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# Allocentric-Heading Recall and Its Relation to Self-Reported Sense-of-Direction

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A sense of direction (SOD) computes the body's facing direction relative to a reference frame grounded in the environment. The authors report on three experiments in which they used a heading-recall task to tap the functioning of a SOD system and then correlated task performance with self-reported SOD as a convergent test of the task's construct validity. On each heading-recall trial, the participant judged the photographer's allocentric heading when photographing a pictured outdoor scene. Participants were tested over the full range of SOD ratings in Experiment 1, and in Experiments 2 and 3 heading-recall at the SOD extremes was tested. In all experiments, there was wide variability in heading-recall accuracy that covaried with self-rated SOD. Parametric manipulation of various task parameters revealed some likely functional properties of the SOD system. The results support the psychological reality of a SOD system and further indicate that there are large individual differences in the efficacy with which the system functions.

*Keywords:* allocentric heading, sense of direction, spatial memory, local views, spatial orientation.

A sense of direction (SOD) is knowledge of the body's facing direction relative to a stable spatial framework anchored to the environment (i.e., its allocentric heading). A well-functioning SOD updates the body's allocentric heading with each turn made by the body as it moves through large-scale space. There is evidence that the physical frameworks relative to which updating occurs are hierarchically nested (e.g., room, building, neighborhood, city, and so on), such that orientation is maintained relative to the most proximal framework that also includes the immediate goal location (Wang & Brockmole, 2003). Thus, a SOD computes the allocentric heading of the body relative to an external reference frame that may differ at different spatial scales (e.g., a room, building, neighborhood, and so on). For our purposes, allocentric heading is functionally defined as the angle formed by the forward axis of the body, or axis of orientation, and a reference direction grounded in the environment.

A common approach to studying human SOD has been to correlate people's self-attributions about their SOD ability with their skill in a variety of navigation-related tasks. This approach has revealed a large number of behavioral correlates of SOD (Bryant, 1982; Hegarty, Richardson, Montello, Lovelace, & Subbian, 2002; Kearnes & Warren, 2001; Kozlowski & Bryant, 1977; Lorenz & Neisser, 1986; Montello & Pick, 1993; Prestopnik & Roskos-Ewoldsen, 2000; Sholl, 1988), and it has produced some interesting inferences about the cognitive processing differences between good sense-of-direction (GSOD) and poor sense-of-direction (PSOD) people (e.g., Hegarty et al., 2002; Sholl, 1988). Although the individual differences approach has been successful in validating the SOD construct, it has been less successful in revealing the functional architecture of a human SOD system. This architecture includes the system's source(s) of input, its functional organization and its representational structure, the computations performed by the system to transform input into an allocentric-heading output signal, and the systems to which its output is directed and with which it interfaces. The state of the research on a human SOD system contrasts with the wealth of neuroanatomical and neurophysiological knowledge about the functional organization of a SOD system in nonhuman mammals that has accumulated since the discovery of head-direction (HD) cells in rats (Ranck, 1984) and monkeys (Robertson, Rolls, Georges-Francois, & Panzeri, 1999). HD cells code the animal's allocentric head-direction and are the basic functional units in animal models of SOD.

The primary purpose of the present experiments was to test whether humans have a SOD system (i.e., an allocentric-heading system) analogous to the HD system in rats and monkeys and to begin to study its functional organization. To this end, we developed a heading-recall task, which tested people's ability to retrieve the body's allocentric heading from pictured scenes of an overlearned environment, by instructing them to judge the direction the photographer faced to take the picture. It is our contention that to perform the task, the allocentric heading from which a familiar scene, or *local view*, is visible must be coded and linked in memory to a visual representation of the scene; functions that neuroscientific evidence suggests characterize an allocentric-heading system (e.g., Aguirre & D'Esposito, 1999; Sharp, Blair, & Cho, 2001). Task performance was correlated with self-rated SOD to provide convergent validity for our contention that the task recruits an allocentric-heading system. Additionally, by manipu-

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Katherine A. DellaPorta conducted Experiment 1 in partial fulfillment of a senior honor's thesis project. Portions of Experiment 1 were presented at the 2004 Annual Meeting of the Psychonomic Society in Orlando, FL. She has since graduated from Boston College.

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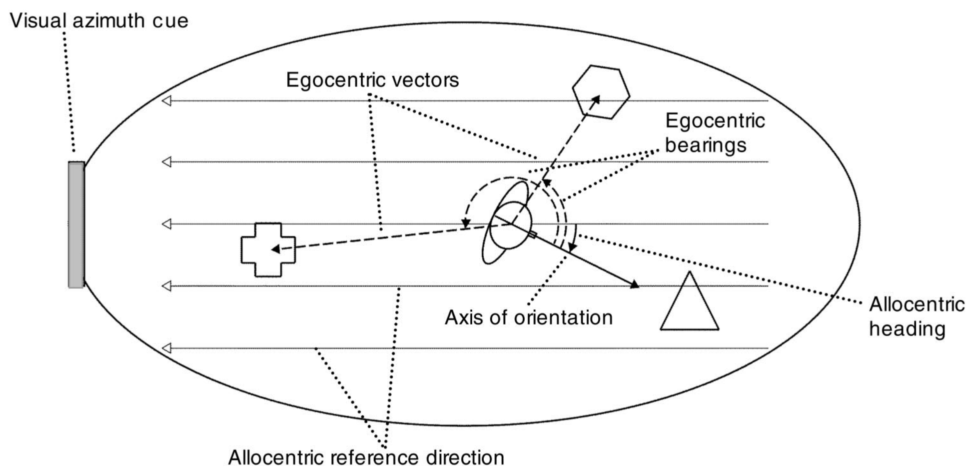


*Figure 1.* Schematic environment illustrating some key terms, which are labeled in the figure.

lating task parameters we expected to gain some preliminary insight into the putative system's functional organization.

## Relation Between the Present Research and Other Research on Spatial Orientation

Before proceeding, it is important to clarify how the current research differs from existing research on spatial orientation, principally research on heading perception and egocentric orientation. We use Figure 1 to help illustrate some of the terminology relevant to making these distinctions. In the schematic environment shown in Figure 1, the unfilled arrowheads point in the direction of the *allocentric reference direction,* which is parallel to the environment's geometric axis of elongation and perpendicular to the salient visual cue at its border. Distinct from the allocentric reference direction, is the body's *axis of orientation*,[1] which is the line that bisects the body into right and left halves and points in the direction of bipedal locomotion. As defined earlier, *allocentric heading* is the angle separating the body's axis of orientation from the environment's allocentric reference direction. *Egocentric vectors*, whose polar coordinates specify the egocentric distance and direction (relative to the axis of orientation) of stationary objects, connect the body to surrounding landmarks. A landmark's *egocentric bearing* is the polar angle of its egocentric vector.

Heading perception research includes studies on the nature of the visual information that enables people to perceive the direction in which the axis of orientation is pointing. In this research, direction is defined unidimensionally, that is, it is a point in the forward field of view that would be situated on the axis of orientation if it were to be extended toward the horizon. In Gibson's (1979) analysis of the structured information embedded in optic flow patterns, he noted that the direction of linear egomotion is specified by a single, static point at the center of an outwardly expanding pattern of radial flow produced by forward linear motion. Subsequent research has shown that people use radial flow (e.g., Warren, Morris, & Kalish, 1988), visual beacons (Warren, Kay, Zosh, Duchon, & Sahuc, 2001), extraretinal signals (e.g., Banks, Ehrlich, Backus, & Crowell, 1996), and static scene analysis (Hahn, Andersen, & Saidpour, 2003) to judge the path of forward motion, and on the basis of radial flow alone people can judge egocentric heading within 1° of visual angle (e.g., Warren et al., 1988). Perception of the path of forward motion is necessary, but not sufficient, knowledge for allocentric heading.

There has also been extensive research on the sources of sensory information important for perceiving the amplitude of the angular body displacements that alter the direction of the axis of orientation. The psychophysical and clinical research in this area has included studies of the perceived displacement angle as a function of the physical displacement angle (for turns executed in place) under different sensory restrictions. Sensory input particularly important for the perception of angular displacement originates internally from the "body" senses and includes vestibular acceleration and deceleration signals, afferent feedback from the moving muscles and joints, and efferent copy of locomotor commands. Systematic disparities between the perceived and the actual angle of a turn have been consistently reported. For example, when instructed to produce a turn of a specified magnitude, participants invariably undershoot the prescribed angle, indicating that perceived angular displacement is an overestimation of produced displacement (Bakker, Werkhoven, & Passenier, 1999; Bles, de Jong, & de Wit, 1984; Israël, Sievering, & Koenig, 1995; Siegler, 2000). The least amount of disparity between the apparent and actual turning angle is observed when all three body senses are combined (Bakker et al., 1999), and it has been reported that the addition of radial optic flow information to the input provided by the body senses does not improve accuracy in turn production (Bakker et al., 1999). Perceived angular displacement has also been studied using turn-reproduction, turn-estimation, and path-integration tasks in both real and virtual environments (e.g., Guedry, 1974; Kearns, Warren, Duchon, & Tarr, 2002; Lambrey, Viaud-Delmon, & Berthoz, 2002; Loomis et al., 1993; Sholl, 1989). As was the case with the perception of that patch of the

[1] We borrow this term from Klatzky (1998), whose formal analysis of the properties differentiating allocentric from egocentric representations includes a discussion of why navigator heading is a property of allocentric but not egocentric space, a distinction that figures prominently in our own analysis.

forward field of view toward which the axis of orientation points, perception of the rotational displacement of the axis of orientation is necessary but not sufficient information for the specification of allocentric heading. Allocentric heading is unknown unless the angle between the axis of orientation and an allocentric reference direction is known.

Finally, spatial orientation has been studied in the context of self-to-object updating, which is the process by which a person stays oriented to surrounding objects when they disappear from view. Self-to-object updating continuously computes the changing spatial coordinates of egocentric vectors during self-locomotion (e.g., Wang & Spelke, 2000). This type of updating appears to be engaged automatically when the body moves relative to stationary objects (e.g., Farrell & Robertson, 1998; Farrell & Thomson, 1998, 1999; Rieser, 1989), but not when objects move relative to the stationary body (Simons & Wang, 1998; Wang & Simons, 1999). At a functional level of analysis, self-to-object updating has much in common with the process of updating allocentric heading.

As with updating allocentric heading, self-to-object updating requires information about the unidimensional direction of the axis of orientation and the magnitude of its rotational displacements (Fery, Magnac, & Israel, 2004). Both types of updating also involve calculating the amplitude of angular displacements, but the similarities end when one considers the reference frame within which the new angles are computed. Self-to-object updating takes place in an egocentric reference frame, with the body's axis of orientation serving as the reference axis relative to which the spatial coordinates of the egocentric vectors are updated. In contrast, when allocentric heading is updated, an axis fixed to the environment is the reference axis, and the body's axis of orientation is updated relative to it. Moreover, unlike objects, which are tangible, an allocentric reference axis may not be directly perceivable. Rather it may need to be inferred from environmental cues, such as the intrinsic structure of the schematic environment as illustrated in Figure 1.

