Loomis 1999; Hamilton and Sutherland 1999; Jacobs et al. 1997, 1998; Sandstrom et al. 1998; Thomas et al. 2001) and extends it in two important ways. First, previous studies have generally not addressed questions related to the use of metric spatial knowledge. It is probably beyond question that humans learn and use metric properties of the environment when learning locations (see, for example Cheng and Spetch 1998). Experiments such as the present one thus offer insight into the nature of the central representations of space upon which human navigational behavior is based. Second, the current experiment illustrates the effective use of immersive (as opposed to desktop) virtual environments in examining human place learning. With the exception of the study by Gaunet and Loomis (1999), all of the aforementioned VE experiments were performed using desktop displays. Generally, these desktop systems are less able to provide a compelling sense of actually being in the learning environment. Moreover, they often use clumsy or arbitrary navigational interfaces, such as effecting simulated self-motion by means of keyboard presses. By involving the vestibular and proprioceptive modalities – sensory systems that are normally used in environmental learning – the present VE system offers a more naturalistic examination the information sources and mechanisms involved in human place learning.

In the introduction, we remarked that place learning is a component of landmark-based navigation. The other component of this process is the computation of a steering vector. Recall the visitor to a city who remembered the location of her hotel in terms of its relationship to several landmarks. At the end of the day, this visitor may find herself across town where she sees a completely different view of these landmarks. In conjunction with her place memory, this view provides, in theory, enough information to guide her back to her hotel. This information thus allows her to compute a steering vector. Navigation of this type is typically referred to as *piloting, place navigation*, or *landmark-based navigation* and is widely recognized as one of the primary bases of navigation that allow flexible wayfinding in large environments (Gallistel 1990). It is an important and yet open question how (or how well) humans are able to process geometric information about landmarks and derive a steering vector. What properties of the environment affect performance on piloting tasks? We have seen that one element of piloting, the formation of a mental representation of place, is largely influenced by distance information. In future work, we wish to ask similar questions about other processes associated with landmark-based navigation. It will also be important to generalize these findings to larger or more complex spaces. Although distance information appears to be important for learning one's location in a simple, sparse virtual environment, it is an open question whether it is as important in more complex, landmark-rich environments.

Acknowledgements

This research was conducted with support from the National Science Foundation, grant #9873432. We thank Travis Moore for assistance with conducting the experiment.

Notes

[1] For the purposes of exposition, we assume uniform probability distribution of spatial locations. We also assume that the degree of imprecision in encoding both distances and bearing differences is the same for each landmark.

[2] Unlike with distance estimations, there is not a well-known relationship between the magnitude of a bearing difference and the degree of imprecision in its memory-based estimate. As a result, we treat error in encoding bearing differences as an additive constant.

[3] The results of analyses using either (DX–AX) or DX as the dependent variable do not differ substantially from those reported here.

[4] We note that the greater effectiveness of distance information relative to bearing difference information might conceivably be due to the limited field of view of our head-mounted display. Because the display's field of view of 48 degrees is considerably less than one's normal field of view in the real world, participants needed to turn their head more than would be necessary in the real world in order to perceive the relative bearings to landmarks. One could thus argue that because angular information required more effort to acquire, its role in place learning was attenuated in the present experiment. However, preliminary evidence from our lab showing a minimal effect of a limited field of view in perceiving spatial layout renders this hypothesis unlikely (Schlichting 1999).

Appendix

X- and Y-coordinates of the landmarks, targets, D, and A (explained in Figure caption 5) for the 12 experimental stimuli. Approximately half of the participants learned configurations one through six; the rest learned numbers seven through 12

	Learning configuration				Testing configuration				
	Land 1	Land 2	Land 3	Target	Land 1	Land 2	Land 3	D	A
1	(2,6)	(3,1)	(–6,–1)	(–1,1)	(5.19,4.06)	(2.86,–1.90)	(–4.52,–1.55)	(0.19,1.07)	(–0.19,–1.07)
2	(–5,1)	(3,–1)	(–1,–4)	(–1,–1)	(–3.27,0.56)	(1.86,2.95)	(2.32,–3.60)	(0.94,–0.94)	(–0.94,0.94)
3	(0,4)	(2,0)	(0,–7)	(0,0)	(–1.68,–2.52)	(–1.56,3.14)	(6.33,1.48)	(–0.67,1.35)	(0.67,–1.35)
4	(–1,3)	(2.42,2)	(–4,–5.20)	(–1,0)	(–3.82,0.78)	(–0.17,3.17)	(4.75,–1.42)	(–1.20,–0.70)	(1.20,0.70)
5	(–5,–0.4)	(3,–2.4)	(–2,–9.4)	(–2,–2.4)	(1.40,–1.67)	(0.14,4.61)	(5.10,1.19)	(–1.80,0.00)	(1.80,0.00)
6	(2,3)	(–4,–1)	(5,–1)	(2,–1)	(–3.69,–0.30)	(–0.04,–3.72)	(1.95,0.69)	(–0.62,2.25)	(0.62,–2.25)
7	(–1,3)	(2.46,2)	(–4,–5.20)	(–1,0)	(–4.56,–0.05)	(–0.55,3.54)	(4.38,–1.06)	(–1.58,–0.33)	(1.58,0.33)
8	(1,2)	(5,0)	(–1,–3)	(1,0)	(0.00,–1.43)	(–4.09,2.42)	(3.02,0.61)	(–0.58,0.49)	(0.58,–0.49)
9	(2,3)	(–4,–1)	(5,–1)	(2,–1)	(–3.62,–0.85)	(0.03,–4.27)	(1.66,3.74)	(–0.55,1.70)	(0.55,–1.70)
10	(2,6)	(3,1)	(–6,–1)	(–1,1)	(4.74,4.34)	(2.41,–1.62)	(–4.06,–2.47)	(–0.26,1.35)	(0.26,–1.35)
11	(–5,1)	(3,–1)	(–1,–4)	(–1,–1)	(–2.51,0.76)	(3.09,3.01)	(0.24,–3.37)	(1.70,–0.74)	(–1.70,0.74)
12	(0,4)	(2,0)	(0,–7)	(0,0)	(–2.46,–2.91)	(0.54,0.88)	(5.54,1.08)	(–1.46,0.96)	(1.46,–0.96)

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