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A Cognitive Model of Strategies for Cardinal Direction Judgments

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ABSTRACT

Previous research has identified a variety of strategies used by novice and experienced navigators in making cardinal direction judgments (Gugerty, Brooks, & Treadaway, 2004). We developed an ACT-R cognitive model of some of these strategies that instantiated a number of concepts from research in spatial cognition, including a visual-short-term-memory buffer overlaid on a perceptual buffer, an egocentric reference frame in visual-short-term-memory, storage of categorical spatial information in visual-short-term-memory, and rotation of a mental compass in visual-short-term-memory. Response times predicted by the model fit well with the data of two groups, college students ($N = 20$) trained and practiced in the modeled strategies, and jet pilots ($N = 4$) with no strategy training. Thus, the cognitive model seems to provide an accurate description of important strategies for cardinal direction judgments. Additionally, it demonstrates how theoretical constructs in spatial cognition can be applied to a complex, realistic navigation task.

Keywords: cardinal directions, cognitive modeling, visual short term memory.

INTRODUCTION

This project focuses on understanding the cognitive processes and structures people use in making a particular type of navigational judgment—using a map to determine the cardinal direction between two objects in the environment. We first developed a cognitive model of some of the strategies people use in making this type of cardinal direction judgment. To develop this model, we used verbal protocol studies of cardinal direction strategies (Gugerty, Brooks, & Treadaway, 2004), behavioral studies of cardinal direction judgments (Gugerty & Brooks, 2001, 2004; Gunzelmann, Anderson, & Douglas,

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2004), studies of other navigational tasks involving map use (e.g., Sholl, 1996, 2001), and studies of basic processes in spatial cognition (e.g., Brockmole & Irwin, 2005). Following the model development, we compared the model's predictions to two sets of human performance data.

Cardinal direction judgments merit investigation for both practical and theoretical reasons. In terms of practical applications, cardinal-direction judgments are used during realistic human navigation tasks, for example, navigation during aircraft or automobile travel. Also, many people find cardinal direction judgments quite difficult (Gugerty & Brooks, 2004); so understanding how people make these judgments can lead to training interventions and technology interfaces that can improve these judgments. In terms of theory, investigating cardinal direction judgments may increase our understanding of some of the basic cognitive processes used in spatial and navigation tasks, including: coordinating externally referenced, allocentric and body-referenced, egocentric information; integrating perceptual information with information in visual short term memory (VSTM); and coordinating categorical with metric information.

To place cardinal direction judgments in the context of other spatial and navigation tasks, we note that spatial cognition can be seen as using two general kinds of cognitive processes—implicit, automatic processes and explicit processes involving controlled, focal attention. Examples of implicit spatial processes include path integration, spatial updating, implicit learning of layouts by exploration and reward, and route following in well-learned environments. On the other hand, explicit, controlled processes are more likely to be used when people navigate within novel environments, use maps to navigate, and communicate navigational information. Of course, many spatial and navigation tasks use both implicit and explicit processes (e.g., Burgess, Spiers, & Paleologue, 2004). Nevertheless, cardinal direction judgments of the type studied here—in which people identified and reported the bearing between two objects in the environment—seem to involve extensive use of conscious strategies and explicit cognitive process.

Our choice of a modeling framework follows from this distinction between implicit and explicit navigation processes. Numerous neural network models have been developed for tasks that emphasize implicit processing such as path integration, learning simple layouts, and distance learning (Dawson, Boechler, & Orsten, 2005; Foster, Morris, & Dayan, 2000; Redish & Touretsky, 1998; Strosslin, Sheynikhovich, Chavarriaga, & Gerstner, 2005). On the other hand, symbolic cognitive models based on modeling architectures such as ACT-R (Anderson et al., 2004) and EPIC (Meyer & Kieras, 1997) are thought to be better suited for modeling tasks where explicit cognitive processes are important. Thus we chose the symbolic, ACT-R framework.

Before describing the details of our model, we describe the specific task that we studied, present some behavioral findings regarding cardinal direction judgments, and describe some of the strategies people use for these judgments that have been identified based on behavioral and verbal protocol studies.