To summarize the above distinctions, consider the following hypothetical scenario. You are visiting a city for the first time and have just emerged from your hotel. You start walking down the sidewalk and based on the radial optic flow produced by your forward motion, you perceive that you are heading directly toward the car parked at the approaching intersection. At the intersection, you execute a 90° clockwise (cw) turn, which you perceive based on signals produced by the body senses, rotational optic flow, and the fact that the aforementioned car is now directly to your left. Your self-to-object updating process updates the location of the hotel that you just exited as now to your right. However, neither the perceived direction of movement, the perceived angle of the turn, nor the updated location of the hotel relative to the body are sufficient to specify allocentric heading. To know, for example, that you were walking west after emerging from the hotel and that you turned north at the intersection, requires additional information. One purpose of the present experiments is to confirm empirically the psychological reality of a system that converts sensory input into allocentric-heading output and to begin to study the functional properties of the putative system. By using cardinal directions to describe allocentric heading in this example, we do not mean to imply that allocentric heading is routinely updated within a cardinal reference system. We used compass terms simply for ease of exposition, and, for now, we take no position on the nature of the allocentric reference axis or framework that is used to code heading. Possible candidates are discussed in the next section.

## Other Points of Clarification

A few additional points of clarification are in order before proceeding. First, because the heading-recall task was motivated by the response properties of HD cells in rats and primates, it is important to acknowledge the functional distinction between head direction and body direction. Single-unit recordings from HD cells indicate that they respond preferentially when the animal's head is aligned with the cell's preferred allocentric direction, irrespective of the head's position relative to the trunk of the body. Functionally, it is the allocentric direction of the body, not the head, that is important for navigation, and, when the head is not facing forward, the body's allocentric direction can be converted from a head-centered to a body-centered reference frame by adjusting for the angle of the head on the neck. Like others, we adopt the simplifying assumption throughout this article that head-centered and body-centered coordinates are in alignment (i.e., the head is oriented straight ahead and does not move). So for now, when referring to a human allocentric-heading system, we treat body direction and head direction as one and the same, and use the terms interchangeably.

Second, the present experiments do not address how allocentric heading is computed. We think it is important to demonstrate first that people code allocentric heading and then turn to the question of how it is coded. When we consider the question of how, a primary issue is the environmental source of information specifying an allocentric reference direction. One likely source includes visual cues that specify directionality, such as the sun's location in the sky, a prominent landmark on the horizon, and salient changes in elevation. Although studied in the context of spatial memory, allocentric reference directions may also emerge from the intrinsic geometric structure of local environments upon initial viewing from certain perspectives (Mou & McNamara, 2002; Shelton & McNamara, 2001). Another possibility is that a critical source of input originates within the body itself, from those systems (vestibular and motor–joint) that code information about the amplitude of angular body displacements. Animal models give a primary role to internally generated velocity signals (e.g., Samsonovich & McNaughton, 1997; Skaggs et al., 1995), with visual control emerging secondarily. In these models, heading is computed by path integration mechanisms within a 360° coordinate system centered on the body but grounded in the environment. The internally generated HD signal comes under visual control to correct for the cumulative error inherent in the inertial system.

Third, the construct of a local view figures prominently in our analysis. The term refers to the visual scene observed from a single location and facing direction in large-scale space (e.g., Samsonovich & McNaughton, 1997). Here the distinction between head and body direction is functionally important because distinctly different local views can be seen from a fixed location and body direction when the head is turned from one side to the other. Thus, local views are like head-centered snapshots of the environment. For now, we define a local view as all that can be seen in the field of view when the head and body are both aligned in the straight-ahead direction. In the present experiments we did not control the contents of the local view, except to take pictures of scenes that we thought student participants would recognize.

## Neuroscientific Background

Some clues to the functioning of a human allocentric-heading system come from rare cases of heading disorientation reported in the neuropsychological literature (Aguirre & D'Esposito, 1999). These cases are characterized by a loss of the ability to derive directional information from prominent landmarks in environments with which the patients are familiar. For example, one such patient was a taxi driver who suddenly lost his knowledge of the direction in which he should proceed while driving his cab, even though he recognized surrounding landmarks and knew his location in space. In addition to intact landmark recognition, these patients can also code and retain over the short-term the egocentric location of perceived objects; however, they appear "unable to recall (or form) the link between directional information and landmark identity" (Aguirre & D'Esposito, 1999, p. 1620). Of interest, in the three cases of heading disorientation reviewed by Aguirre and D'Esposito, the locations of the lesions included the right retrosplenial (i.e., posterior cingulate) region, which is one region in which HD cells are found in rats. Although the evidence is indirect, Aguirre and D'Esposito suggested that the disorder may be caused by the disruption of a system specialized for coding the orientation of the body in a spatial framework anchored to the environment.

Other relevant evidence comes from studying the response properties of HD cells in rats and monkeys. In both species, HD cells code the orientation of the animal's head in environment-centered coordinates. The cells have Gaussian response curves, with peak responses when the animal's head is aligned with the cell's preferred allocentric direction. The cells respond to their preferred direction across multiple locations in the task environment and are indifferent to the visual changes that accompany these changes in location. Collectively the cells' preferred directions are evenly distributed throughout the 360° of space surrounding the animal. As an animal changes the orientation of its head, the cells that "prefer" the new heading increase their firing to a maximum rate, whereas the cells that prefer the old heading decrease their firing rates toward baseline.

Once an animal is familiarized with a stable visual environment, its HD cells will continue to respond selectively to their preferred directions for short periods even when the animal moves about freely in the dark, indicating that the cells are driven by internally generated idiothetic (self-motion) signals from the vestibular and motor–joint systems (i.e., the "body" senses). When previously stable visual cues at the periphery of the task environment are rotated while the ground under the animal remains stationary, the HD cells shift their direction fields in phase with the visual rotation (e.g., Taube, Muller, & Ranck, 1990), showing that the direction fields are anchored to visual cues in the environment. Thus, HD cells are thought to be initially under the control of the body senses, but with learning, come to be dominated by visual azimuth cues. Visual control over HD signals corrects for cumulative error characteristic of idiothetically based computations of rotational displacement. For a more detailed review of these and other properties of HD cells, see Baird, Taube, and Peterson (2001), and for a review of their computational properties and neuroanatomical substrate see Sharp, Blair, and Cho (2001).

The findings that HD cells come under direct visual control motivated the present heading-recall task. In neural network models of the HD system, there are modifiable connections between stored visual representations of local views and HD cells, which are strengthened when HD and local-view cells are simultaneously active (e.g., Samsonovich & McNaughton, 1997). If humans have equivalent circuitry, then a heading-disorientation disorder could result either from damage to a HD network that computes a heading signal or from a disruption in the connections between local views and heading signals. To perform the heading-recall task successfully, the connections between local views and body-direction signals must be retrieved from memory. Hence, the heading-recall task tests the accessibility of such connections in long-term memory.

## Self-Rated Sense of Direction

A second objective of the present experiments was to test whether self-rated SOD reliably predicts heading recall. People's self-attributions about their SOD are highly stable, as indicated by the test–retest reliability for single-item scales of .90 (Hegarty et al., 2002) to .93 (Bryant, 1982). Typical of the single-item scales used to measure SOD is the Kozlowski and Bryant (1977) 7-point scale on which the respondent rates "How good is your sense of direction?" from *poor* to *good*. The construct validity of single-item SOD measures, such as the Kozlowski and Bryant (K&B) scale, is indicated by their correlations with a variety of navigation-related skills, most notably the ability to point to unseen landmarks from imagined or actual observation points (Bryant, 1982; Hegarty et al., 2002; Kozlowski & Bryant, 1977; Lorenz & Neisser, 1986; Montello & Pick, 1993; Prestopnik & Roskos-Ewoldsen, 2000; Sholl, 1988), but also the ability to integrate a series of local views of a novel environment into a coherent representation of its layout (Hegarty et al., 2002; Muehl & Sholl, 2004), self-reported use of survey navigational strategies (Prestopnik & Roskos-Ewoldsen, 2000), perspective-taking in large-scale space (Sholl, 1988), and so on.

Despite the demonstrated test–retest reliability and construct validity of the single-item scales, a multi-item SOD scale is preferable from a psychometric perspective. According to classical test theory, a single item measures both a person's true ability and random error, and as such, true aptitude, when measured by a single item, is unknowable because it is obscured by random error. If multiple items are sampled from the relevant content domain and if measurement error is truly random across items, then averaging scores across multiple items cancels out random error, leaving behind a pure ability measure. When the assumptions underlying the theory are met, multi-item measures are superior to single-item measures, particularly when the content domain is broad and multifaceted. However, because of their pragmatic advantages, single-item self-report scales have been frequently used to measure psychological attributes in social and personality research (Gosling, Rentfrow, & Swann, 2003) and may be appropriate choices for single-faceted aptitudes (e.g., Robins, Hendin, & Trzesniewski, 2001). After exhaustive testing of the reliability and construct validity of a single-item measure of self-esteem, Robins et al. (2001) concluded that single-item scales provide a reliable and valid alternative to multi-item scales when the to-be-measured construct is "highly schematized," single-faceted, and consciously accessible.

In part because of their psychometric advantages, there has been recent interest in the development of multi-item measures of SOD. This interest is also fueled by the belief held by some that SOD is a multifaceted construct. A recent example of a multi-item scale is the Santa Barbara Sense of Direction (SBSOD) scale developed by Hegarty et al. (2002), which measures self-reported skill and aptitude across many facets of navigation. In the SBSOD Scale, respondents rate the extent of their agreement with 15 different self-referential statements related to navigation ability (i.e., "I don't enjoy giving directions," "I am very good at reading maps," "My 'sense of direction' is very good," and so on) (Hegarty et al., 2002, pp. 445–446). The scale is highly reliable, with an internal reliability of .88 and a test–retest reliability of .91, and its construct validity is indicated by its moderate correlations with a variety of environmental tasks including people's ability to point toward familiar landmarks, the integration of local views into a coherent spatial representation, and large-scale path integration.

In the present experiments, we directly compare the two measures. If SOD is a construct that has the properties hypothesized by Robins et al. (2001), then the single-item K&B scale and the multi-item SBSOD scale should account for similar amounts of variability in heading-recall performance.

## Experiment 1

In Experiment 1, we used a four-alternative, forced-choice (AFC) heading-recall task (a variant of the task used by Sholl and Muehl (2000) to measure people's ability to retrieve allocentric heading from local views of a known environment. The four heading alternatives were magnetic north (N), south (S), east (E), and west (W). Throughout the manuscript, allocentric heading will be described using magnetic compass directions. We use a magnetic reference frame for ease of description, because the vertical grid lines on the Boston College (BC) map (and the map in Figure 2) are aligned with magnetic north ("the direction indicated by a magnetic compass"), not grid north (the direction "parallel to the central meridian on the National Grid").[2] The N, S, E, and W headings were selected because they line up with the "built geometry" of the campus, not because they are aligned with cardinal compass directions. As can be seen in the map in Figure 2, the sides of most of the campus buildings run parallel to the cardinal directions, giving the campus an intrinsic structure with major axes running in the north–south and east–west directions. We tested four headings because that number falls within the range of headings (from two to nine) that Baird et al. (2001) estimated can be behaviorally distinguished by humans and nonhuman animals. Their estimate is based on a population-response model applied to a population of HD cells, each having a Gaussian response profile and each with a different preferred direction (ranging in 1° increments from 1° to 360°).

Figure 2 illustrates the task and before describing it in detail we define the terminology we will use: *picture heading* is the allocentric heading of the photographer when taking the picture; *default heading* is the participant's allocentric heading when performing the task; *response heading* is the heading the participant produced for each picture; *decision latency* is the time it took the participant to decide on the response heading, and *rotation time* is the time it took the participant to physically rotate through the shortest angle from the default heading to the response heading.

As illustrated in the bottom, left-hand panel of Figure 2, participants were seated in a swivel chair at the center of an implicit circle. On the perimeter of the circle were four hatch marks, each cueing the direction of one of the four alternative picture headings (N, S, E, or W). Although the hatch marks are labeled with their compass directions in the figure and the compass points are used to describe direction in the text, no compass labels were used in the experiment itself. Participants were assigned one of the four alternative picture headings as their default heading. The manipulation of default heading allowed us to test whether the participant's actual heading relative to the task environment affected heading retrieval. A computer was positioned in front of the participant's default heading at about eye level. The bottom panels of Figure 2 illustrate the condition in which north was the default heading.

A typical trial is illustrated in the bottom center and right-hand panels of Figure 2. On each trial a single picture of a campus scene was shown on the computer screen (bottom, center panel). To help the reader locate the scene depicted in the picture, the picture was duplicated at the top of Figure 2 and linked to its location on a map of the campus. The base of the arrow linked to the picture depicts the photographer's location and the direction of the arrowhead is the photographer's allocentric heading.

The participant's task was to judge the direction the photographer faced (i.e., the photographer's allocentric heading) at the location the picture was taken and then to rotate in place to face in the judged direction. If the local view depicted in the picture is linked in memory to the allocentric-heading signal active when the scene was observed in the natural environment, then participants should be able to access body heading directly from the picture. For the picture depicted in Figure 2, the photographer's allocentric heading was south when taking the picture, so the correct response was to rotate to south, which from a default heading of north was a 180° turn.

We chose body rotation as the response output, because of its compatibility with the output of the allocentric-heading system. Participants always rotated through the shortest angle from their default heading, and if the picture was taken from the default heading, then, of course, no rotation was needed. To respond appropriately, participants needed to know their allocentric heading within the task environment. So, the experiment was conducted in a laboratory with a window offering an outside view to orient them visually. Timing procedures were developed to disentangle the rotation time from decision latency.

We hypothesize that the following sequence of processing steps must be executed for successful performance on the heading-recall task. First, the local view depicted by the picture is recognized and the location from which the scene is visible is retrieved from spatial memory. Second, because local views are hypothesized to be connected directly to body-direction signals, allocentric heading

[2] The direction of magnetic north is about 25° counterclockwise from the direction of grid north. The direction of grid north is depicted by the *compass rose* on the map at http://www.bc.edu/about/maps/s-chestnuthill/. The definitions of magnetic and grid north are from http://www.ordnancesurvey.co.uk/oswebsite/aboutus/reports/misc/north.html.

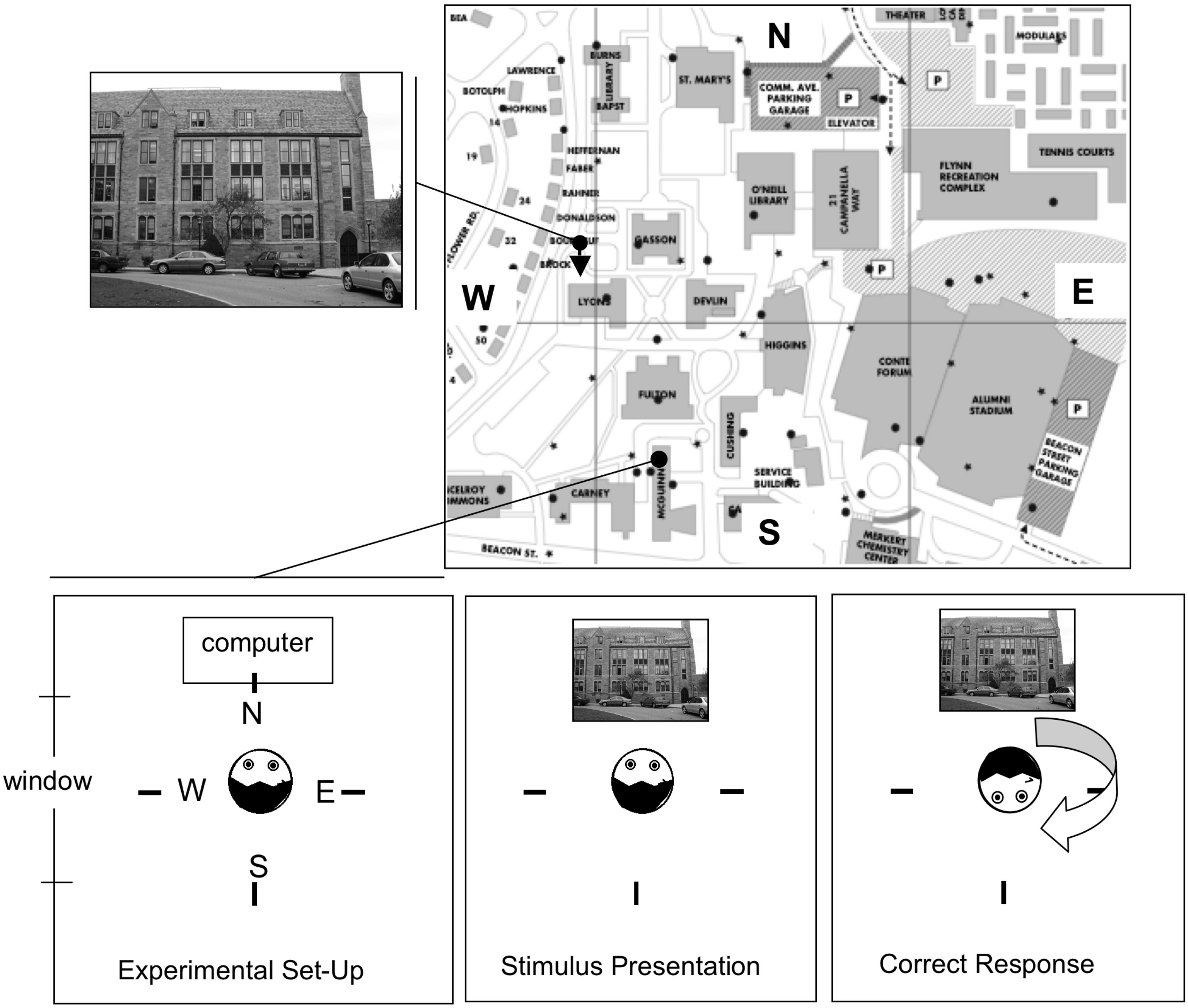


*Figure 2.* Schematic illustration of the 4AFC task used in Experiment 2. At the top left is a sample picture, and the arrow on the map points to the scene visible in the picture. The base of the arrow shows the photographer's approximate location when taking the picture and the arrowhead points in the photographer's facing direction. The bottom left panel illustrates the experimental set-up in the north default-heading condition, and it is connected to a filled circle on the map at the location where the experiment was conducted. The other two bottom panels illustrate a typical trial. In the center panel the picture is presented on the computer screen, and the right-hand panel illustrates the picture-heading for that picture.

is retrieved by activating this connection. The retrieved allocentric heading is compared to the default allocentric heading, and the signed angular disparity between the two is output to motor control centers for response execution. We used local views that were highly familiar to BC undergraduates to minimize any variability in performance related to the local-view recognition stage of processing. Therefore, it was our expectation that most of the variability in performance would arise from those processing stages involving allocentric heading. Following Hegarty et al. (2002), we used a correlational approach in Experiment 1, collecting K&B[3] and SBSOD ratings from a random sample of male and female participants and correlating them with performance on the heading-recall task.

## *Method*

*Participants.* Thirty-two undergraduates (16 male and 16 female) who had been on campus for at least two full semesters served as participants in

[3] We modified the scale by replacing the modifier *good* with the modifier *excellent*, thus, participants rated their SOD on a 7-point scale from *poor* to *excellent*.

this experiment either in partial fulfillment of a course research participation requirement or for pay.

*Materials.* Forty pictures of the Chestnut Hill Campus of BC served as stimuli in this experiment, with 10 pictures each in the N, S, E, and W picture-heading conditions. The allocentric heading from which each picture was taken was measured to the nearest degree with a Magellan Platinum GPS Navigator. The pictures were taken from different locations that were widely distributed across those parts of campus familiar to all undergraduates. Each picture had been rated for its familiarity on a scale from 1 (*unfamiliar*) to 5 (*very familiar*) by an independent sample of either 20 or 25 undergraduates. From a total pool of 130 pictures, the 10 pictures with the highest familiarity ratings were selected for each picture-heading condition, with the restriction that average familiarity was comparable across picture headings. Mean familiarity is shown in Table 1.

*Design.* The research methodology was both correlational and experimental. Participant selection was random (with the restriction of an equal number of male and female participants), and each participant's accuracy rate and mean decision latency on the heading-recall task were correlated with his or her self-rated SOD. Each participant was randomly assigned to a default heading condition with the restriction of an equal number of participants in each condition—half male and half female—and picture heading was manipulated within subjects.

*Procedure.* After signing a consent form, the participant looked out the window to identify the direction of north. The purpose of this exercise was to make sure participants were oriented to the outside environment. Four male and four female participants were randomly assigned to each of the four default-heading conditions. The experimenter initiated each trial by pushing a button that both triggered the presentation of a single picture at the center of the computer screen and started an internal computer timing routine. Simultaneous with the button press the experimenter started a stopwatch. As soon as the participant decided from which of the four headings the picture was taken, the participant pressed a response button that terminated the computer-controlled timing routine, and then he or she turned to face in the decided direction. Participants were instructed to make their turn by rotating through the smallest possible angle. The participant cued the experimenter that his or her turn was complete by raising his or her index finger, at which point the experimenter stopped the stopwatch and recorded the time and the response heading. The participant turned back to face the computer screen and the next trial was initiated.