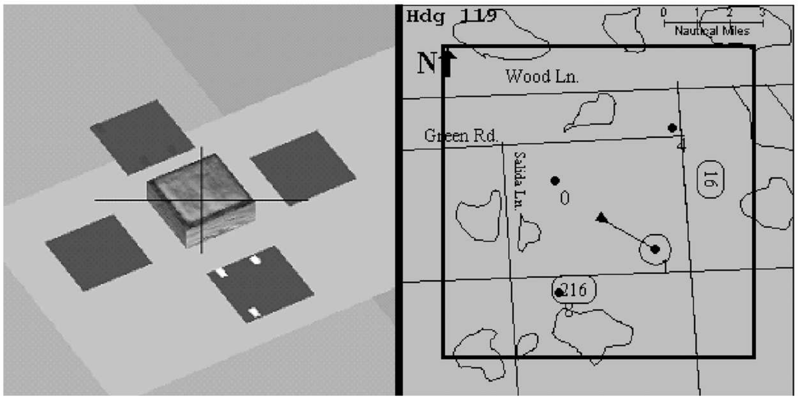

Figure 1. Example cardinal direction problem. The north-up map is on the right. The participant's aircraft is shown by a triangle and the current target by a dot surrounded by a circle. In this problem the aircraft is headed to the southeast. The 3D, forward view is on the left. It shows a central building surrounded by four parking lots, one of which (the lower right in this case) has cars in it. The task was to identify the bearing from the building to the parking lot with the cars, west in this problem.

Then we describe the decisions we made about the cognitive processes and structures to instantiate in our cardinal direction model, while attempting to ground these decisions in prior research and theory in spatial cognition. Following this, we describe the cognitive model in detail.

Figure 1 shows an example of the cardinal direction task used in this study. Participants must use information from a north-up map about the heading of their aircraft and information about a novel configuration of objects in the 3D forward view (as seen from their aircraft) in order to determine the bearing between two objects in the 3D view. Participants are required to express this bearing as a cardinal direction.

Decisions Regarding Overall Strategies to Model

Prior research has shown that the task shown in Figure 1 is quite difficult—e.g., 60% accuracy for novices' judgments (Gugerty & Brooks, 2001). Also, both accuracy and speed of cardinal direction judgments decline as the map heading becomes more misaligned with north (Gugerty & Brooks, 2001, 2004; Gunzelmann, Anderson, & Douglas, 2004). Some studies have shown a reversal of this misalignment cost for southerly map headings, which can be attributed to use of a specialized strategy of determining the bearing to the 3D target as if the map heading were north and then reversing this bearing (Gugerty & Brooks, 2001, 2004). At the worst alignment (heading to the southeast or southwest), novices' accuracy was about 45% on a task where chance performance was 25%. Experts are more accurate and faster than novices but show the same pattern of degraded performance when heading is misaligned with north (Gugerty & Brooks, 2004). These behavioral data showed that accuracy and speed of cardinal direction judgments are strongly degraded by increasing the misalignment of the participants' map heading with the map reference heading of north. They also suggest the use of multiple strategies for coping with misalignment. These include special-case strategies such as the north-heading strategy (for a quick readout of bearings from the 3D view for map headings of north) and the south-reversal strategy just described, as well as other general-purpose strategies applicable when the map heading is between north and south.

We conducted two verbal protocol studies (Gugerty & Brooks, 2001; Gugerty et al., 2004) to identify the general-purpose strategies used for headings between north and south. These studies used 6 novice and 10 experienced navigators (college students and aircraft pilots, respectively). Most participants were very consistent in their preferred strategy. The most common strategy for both novices and experts was called heading referencing (used by 50% of participants). This involves first determining the aircraft heading on the map and expressing it as a cardinal direction, then mapping this heading to the vector ahead in the forward view, then determining the bearings from the central building to the far (top) lots in the forward view, then if necessary determining the bearings from the building to the near (bottom) lots, and finally responding. The next most frequent strategy was mental rotation (used by 25% of participants). The remaining 25% of the participants used the heading referencing strategy for some types of cardinal direction problems and the mental rotation strategy for other types.

One type of mental rotation strategy involves first determining the angle formed in the forward view by the line from the viewer to the building and the line from the building to the lot with the cars, then mentally translating this angle to the map so its vertex overlays the aircraft's target, and then rotating the angle about its vertex until the angle leg from the viewer to the vertex aligns with the map line from the aircraft to the target. At this point, the rotated angle leg from the vertex to the lot with cars points to the correct cardinal direction. Gunzelmann et al. (2004) also presented verbal protocol evidence for the use of this mental rotation strategy. Gunzelmann et al. (2004) developed an ACT-R cognitive model of the mental rotation strategy just described. In the current project, we developed ACT-R models of the heading referencing, north-heading and south-reversal strategies.