Decision latency was the time measured by the computer from picture onset to the button press. Total latency was the time measured on the stopwatch from picture onset to the raised index finger. For each trial, the rotation time was calculated by subtracting the decision latency from the total latency.

We measured rotation time to ensure that the retrieval process did not leak into the response execution stage of the task. For each participant, the 40 rotation times were sorted by response heading, and rotation times were averaged across all the trials that produced the same response heading regardless of accuracy. Response accuracy is irrelevant when computing rotation time, as the following example illustrates for a north default heading. For those facing north at the beginning of each trial, all west response headings were produced by a 90° counterclockwise (ccw) rotation irrespective of the picture heading that produced the response. Similarly, all S response headings were produced by either a 180° cw or ccw rotation, regardless of picture heading, and the same applied to E response headings, which were produced by a 90° cw rotation. So, for the response heading equal to the default heading, the rotation angle was 0°; for the response headings 90° cw or ccw from the default heading, the rotation angle was 90°, and for the response heading 180° from the default heading, the rotation angle was 180°. We reasoned that if rotation time was not contaminated with decision time, it should increase linearly with the magnitude of the rotation angle.

For decision latencies, all analyses were restricted to correct responses and to eliminate outliers, decision latencies were trimmed as follows. For each participant, any latency that was more than 2.5 *SD* above the mean of his or her distribution of correct decision latencies was excluded from analysis.

Eight practice trials were presented with feedback in a fixed serial order, during which the experimenter ensured that the participant understood the task. They were followed by the 40 experimental trials in a separate random order for each participant. Some participants had difficulty understanding the task in a way that we did not anticipate, and for those participants the initial, standard instructions were embellished on an ad hoc basis. After having run eight participants, we incorporated these extra instructions into the standard instructions read to each participant. The conceptual difficulty corrected by the additional instructions is described in the following syllogism: The picture depicts a scene in the photographer's forward field of view; I am looking at the picture in my forward field of view; therefore, my perspective of the scene will always be the same as the photographer's. To help overcome this difficulty, we added: "If you were taking the picture and standing in the location on campus where the photographer stood, would you face in the same direction you are now facing or a different direction? If a different direction, in what direction would that be?"

After completing the heading-recall task, participants completed K&B and SBSOD scales. The K&B scale produces discrete ratings that range from 1 (*poor SOD*) to 7 (*excellent SOD*). SBSOD scores are continuous (averaged over 15 items), and they also vary from 1 (*low end of the scale*) to 7 (*high end of the scale*). For a complete description of the SBSOD, see Hegarty et al. (2002).

Table 1
*Mean Familiarity Ratings (Standard Deviations in Parentheses) for Pictures Used in Experiments 1–3 as a Function of Allocentric Heading*

| | Picture heading | | | |
|---|---|---|---|---|
| Experiment | North | East | South | West |
| 1 | 4.41 (0.16) | 4.39 (0.23) | 4.40 (0.34) | 4.48 (0.16) |
| 2 and 3 | 4.35 (0.20) | 4.27 (0.39) | 4.27 (0.43) | 4.43 (0.20) |
| | Northeast | Southeast | Southwest | Northwest |
| 3 | 4.30 (0.45) | 4.30 (0.31) | 4.23 (0.31) | 4.03 (0.27) |

*Note.* There were 10 pictures in each picture-heading condition in Experiment 1 and 12 pictures in each picture-heading condition in Experiments 2 and 3.

## Results

*Accuracy.* A 2 (Gender: male, female) × 4 (Default Heading: N, E, S, W) × 4 (Picture Heading: N, E, S, W) ANOVA with repeated measures on the last factor showed a main effect of picture heading, $F(3, 72) = 3.32$, $MSE = 157.64$, $p = .03$, qualified by an interaction with default heading, $F(9, 72) = 3.86$, $MSE = 157.64$, $p < .01$. The interaction was attributable to the following response pattern. For each default heading, performance was significantly better (LSD = 12.49 percentage points) for aligned picture headings than for those that were 180° misaligned. For example, participants whose default heading was west were significantly more accurate at retrieving west than east picture headings, but for participants whose default heading was east the reverse was true. The same pattern was observed for participants whose default headings were N and S.

To analyze this pattern statistically, we collapsed across the default-heading conditions and recoded the picture headings in terms of their deviation from the participant's default heading. We call this variable *heading disparity*, which is measured cw from the default heading in degrees. For a 0° heading disparity, the picture heading was aligned with the default heading, for a 90° heading disparity, the picture heading was 90° cw from the default heading, and so on. The mean proportion of correct trials as a function heading disparity is shown in the left-hand panel of Figure 3. A 2 (Gender) × 4 (Heading Disparity: 0°, 90°, 180°, 270°) ANOVA with repeated measures on the last factor indicated a significant effect of heading disparity, $F(3, 72) = 9.87$, $MSE = 0.016$, $p < .001$. By a least significant difference test (LSD = 0.06), the 180° condition was significantly less accurate than the 0° condition, the 90° condition was midway between the 0° and 180° conditions, and the 270° condition was not significantly different from the 0° condition. There were no other main or interaction effects.

*Rotation time.* A one-way, repeated-measures ANOVA was conducted on the rotation times. There was a significant linear trend relating turn latency to magnitude of the turn angle, $F(1, 31) = 536.54$, $MSE = .044$, $p < .001$, with turn latencies of 1.544, 2.096, and 2.743 s for 0°, 90°, and 180° turns, respectively. The magnitude of the turn angle accounted for 94.5% of the variability in turn latency, indicating that we were successful in separating the time it took to make a decision from the time it took to make a physical turn.

*Decision latency.* There were 1.97% (of 761 response times) outliers trimmed from the correct decision latencies. Some participants had such low accuracy rates that there were too few decision latencies to provide a meaningful measure of processing time. Therefore, a 50% or higher accuracy rate was set as a criterion for the inclusion of a participant in the analysis. The data from 18 (7 female and 11 male) participants were analyzed. Of the remaining participants, 17 had $M = 17.724$ s) was more than 5 *SD* above the mean of the distribution of the means of those participants included in the analysis.

Because a Default Heading × Picture Heading analysis would have been unbalanced, we collapsed across the two variables and conducted a 2 (Gender) × 4 (heading disparity: 0°, 90°, 180°, 270°) ANOVA with repeated measures on the last factor. An effect of heading disparity, $F(3, 48) = 2.50$, $MSE = 2.11$, $p = .07$, approached significance. Mean decision latencies as a function of heading disparity are shown in the right-hand panel of Figure 3. A least significant difference post hoc test (LSD = 0.97 s) indicated that decision latencies in the 180° heading-disparity condition were significantly greater than those in the 0° heading-disparity condition. No other main or interaction effects were significant.

*SOD.* The correlation between the two SOD measures is listed in Table 2. Mean accuracy and mean correct decision latency were computed for each participant and correlated with the SOD ratings. Those correlations are reported in Table 3, along with the unstandardized regression weights. The latter will be used to make comparisons across experiments. Both of the SOD measures were highly positively correlated with accuracy and modestly negatively correlated with decision latency. The negative correlation with decision latency is largely attributable to male ($r_{KB} = -.73$, $r_{SBSOD} = -.65$) rather than female ($r_{KB} = -.19$, $r_{SBSOD} = -.31$) participants.

Inspection of the bivariate distributions indicated that there was no overlap in the accuracy rates of those at the extreme ends of the K&B scale. People who rated themselves at the low end of the scale (1 and 2 ratings; $n = 5$) performed at chance with an accuracy rate of 21.5%, whereas people who rated themselves highly (6 and 7 ratings; $n = 6$) had an 89.2% accuracy rate. Further inspection indicated that the SBSOD scale was better than the K&B scale at predicting heading-recall performance for those participants in the midrange of the scale. This observation was confirmed by the following post hoc analysis. If the 11 people at the ends of the K&B scale were removed from the correlational analysis, the resultant correlation with heading-recall accuracy was .23, $p > .05$, compared with a .42, $p < .05$, correlation for the SBSOD scale.

*Local views.* To determine whether familiarity with the local view or the distance of the local view from the participant's actual location in the task environment predicted heading-recall accuracy or decision latency, or both, correlations were computed with local view as the unit of analysis. The correlations are reported in Table 4, and none were significantly different from zero. The absence of a correlation with familiarity is probably due to the restricted range of familiarity scores used in Experiment 1. However, distances were not similarly restricted, ranging from 100 to 1,716 feet from the laboratory.

## *Discussion*

Heading-recall accuracy correlated highly with both the K&B and SBSOD measures of SOD. Although on average, heading recall reached only modest levels of accuracy ($M = 59.4\%$ cor-

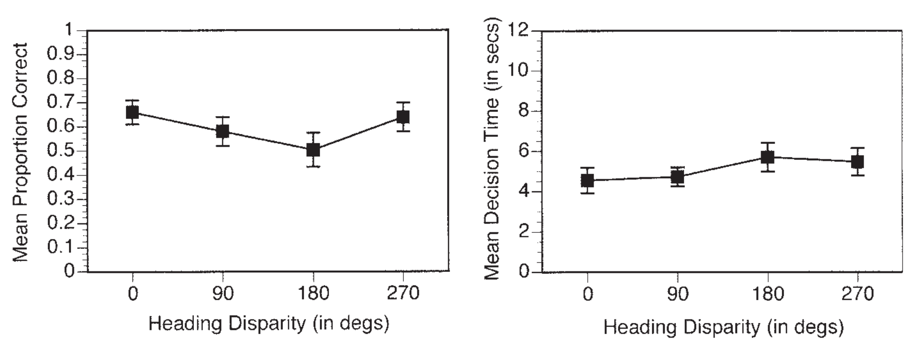


*Figure 3.* Mean accuracy rate and decision latency as a function of heading disparity in Experiment 1. Error bars are the standard errors of the mean.

Table 2
*Reliability Measures for SOD Self-Rating Scales*

| Experiment | Reliability measures | | |
|---|---|---|---|
| | $K\&B_p{}^a$/K&B | $K\&B_p{}^a$/SBSOD | K&B/SBSOD |
| 1 | | | .89 |
| 2 | .94 | .97 | .92 |
| 3 | .87 | .79 | .88 |

*Note.* The Kozlowski and Bryant (K&B) and Santa Barbara Sense of Direction (SBSOD) ratings were collected at the beginning of the experimental session in Experiments 2 and 3 and at the end of the session in Experiment 1. $K\&B_p$ are the pretest ratings that were used to screen participants for inclusion in the experiments.
[a] For correlations involving $K\&B_p$, $n = 12$ in Experiment 2 and $n = 30$ in Experiment 3. For all other correlations, $n = 32$ in Experiment 1, $n = 16$ in Experiment 2, and $n = 32$ in Experiment 3.

rect), the average fails to capture the wide variability in performance. This variability was described earlier in relation to the K&B ratings, and it is equally apparent in relation to the SBSOD scores. For participants at the upper quartile of the SBSOD scale, mean accuracy and latency were 82.2% and 4.120 s, respectively,[4] and for those at the lower quartile, the means were, 28.4% and 7.817 s, respectively. Although both the K&B and SBSOD measures accounted for a significant proportion of the variability in heading recall (46.2% and 54.8%, respectively), the SBSOD scale was better at discriminating people in the middle of the SOD scale. We interpret this finding as follows. People have a clear awareness of SOD system functioning when the system functions either very poorly or very well, but at intermediate levels of functioning self-awareness emerges from the variety of navigational skills to which the SOD system contributes.