Global Cognitive Processes in Cardinal Direction Judgments

Peoples' verbal descriptions of these general-purpose strategies for cardinal direction judgments—heading referencing and mental rotation—suggest that the strategies involve two major cognitive processes: sequentially shifting focal attention to parts of the map and 3D display, and maintaining and transforming spatial information in a short-term memory representation that is overlaid on a perceptual representation. Evidence for the first process—attention shifting—comes from patterns of eye movements in an unpublished pilot study of the heading referencing strategy in our laboratory, and from an eye-movement study of the mental rotation strategy by Gunzelmann et al. (2004). Our heading referencing model involved a systematic pattern of attention shifts during each step of the strategy.

The second cognitive process mentioned here—overlaying memory and perceptual representations—suggests that cardinal direction judgments involve the process of "memory-percept integration" that has received much recent study (Brockmole & Irwin, 2005; Brockmole, Irwin, & Wang, 2003; Brockmole & Wang, 2003). These studies have shown that perceived spatial information can be stored in VSTM for periods of a few seconds. During the storage period the VSTM information can be mentally transformed, e.g., resized or rotated, and then the stored information can be quickly integrated with newly perceived information. Others have pursued related research suggesting that visual perception and VSTM use the same cognitive and neurological systems and that the VSTM spatial array is effectively overlaid on the perceived array (Awh, Jonides, & Reuter-Lorenz, 1998; Jonides, Lacey, & Nee, 2005). Most of these studies of memory-percept integration use simple stimuli such as dot arrays. The current research on cardinal direction judgments investigates how this cognitive process could operate in a more complex and realistic task. Thus, we included a VSTM buffer that is overlaid on a visual-perceptual buffer in our model of heading referencing.

Modeling Categorical vs. Metric Spatial Information

An important question in developing our cognitive model concerned what kind of spatial information is stored in VSTM. Kosslyn and colleagues (Kosslyn et al., 1989; Kosslyn, Flynn, Amsterdam, & Wang, 1990) developed a distinction between two methods of representing spatial information, a coordinate system that represents more specific, metric information about spatial location, and a categorical system that represents more abstract, spatial relations such as on, left, and above. These researchers suggest that both the coordinate and categorical systems are part of the brain's dorsal "where" system and are primarily localized in the posterior parietal lobes. Also, they presented evidence that the categorical system is localized in the left hemisphere and the coordinate system in the right hemisphere (Jager & Postma, 2003; Kosslyn et al., 1989). Huttenlocher and colleagues (Huttenlocher, Hedges, & Duncan, 1991; Newcombe, Huttenlocher, Sandberg, Lie, & Honnson, 1999) provided evidence that people use both coordinate and categorical representations in spatial tasks; and Tversky (2003) has emphasized the importance of categorical representations in navigation tasks.

The two main cardinal direction strategies described above—mental rotation and heading referencing—can be differentiated in terms of how and when they use coordinate and categorical spatial representations. In Gunzelmann et al.'s (2004) ACT-R model of a mental rotation strategy, the modeled participant first encodes a representation of the angle formed by the viewer, the center building and the target and then stores this angle in VSTM. The VSTM angle is then translated from the 3D display to the map display. While the VSTM angle is overlaid on the perceived map display, the angle is rotated until the leg of the VSTM angle corresponding to the viewer-to-building bearing is aligned with the same bearing in the perceived map. In this strategy, it seems that the angle information that is stored and transformed in VSTM is not categorical and is better represented as coordinate spatial information; and this is how Gunzelmann et al. represent it. Only at the last step of their model, after the VSTM angle is rotated, is coordinate spatial information converted into categorical information, i.e., a cardinal direction.

In contrast, heading referencing makes use of categorical representations very early. In the first step of the strategy, the position of the aircraft and the target on the map are used to encode a categorical representation of the aircraft heading as a cardinal direction. Our assumption is that people usually reason about cardinal directions using a small number (e.g., four or eight) qualitatively different directions, and that these directions are best described as categorical spatial relations, not coordinate ones. In later steps of heading referencing, the categorical heading representation is integrated with the perceptual representation of the 3D display, and further inferences are made about bearings to objects in the 3D display. As mentioned earlier, we feel that these inferences about bearings in the 3D display during heading referencing involve overlaying a VSTM representation on a perceptual one. However, we hypothesized that the VSTM information is encoded categorically for the heading referencing strategy, in contrast to the coordinate VSTM representation used in the mental rotation strategy. That is, in our model, people are storing a categorical cardinal-direction label rather than a spatial coordinate.