Crossing default heading with picture heading produced an interesting, but unexpected, finding: the decrement in accuracy and latency for picture headings 180° opposed to the default heading. This finding can be explained by an inhibitory effect of the actual body heading on heading signals 180° opposed to it, and the roughly quadratic function that was observed for accuracy is predicted by continuous attractor network models of head-direction system function in animals (e.g., Sharp et al., 2001; Zhang, 1996). We will discuss the implications of the effect of heading disparity further in the General Discussion section, and planned comparisons test for quadratic trend in Experiments 2 and 3.

The failure to find a correlation between the distance of the local view from the test site and its mean decision latency and accuracy argues against an important alternative to our hypothesis that body heading is retrieved directly from long-term memory. The alternative is that the local view is retrieved from memory, but not the associated allocentric-heading signal. Instead, the body heading from which the local view is visible is reconstructed in working memory at retrieval. Sholl's self-reference system model of spatial retrieval (e.g., Easton & Sholl, 1995; Sholl, 2000; Sholl & Nolin, 1997) can explain how reconstruction might occur.

The local view could serve as a retrieval cue for location in an object-to-object representation of interlandmark relations. A translation transformation could then be imagined whereby a representation of the body axes is mentally detached from the actual body axes and mentally translated, holding allocentric heading constant, within the object-to-object representation from the body's actual location to the cued location (for a complete discussion of this and other self-reference system functions see Sholl, 2001). Previous findings reported by Easton and Sholl (1995) in a perspective-taking task suggested that such linear transformations of perspective occur in real time, as if memory of object-to-object relations is extended in a representational space (although see May, 2004, for an alternative account). Once mentally located at the location cued by the local view, the axis of orientation could be mentally rotated until the depicted scene comes into view. The rotated heading is the picture heading. Next we describe why the distance findings refute this account.

The correlational analysis of distance was conducted with local view as the unit of analysis. In this regard it is important to acknowledge the following. For each local view, the disparity between default heading and picture heading was counterbalanced across participants in the experimental design. However, because a valid indicator of processing time is only provided by correct response, this disparity was not counterbalanced in the computed latency mean.[5] In light of this, the net effect of mental rotation time should vary randomly across local views. In contrast, the time to linearly traverse from the actual to the cued location in the object-to-object system should vary systematically with distance (e.g., Easton & Sholl, 1995, Experiment 3). The finding of no correlation between latency and distance argues against the use of a linear perspective transformation to reconstruct in working memory the allocentric heading from which the local view is visible.

Experiment 2 was designed to replicate and extend the findings of Experiment 1 by addressing two limitations in its design. First, in Experiment 1 we relied on a random sampling to select participants. Because extreme self-ratings are less frequently observed in the population than moderate self-ratings, the disparity observed in heading-recall performance at the extremes of the SOD continuum was based on a small sample. To test the reliability of the observed performance disparity, we replicated Experiment 1, but used the K&B scale to prescreen participants, selecting for participation those from the low (ratings of 1 or 2) and the high (ratings of 6 or 7) extremes. Second, in Experiment 1, participants rated their SOD after having completed the heading-recall task. Previous research is mixed regarding carryover effects between SOD ratings and task performance and the directionality of such effects should they exist (Hegarty et al., 2002; Heth, Cornell, & Flood, 2002). Therefore, in Experiment 2 participants rated SOD before the heading-recall task.

## Experiment 2

### *Method*

*Participants.* Nineteen undergraduates with a minimum of two semesters of residency at BC were preselected for participation based on their

[4] If one outlier in the upper quartile was removed, mean accuracy was 90.4% and latency was 3.851 s.

[5] To elaborate this point, for a single local view, the picture heading was constant. That is, if the local view is visible when facing east, the picture heading was east. The variable that took on different values for different participants was the participant's default heading, or the extent of the alignment between the default heading and the picture heading.

Table 3
*Correlations ($r_{xy}$) and Unstandardized Regression Weights ($b_{yx}$) Relating Self-Rated Sense of Direction to Heading-Recall Accuracy and Correct Decision Latency in Experiments 1–3*

| | Heading-recall accuracy | | | | | Decision latency | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | K&B$_P$[a] | K&B | | SBSOD | | K&B$_P$[a] | K&B | | SOD | |
| Experiment | $r_{xy}$ | $r_{xy}$ | $b_{yx}$ | $r_{xy}$ | $b_{yx}$ | $r_{xy}$ | $r_{xy}$ | $b_{yx}$ | $r_{xy}$ | $b_{yx}$ |
| 1 | | .68*** | 14.10*** (2.77) | .74*** | 19.80*** (3.32) | | −.39** | −0.92** (0.40) | −.44** | −1.35** (0.50) |
| 2 | .67* | .82*** | 10.34*** (1.96) | .69** | 10.18** (2.82) | .04 | −.15 | −0.26 (0.44) | −.12 | −0.23 (0.52) |
| 3 | .44* | .51** | 6.20** (1.93) | .51** | 9.76** (2.97) | .00 | −.02 | −0.04 (0.38) | −.10 | −0.31 (0.58) |

*Note.* Standard errors of estimate are in parentheses. K&B = Kozlowski and Bryant; SBSOD, Santa Barbara Sense of Direction.
[a] For correlations involving K&B$_P$, $n = 12$ in Experiment 2 and $n = 30$ in Experiment 3. For all other correlations, $n = 32$ in Experiment 1, $n = 16$ in Experiment 2, and $n = 31$ in Experiment 3.
* $p \leq .05$. ** $p \leq .01$. *** $p < .001$ (two-tailed).

K&B ratings. In most cases, these ratings were collected at the beginning of the academic semester during the mass-testing of students eligible for the psychology department human subjects pool. Other ratings were obtained electronically in response to mass e-mails sent to all students majoring in psychology and to those in other College of Arts & Sciences departments. Eight students who rated themselves at the low end of the K&B scale (within 2 points of *poor*) formed the PSOD group and 11 students who rated themselves at the high end of the scale (within 2 points of *excellent*) formed the GSOD group. Because of scheduling uncertainties, the GSOD sample contained three more participants than the eight needed for a balanced design. As a result, there were extra GSOD participants in some factor-level combinations (i.e., SOD × Gender × Default Heading). For those combinations, in keeping with the extreme-groups approach used in Experiment 2, we selected for inclusion for further analysis the participant with the highest ratings on both the K&B and SBSOD scales.

*Procedure and design.* The procedure was the same as that followed in Experiment 1 with the following modifications. Four practice trials with feedback preceded the experimental trials. Two pictures were added to each picture-heading condition to bring the total in each condition to 12. The revised familiarity means are reported in Table 1. The experimental design was a completely crossed factorial with three between-subjects variables (gender, SOD, and default heading) and one within-subjects variable (picture heading). Because only one participant was assigned to each factor-level combination, the full factorial design could not be analyzed. Instead, we combined the default-heading and picture-heading variables to generate a heading-disparity variable.

Table 4
*Correlation of Familiarity and Distance With Decision Latency and Accuracy With Local View as the Unit of Analysis in Experiments 1–3*

| | | Local view familiarity | | Local view distance | |
|---|---|---|---|---|---|
| Experiment | $n$[a] | Decision latency | Proportion correct | Decision latency | Proportion correct |
| 1 | 40 | −.04 | −.04 | +.17 | −.15 |
| 2 | 48 | −.19 | +.06 | +.03 | −.25 |
| 3 | 96 | −.16 | .08 | +.29** | −.19 |

[a] Number of local views on which correlations are based.
** $p < .01$.

## Results

*Accuracy.* A 2 (SOD: GSOD, PSOD) × 2 (Gender: male, female) × 4 (Heading disparity: 0°, 90°, 180°, 270°) ANOVA with repeated measures on the last factor was conducted on the proportion correct. Mean accuracy as a function of SOD and heading disparity is plotted in Figure 4. There was a main effect of SOD, $F(1, 12) = 15.43$, $MSE = 0.126$, $p = .002$, favoring GSOD ($M = .80$) over PSOD ($M = .45$) participants. There were no other significant main or interaction effects by omnibus $F$ test. A planned quadratic trend analysis of the effect of heading disparity was significant for the GSOD group, $t(36) = 2.03$, $p = .03$, $r_{contrast} = 0.32$,[6] but not the PSOD group, $t(36) < 1.0$.

*Rotation time.* A planned linear trend analysis conducted on rotation times was significant, $F(1, 15) = 176.58$, $MSE = .078$, $p < .001$, with latencies of 1.022, 1.732, and 2.336 s for 0°, 90°, and 180° turns, respectively. The absolute magnitude of the turning angle accounted for 92.2% of the variability in rotation time.

*Decision latency.* Trimming outliers eliminated 1.44% (7 of 478 correct responses) of the decision latencies. One-half of the PSOD participants, whose accuracy rates ranged from 19% to 33%, failed to meet the 50% accuracy-rate criteria. Therefore, we did not include the PSOD group in the analysis. We also excluded from the analysis a GSOD outlier whose mean decision latency ($M = 14.785$ s) was 5 $SD$ above the mean ($M = 5.387$ s) of the distribution of the other GSOD means. There was one GSOD participant whose accuracy rate (48% correct) was below the 50% criterion, but because we were concerned about small sample size, this participant was included in the analysis.

A 2 (Gender) × 4 (Heading Disparity) ANOVA with repeated measures on the last factor showed an effect of heading disparity that approached significance, $F(3, 15) = 2.82$, $MSE = 0.75$, $p = .07$. Mean decision latencies as a function of heading disparity are plotted in Figure 4, and a planned quadratic contrast, $t(15) = 2.68$, $p < .001$, $r_{contrast} = 0.57$, confirmed a performance profile similar

[6] The contrast $r$ ($r_{contrast}$) is the partial correlation between the lambdas for quadratic trend and the individual scores, with noncontrast sources of variability partialed out (Rosnow & Rosenthal, 1996).

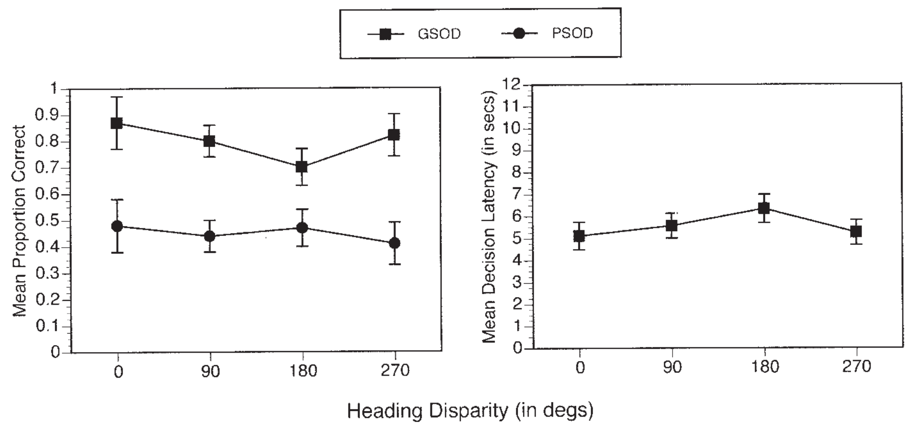


*Figure 4.* Mean accuracy rate and decision latency as a function of SOD group and heading disparity in Experiment 2. Error bars are the standard errors of the mean.

to that observed for accuracy. There were no other significant main or interaction effects.

*SOD.* Reliability measures for the SOD scales are listed in Table 2. Although it is not apparent from the K&B test–retest correlations, 5 of the 7 male participants showed a slight regression toward the mean from the first administration of the K&B scale to the second, as did 2 of 8 female participants. In most cases, scores changed by 1 point, but 2 male participants showed a 2-point regression toward the mean. Consequently, although all participants were selected from the ends of the SOD continuum, at testing some participants (4 male and 0 female) fell in the K&B midrange (ratings of 3–5). This is perhaps unavoidable when one is sampling from the extremes, but it is notable that male self-ratings were less stable than female self-ratings.

One of the costs of using an extreme-groups approach is that information about individual SOD ratings is lost (for a critical review of the extreme-groups approach, see Preacher, Rucker, MacCallum, & Nicewander, 2005). Therefore, in Table 3 we report the correlations between the two SOD measures and mean heading-recall accuracy (% correct) and latency, even though with sampling from the SOD extremes, as we did in Experiment 2, there is a risk of inflating the estimated population correlation (Preacher et al., 2005). Preacher et al. simulated the effect of omitting the middle of the *x* distribution (in our case the SOD distribution) on the sample correlation between *x* and *y*. They found little effect on very high or very low correlations; however, for correlations around .70, such as we observed in Experiment 1, omitting the middle one third (one half) of the distribution increased the correlation by .06 (.10) unit. We omitted between roughly one third and one half of the middle of the distribution, and if we split the difference to estimate gain, the Experiment 2 correlations may be inflated by about .08 unit. Preacher et al. recommend using unstandardized regression weights as measures of effect sizes in extreme-groups designs, because their values are not affected by omitting the midrange. Therefore, we include unstandardized regression weights in Table 3 to facilitate comparisons across experiments.

To further facilitate comparisons across experiments, the line graph in Figure 5 plots the mean accuracy as a function of K&B self-rating for each experiment.[7] The bar graph overlaid at the bottom of the figure plots the K&B frequency distribution for each experiment, that is, the proportion of K&B ratings of each value in the sample distribution. Comparing Experiment 2 to Experiment 1 shows that (a) not unsurprisingly, extreme-groups sampling largely eliminated the middle of the SOD distribution and (b) with the exception of the "2" ratings, the accuracy distributions were very similar across the two experiments. The same data depicted in Figure 5 for the K&B scale are reported in Table 5 for the SBSOD scale, which shows generally the same pattern as the K&B scale, but not quite as cleanly.

*Local views.* With local view as the unit of analysis, local-view familiarity and distance from the test site were correlated with the mean decision latency for correct responses and the proportion correct. The correlations are reported in Table 4, and as in Experiment 1 they do not differ significantly from zero.

## Discussion

Experiment 2 used an extreme-groups approach to replicate the heading-recall performance differences observed in Experiment 1. Comparing performance across the two experiments is complicated by their different sampling procedures. That said, both the regression weight comparisons (Table 3) and the distribution comparisons (Figure 5 and Table 5) show a strong linear relation between SOD ratings and heading-recall accuracy, but with a steeper slope in Experiment 1 than Experiment 2. The difference in slopes may be attributable to the fact that SOD ratings were collected after heading recall in Experiment 1 and before heading recall in Experiment 2. Therefore, in Experiment 1, but not Experiment 2, heading-recall performance could have carried over to affect SOD self-ratings. Nevertheless, whether we used the K&B, $K\&B_P$, or SBSOD ratings to dichotomize Experiment 2 participants into extreme groups, the between-groups disparity in

[7] The decision latency data were not compared across experiments because of the instability of the data for those participants with low accuracy rates.

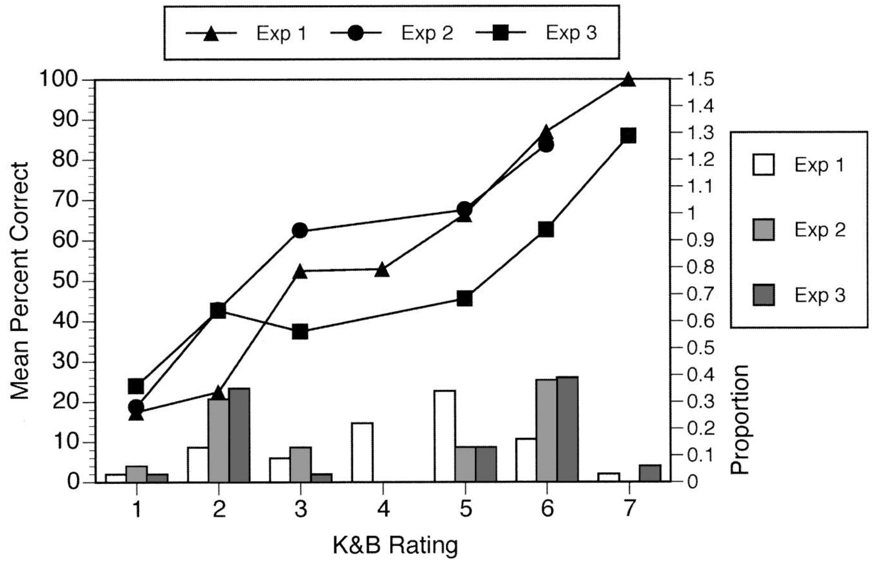


*Figure 5.* K&B frequency distributions in Experiments 1 to 3 (bar graph with proportion correct scaled on the right-hand *y*-axis) overlaid on a line graph of mean accuracy rate as a function of K&B self-rating.

heading-recall accuracy was substantial. Thus, Experiment 2 replicates the finding that heading-recall accuracy and self-rated SOD are highly associated, providing convergent validity for our hypothesis that heading recall measures the functioning of an allocentric-heading system.

Planned comparisons also replicated the quadratic relation between heading disparity and heading-recall performance that was observed in Experiment 1. However, in Experiment 2 the effect was limited to the GSOD group. It was not apparent in PSOD accuracy, and PSOD decision latencies could not be analyzed. The quadratic trend is produced by a clear decrement in the retrieval of the picture heading 180° opposite the default heading, with intermediate or null retrieval decrements for picture headings either 90° cw or ccw from the default heading.

In Experiment 3, we increased the difficulty of the heading-recall task both to test further the functional properties of an allocentric-heading system and to assess the effect of a more challenging task on correlations with self-reported SOD. An extreme-groups approach was used, and the functional granularity of the system was tested with an 8AFC task. Picture headings midway between those used in Experiment 1 were added to the experimental design, so that neighboring headings differed by 45° rather than 90°. By increasing the number of response alternatives to eight, we are approaching the upper limit of the number of allocentric headings hypothesized to be behaviorally distinguishable by Baird et al. (2001).

## Experiment 3

### Method

*Participants.* Thirty-two BC undergraduates were recruited for participation in a manner similar to that used in Experiment 2. The 16 partici-

Table 5
*Santa Barbara Sense of Direction (SBSOD) Frequency Distributions in Experiments 1–3 and Mean Accuracy at Each Interval in the Distribution*

| | Experiment | | | | | |
|---|---|---|---|---|---|---|
| | 1 | | 2 | | 3 | |
| Score | Proportion (*n* = 32) | Mean accuracy | Proportion (*n* = 16) | Mean accuracy | Proportion (*n* = 31) | Mean accuracy |
| 1.5 | .00 | | .06 | 72.9 | .03 | 27.1 |
| 2.5 | .22 | 28.6 | .31 | 38.8 | .10 | 41.1 |
| 3.5 | .22 | 40.4 | .13 | 45.8 | .29 | 38.3 |
| 4.5 | .31 | 76.0 | .06 | 83.3 | .16 | 55.2 |
| 5.5 | .22 | 79.6 | .25 | 72.9 | .35 | 63.1 |
| 6.5 | .03 | 100.0 | .19 | 87.5 | .06 | 77.1 |

*Note.* Frequencies are reported as the proportion of participants in each SBSOD interval, accuracy as percent correct, and the SBSOD intervals are labeled with their midpoints.

pants from each of the two K&B extremes included an equal number of males and females.

*Materials.* The N, S, E, and W picture sets were the same as those used in Experiment 2. NE, NW, SE, and SW picture sets were generated using a procedure similar to that described in Experiment 1. Picture familiarity was rated by an independent group of 22 undergraduates and from a total pool of 77 pictures, those with the highest familiarity ratings were included in the NE, NW, SE, and SW picture sets. Mean familiarity ratings are listed in Table 1.

*Design and analysis.* Default heading was completely crossed with picture heading to create an 8 (Default Heading: N, NE, E, SE, S, SW, W, NW) × 8 (Picture Heading: N, NE, E, SE, S, SW, W, NW) design with repeated measures on the second factor. The design called for the assignment of a single participant from each of the four Gender × SOD categories to each default heading. A 2 (Gender) × 2 (SOD) × 8 (Heading Disparity: 0°, 45°, 90°, 135°, 180°, 225°, 270°, 315°) ANOVA was planned with repeated measures on the last factor. However, because of experimenter error, the default headings for 18 of the 32 participants were recorded incorrectly. Consequently, default heading was not counterbalanced across the SOD × Gender groups. For those 18 participants, default headings were computed from the rotation time data. This approach was validated by the clear separation between decision time and rotation time in Experiments 1 and 2, as indicated by the fact that in those experiments 90% of the variance in rotation time was accounted for by the magnitude of the physical turn.

Default headings were computed as follows. As in the analysis of rotation time in Experiments 1 and 2, for each participant, the rotation times for all 96 trials were sorted by response heading, and the mean rotation time was computed for each of the 8 alternative response headings. The typical rotation–time profile was as follows. The response heading with the shortest rotation time was directly opposite the response heading with the longest rotation time, and rotation time systematically increased in both a cw and ccw direction from the former to the latter. The response heading that had the shortest rotation time and from which rotation times increased linearly in both directions was assigned as the default heading. To verify that default headings were correctly assigned, rotation times were regressed onto the angular disparity between each response heading and the assigned default heading, and the results of this analysis are reported at the beginning of the Results section.

To provide convergent validity for the default headings computed from the rotation–time data, we contacted all participants and asked them to report their default headings. We sent them a schematic diagram of the lab room showing the window, door, and so forth and asked them to report the direction they faced when sitting in front of the computer. The response rate was 75% (students were contacted in the summer, and we were unable to reach the other 25%). Of the nine respondents whose default headings had been properly recorded, eight reported default headings consistent with those recorded and one was not sure of her default heading. Of the 15 respondents for whom we had no accurate record of default heading, 13 remembered their default heading as the same as the one we computed from the rotation–time data. We were therefore confident that the default headings were assigned correctly.

After the default headings were computed, it became clear that default heading was not balanced across each gender by SOD group. Although participants had been tested in all eight default-heading conditions, there were varying numbers of participants in each. To control for default-heading orientation in the analysis of heading disparity and to counterbalance default heading across SOD group, we selected a subset of participants for inclusion in a 2-factor (SOD × Heading Disparity) ANOVA. The eight participants selected from each SOD group each performed the task from a different default heading, so that each of the eight default headings was represented in each SOD group. In those cases in which there was more than one participant to assign, we selected the one with the most extreme SOD ratings. We subsequently conducted the same analysis on the entire 31 participants for whom we were able to compute default headings. The results were virtually identical, and hence we report the results for both the subset and the full set of participants.

*Procedure.* The procedure was similar to that used in Experiment 2. After signing a consent form and completing the K&B and SBSOD self-rating scales, the participant looked out the window to identify the direction of north. The participant was then seated facing the computer in one of the eight default headings. The eight alternative picture headings were indicated by color-coded markers arranged in a circle on the floor surrounding the participant. Following a set of standard instructions explaining the task, eight practice trials were presented with feedback in a fixed serial order, during which the experimenter ensured that the participant understood the task. The practice trials were followed by 96 experimental trials in a separate random order for each participant. A short break was offered halfway through the experimental trials.

## Results

*Rotation times.* In Experiment 3, rotation times were used to compute the 18 default headings that had been recorded improperly. One of the 18 participants was excluded from all further analyses, because his computed default heading was ambiguous. A second participant was excluded from the rotation-time analysis, because two response headings contained zero entries. To analyze the validity of the default-heading variable in Experiment 3, rotation times were regressed onto the rotation angles computed from the assigned default headings for all 31 participants whose data are reported in the following sections. An erroneously assigned default heading would produce incorrect rotation angles and introduce noise into the function relating rotation time to rotation angle. Thus, the validity of default heading assignments is indicated by a regression function that accounts for as much of the variability in rotation time in Experiment 3 it did in Experiments 1 and 2.

A quadratic trend analysis was conducted on rotation time as a function of the angular disparity between the assigned default heading and each response heading. Angular disparity was measured in a cw direction from 0° (the alignment of the default heading) to 315°. The relation between angular disparity and rotation angle is illustrated in the following example. If NE is the default heading, the cw angular disparity between it and an E response heading is 45°, and an east response is produced by a 45° cw rotation from NE. A N response heading deviates 315° cw from a NE default heading, and a N response is produced by 45° ccw rotation from NE.

Figure 6 shows the quadratic function that accounted for 93.7% of the variability in rotation times, $F(1, 29) = 434.09$, $MSE = .062$, $p < .001$. Rotation time for the default heading (a 0° rotation angle) was plotted at both ends of the *x*-axis to emphasize the symmetry of the function. Because participants rotated through the smallest physical angle, the left-hand side of the function measures the rate of cw rotation from the default heading, and the right-hand side of the function measures the rate of ccw rotation from the default heading.

*Accuracy.* First, we report the results of the ANOVA conducted on the counterbalanced subset of 16 participants and then the results of the ANOVA conducted on the full set of 31 participants. A 2 (SOD: good, poor) × 8 (Heading Disparity: 0°, 45°, 90°, 135°, 180°, 225°, 270°, 315°) ANOVA with repeated measures on the last factor showed a main effect of SOD, $F(1, 14) = 14.34$, $MSE = 0.178$, $p = .002$, and a main effect of heading disparity, $F(7, 98) = 3.09$, $MSE = 0.030$, $p = .006$. The interac-

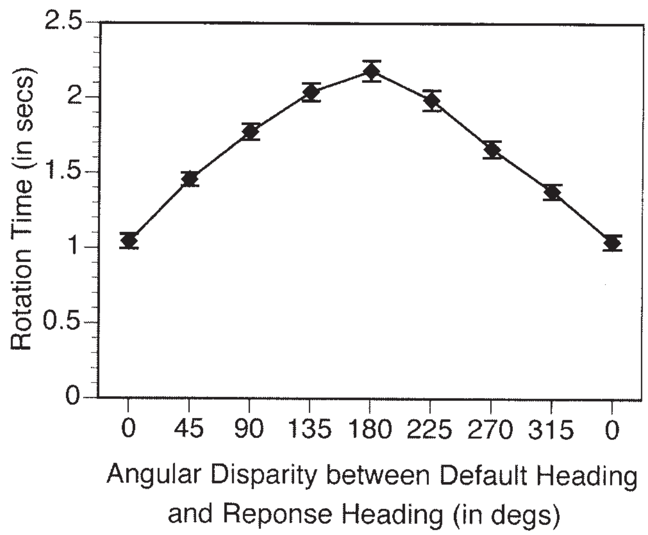


*Figure 6.* Mean rotation time as a function of the cw deviation of the response heading from the assigned default heading. The default heading (0°) is plotted at both ends of the function to illustrate its symmetry.

tion between SOD and heading disparity was nonsignificant, $F(7, 89) = 1.10$. Planned contrasts showed a significant quadratic function relating accuracy to heading disparity for both the GSOD group, $t(98) = 3.45$, $p < .001$, $r_{\text{contrast}} = .33$, and the PSOD group, $t(98) = 1.89$, $p = .03$, $r_{\text{contrast}} = .19$.

Virtually the same outcome was observed when the ANOVA was conducted on all 31 participants. Therefore, mean accuracy as a function of heading disparity for the full set of participants is shown in Figure 7. There was a main effect of SOD, $F(1, 14) = 6.61$, $MSE = 0.402$, $p = .02$, favoring the GSOD ($M = .63$) over the PSOD ($M = .43$) group. There was also a main effect of heading disparity, $F(7, 203) = 4.76$, $MSE = 0.026$, $p < .001$, and planned quadratic trend analyses indicated a significant quadratic trend for both the GSOD group, $t(203) = 4.97$, $p < .001$, $r_{\text{contrast}} = .33$, and the PSOD group, $t(203) = 1.71$, $p = .05$, $r_{\text{contrast}} = .12$.

To assess whether default heading relative to the intrinsic structure of the outdoor environment affected recall, we divided the 31 participants into those whose default headings were aligned with the intrinsic structure (N, S, E, W) and those whose default headings were misaligned (NE, SE, SW, NW). It was also of interest to test whether picture-heading alignment was similarly affected by intrinsic structure, and for that purpose we dichotomized picture headings into aligned and misaligned categories. A 2 (Gender) × 2 (SOD) × 2 (Default-Heading Alignment: aligned, misaligned) × 2 (Picture-Heading Alignment: aligned, misaligned) ANOVA with repeated measures on the last factor was performed. Default-heading orientation was not counterbalanced within the aligned and misaligned categories. That is, there were an unequal number of N, S, E, and W (NE, SE, SW, and NW) default headings in the aligned (misaligned) condition. Therefore, in reporting the effects of alignment, we rely on the assumption that at this coarser level of analysis, all aligned (misaligned) default headings will have similar effects on the retrieval of aligned and misaligned picture-headings. Further, we restricted the results reported to effects involving alignment.

An interaction between default-heading alignment and picture-heading alignment, $F(1, 23) = 3.61$, $MSE = 0.007$, $p = .07$, approached significance. The interaction was attributable to better aligned ($M = .62$) than misaligned ($M = .55$) picture-heading recall when the default heading was aligned with the built environment, $t(23) = 2.4$, $p = .02$, but no difference between aligned ($M = .49$) and misaligned ($M = .50$) picture-heading recall when the default heading was misaligned with the built environment, $t(23) < 1.0$. Default heading alignment also interacted with SOD, $F(1, 23) = 8.97$, $MSE = 0.007$, $p < .01$, and gender, $F(1, 23) = 9.46$, $MSE = 0.07$, $p < .01$. The interactions were attributable to the following. There was no effect of default-heading alignment for the GSOD group, $t(23) < 1.0$, but an advantage of aligned over misaligned default headings for the PSOD group, $t(23) = 2.14$, $p = .04$. Similarly, there was no effect of default-heading alignment for male participants, $t(23) < 1.0$, but an advantage of aligned over misaligned default headings for female participants, $t(23) = 2.18$, $p = .04$. There were no other effects involving either picture-heading or default-heading alignment.

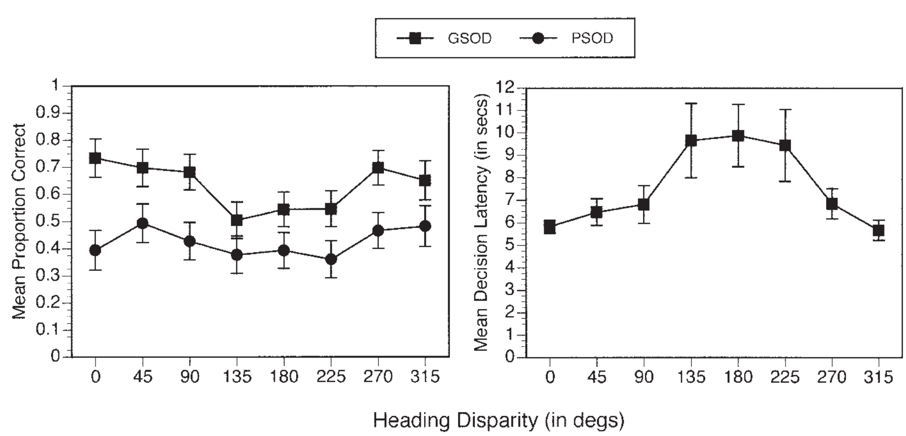


*Figure 7.* Mean accuracy rate and decision latency as a function of SOD group and heading disparity in Experiment 3. Error bars are the standard errors of the mean.

*Decision latency.* Trimming outliers eliminated 1.7% of the correct decision latencies. As in the prior experiments, an insufficient number of PSOD participants met the 50% accuracy criterion for inclusion in the analysis. Consequently, no analysis was conducted on PSOD decision latencies. A 2 (Gender) × 8 (Heading Disparity) ANOVA was conducted on both (a) the subset of GSOD participants whose default headings were counterbalanced ($n = 8$, all responded at ≥50% accuracy) and (b) on the full set of GSOD participants who met the 50% accuracy criterion ($n = 12$). The results were virtually indistinguishable and to avoid redundancy, we report just the results from the larger sample and plot those means in Figure 7. The analysis showed a main effect of heading disparity, $F(7, 70) = 4.53$, $MSE = 8.367$, $p < .001$, characterized by a significant quadratic trend, $t(70) = 5.20$, $p < .001$, $r_{\text{contrast}} = .53$.

*SOD measures.* The reliability indices for the SOD measures are reported in Table 2, the SOD frequency distributions and mean accuracy rates are reported in Table 5 and Figure 5, and the correlations with accuracy and decision latency are reported in Table 3. Although the correlations relating SOD to heading recall and accuracy were significant, they were substantially lower than those observed in Experiments 1 and 2. Along with the lower correlations, the unstandardized regression weight predicting the accuracy rate from K&B self-ratings is smaller in Experiment 3 than in the other experiments. A less clear picture emerges when unstandarized regression weights are compared for the SBSOD scale.

*Local views.* The proportion of participants who correctly retrieved the picture heading and the mean latency for correct decisions were calculated for each local view. These values were correlated with each local view's mean familiarity rating and its distance from the test site. The correlations are reported in Table 4. There was a significant +.29 correlation between decision latency and distance, which is discussed below.

## Discussion

In Experiment 3, the number of picture headings was doubled, thereby increasing task difficulty by requiring finer-grained discriminations between alternative headings. We were interested both in how increased task difficulty would impact heading-recall performance at the SOD extremes and in what the greater demands placed on the allocentric-heading system would reveal about its underlying functional properties. In answer to these questions, the cleanest comparison is between the two experiments that used an extreme-groups approach—Experiments 2 and 3. For outcomes related to self-rated SOD, we limit our discussion to the K&B self-ratings. We do so primarily to avoid redundancy, because the K&B outcomes were largely similar to the SBSOD outcomes. But we also focus on the K&B outcomes because they were somewhat clearer than the SBSOD outcomes. First, we discuss the outcomes related to extreme-group performance and then turn to a discussion of the functional properties of the system.

The various measures relating self-rated SOD to heading-recall performance converge to show that the effect of increased task difficulty was limited to the middle and high end of the SOD continuum. Comparison of mean accuracy rates indicated that GSOD accuracy rates were impaired on the 8AFC relative to the 4AFC task (*M*s = .63 and .80, respectively) but PSOD accuracy rates were not (*M*s = .43 and .45, respectively). The correlational analysis showed that SOD accounted for considerably less of the variability in accuracy on the 8AFC than on the 4AFC task, and the K&B unstandarized regression weights indicated that each 1-point increase in K&B rating predicted a smaller increment in 8AFC than 4AFC accuracy. The Experiment 3 function relating heading-recall accuracy to K&B self-ratings in Figure 5 had the lowest slope of all the experiments, which was principally attributable to the relative drop off in 8AFC performance at the middle and upper end of the K&B continuum. The drop off in the accuracy rate for those reporting better SODs suggests that the 8AFC task challenged the upper limits of sensitivity of the allocentric-heading system. Failure to find a decrease in accuracy at the low SOD extreme is probably attributable to a floor effect. Examination of the accuracy rate distribution for the 13 low-extreme participants (1s or 2s) in Experiment 3 indicated that scores were stacked up at the low end of the accuracy-rate distribution. The modal accuracy rate ($n = 5$) was between 10% and 20%. Chance performance was 12.5% on this task, and no participant had <10% correct.

A quadratic relation between heading disparity and heading-recall performance is consistent with continuous-attractor network models of head-direction system functioning. Such models predict progressively greater inhibition of HD signals with increasing disparity from the active HD signal. In Experiment 2, quadratic functions were observed at four levels of heading disparity, and Experiment 3 replicated and extended this finding to eight levels of heading disparity. If a quadratic function is indeed a marker of an underlying continuous attractor network, the stronger quadratic functions observed for the GSOD group than for the PSOD group suggest a less stable network organization in the latter group.

The Experiment 3 results also begin to address the role of the intrinsic structure of the built environment on allocentric-heading system functioning. In Experiments 1 and 2, allocentric headings aligned with the environment's intrinsic structure were tested. In Experiment 3, we added diagonal headings that were 45° out of alignment with that structure. An aligned default-headings advantaged aligned picture headings in Experiment 3, but a comparable effect was not found for the misaligned default-headings. At minimum, this result indicates that the allocentric-heading system is sensitive to the intrinsic structure of the local environment. The finding that default-heading alignment affected the performance of the PSOD group and the female group but not that of the GSOD group and the male group suggests that the allocentric-heading system may be more sensitive to the geometric structure of the immediate surroundings in some groups than in others.

Finally, there was a modest positive correlation between local-view distance and decision latency. Although accounting for only 8% of the variability in decision latencies, an effect of distance could indicate some degree of reliance on the egocentric strategy described earlier. We think this is unlikely because an egocentric strategy could not explain the quadratic function relating decision latency to heading disparity. Local-view recognition is an alternative locus for an effect of distance, with nearby local views being primed by the outdoor environment. Additional research will be needed to resolve this issue, and it will not be discussed further here.

## General Discussion

In the experiments reported in this article, we used a forced-choice heading-recall task to test the functional properties of an allocentric-heading system and then related heading-recall performance to self-reported SOD. Performance on the 4AFC task used in Experiment 1 provided behavioral evidence that local views convey directional information and that people's sensitivity to this information is highly correlated with self-reported SOD. Experiment 2 replicated the disparity in heading recall at the SOD extremes, although the observed performance disparity was not as large as that in Experiment 1. This finding was probably attributable to the fact that SOD ratings were collected after heading recall in Experiment 1 but before heading recall in Experiment 2. Task difficulty was increased in Experiment 3 with an 8AFC, which had the effect of depressing the accuracy rates at the high SOD extreme. Failure to find impaired performance at the low SOD extreme was probably due to a floor effect. In sum, both heading recall and self-rated SOD appear to measure the functional efficacy of a common cognitive system. We contend that the system in question is an allocentric-heading system, which computes allocentric heading during navigation and links heading signals to local views of the navigated environment. The extreme variability in performance observed in these experiments suggests that the allocentric-heading system functions at different levels of efficacy in different individuals.

In each of the three experiments, the single-item K&B SOD scale and the multi-item SBSOD scale accounted for similar levels of variability in heading-recall performance. This is unsurprising given the high positive correlation between the two scales (see Table 2). This finding suggests that single-item SOD scales serve as adequate substitutes for multi-item scales, despite their psychometric disadvantages. As reviewed earlier, based on their analysis, Robins et al. (2001) concluded that single-item scales can be substituted for multi-item scales when the to-be-measured construct is single-faceted, "highly schematized," and consciously accessible. We review these criteria in reverse order to assess the extent to which they characterize the SOD construct. First, because much cognitive processing takes place outside of conscious awareness, the validity of self-reported cognitive ability is generally considered suspect. However, in the case of SOD, a poorly functioning allocentric-heading system has highly salient behavioral consequences, which are consciously accessible. Second, SOD is also a highly schematized construct with well-known behavioral consequences—people with a good SOD can easily find their way in new environments; whereas, people with a PSOD get lost. Whether SOD meets the third criterion is subject to debate. Our view is that SOD is a single-faced construct that is instantiated in an allocentric-heading system. However, others view it as a multifaceted construct (Hegarty et al., 2002), and which of these two perspectives is correct cannot be resolved with a correlational approach.

We now turn to a discussion of the properties of the allocentric-heading system itself. In all three experiments, default heading systematically influenced heading-recall performance. Generally, participants were most accurate when the picture heading was aligned with their default heading, least accurate when the picture heading was 180° opposite their default heading, and intermediately accurate for intermediate picture headings. In the subset of participants whose latency data were analyzable, the same pattern was observed. As mentioned earlier, this quadratic function is predicted by a continuous attractor network of HD units. As a reminder, for ease of discussion we treat HD and body direction as identical in orientation.

Continuous attractor networks have been used to model the response properties of HD cells in rats (Goodridge & Touretzky, 2000; Redish, Elga, & Touretzky, 1996; Samsonovich & McNaughton, 1997; Skaggs, Knierim, Kudrimoti, & McNaughton, 1995; Zhang, 1996) and monkeys (Stringer, Trappenberg, Rolls, & de Araujo, 2002). At a functional level, a continuous attractor network has been described as a collection of HD units arranged in a ring, with each unit tuned to the direction of an arrow projecting outward through the unit from the ring's center. A single bubble of activity is centered over the unit tuned to the animal's current allocentric heading. The movement of the activity bubble around the ring is yoked to body rotation, so that activity is always centered on the HD unit tuned to the allocentric heading aligned with the axis of orientation. The net effect of the excitatory and inhibitory interconnections between the units permits only one bubble of activity at any moment in time.

Applying a generic continuous attractor model to the response profiles observed in heading recall suggests the following interpretation of the quadratic function relating heading-recall performance to heading disparity. The HD system signals the participant's default heading with a bubble of activity centered over the HD unit tuned to the allocentric direction of the axis of orientation. While active, this unit inhibits the activity of other units in the network. The inhibition is progressively stronger as the disparity in preferred direction increases, with the unit tuned to the direction opposite the active unit receiving the greatest inhibitory input. If allocentric heading is retrieved by activating the HD unit linked to a visual representation of a local view in spatial memory, as we believe to be the case, then the more the activity of the HD unit is suppressed, the less likely its directional signal will be retrieved.

To summarize, the present findings provide preliminary behavioral support for a human allocentric-heading system with functional properties similar to those observed in nonhuman animals. These properties include a continuous attractor network of HD units, each of which signals a different allocentric heading, and each of which is connected to a set of local views visible from the unit's preferred heading. The system can behaviorally discriminate up to eight alternative allocentric headings, but there are large individual differences in the efficacy of system functioning. More research will be needed to verify our interpretation of the findings, but we believe they are sufficiently promising to justify the effort.

As is the case with any initial inquiry, many important questions remain unanswered. Some of these questions have been raised earlier in the article. Generally, they concern the structure and function of a human allocentric-heading system—how is an allocentric reference direction perceived, what is the impact of the intrinsic structure of the local environment on allocentric-heading system functioning, at what point in the processing flow does body direction assume primacy over head direction, how does the system interface with the other systems (e.g., memory systems and perceptual-motor systems) that contribute to human navigation, and what are the adaptive implications of such wide variability in the functional efficacy of a system so important to human survival. We look forward to continued research on these important issues.

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