Another question involved how many cardinal direction categories to use in the model. Much research supported the use of at least the four cardinal directions (Gugerty & Brooks, 2000, 2004; Loftus, 1978). In addition, some of the findings of Huttenlocher et al. (1991) and Tversky and Schiano (1998) suggest that people employ two subcategories within each of the four quadrants formed by the cardinal directions. These studies led us to assume that people represent cardinal directions in VSTM using eight categories: north, northeast, east, southeast, south, southwest, west and northwest. Finally, we note that the VSTM buffer in our model also stored some metric information; in particular, it could store the location coordinates of the focus of attention.

Modeling with Egocentric vs. Allocentric Representations in VSTM

Another question in developing our heading referencing model was whether to use an egocentric, body-centered reference frame or an allocentric, external reference frame in VSTM. Sholl (1996, 2001; Sholl & Nolin, 1997) has presented a model of some of the key short-term representations of spatial information used in navigation tasks. Based on evidence in Sholl (1999), she suggests that memories of maps are retrieved into an egocentric short-term-memory buffer that is retinocentric and 2D; while memories of 3D configurations of objects are retrieved into an egocentric, 3D buffer. Others have suggested that since peoples' representations of the 3D, forward view are used to guide their actions during navigation and locomotion, objects in the forward view are represented egocentrically (Berthoz, 1991). Therefore, we assumed that the spatial reference frame in the VSTM buffer uses egocentric coordinates such as far, near, right, and left, and implemented this in our model. Since cardinal direction judgments by definition apply to the horizontal plane and do not require the altitude dimension, we assume that when the VSTM buffer is used to represent the 3D display, it represents the 2D horizontal plane extending in depth. We make no claims in this model regarding the 3D character of the VSTM buffer.

Huttenlocher et al. (1991) provide evidence that people prefer to code the locations of objects in space in terms of polar coordinates, with the origin of the polar reference frame centered on the self or on a focal external object, and with object locations coded in terms of angular heading and radial distance with respect to the origin. Tversky and colleagues (Bryant & Tversky, 1999; Franklin & Tversky, 1990) showed that people conceptualize the space around the body using the egocentric reference axes of head-feet, front-back, and right-left. These findings suggested that people would code the objects in the 3D, forward view (e.g., Figure 1) in terms of a central focus location (the central building) and locations beyond, before, left of, and right of the building. In the model, these locations were named "origin," "far-center," "near-center," "left," and "right," respectively, as shown in Figure 2. Moratz and Tenbrink (2006) developed a model of the spatial terms needed to understand and communicate navigational actions, and validated this model against peoples' use of spatial terms. Their model included egocentric terms for the far-near and right-left axes, such as those mentioned above, but also included terms reflecting the diagonal axes, such as "far-right," "near-right," "near-left," and "far-left." Thus, we also included these diagonal spatial categories in the model (see Figure 2).

These eight polar categories are all at a single radial distance from the origin, because the four parking lots in our scenes were all at a single distance from the origin. Thus, the location categories in the model were the simplest location coding needed for this task, but would not work for more complex object configurations. We used the simplest location coding for our task because people often induce and use spatial categories that are tuned

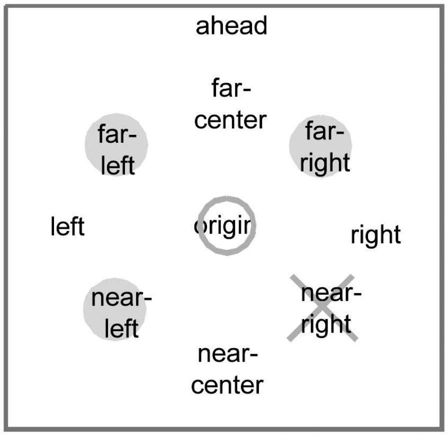

Figure 2. Egocentric spatial locations used in the VSTM buffer of the model, shown overlaid on the 3D display objects in gray. Filled circles are empty parking lots; X is the lot with the cars; unfilled circle is the central building.

to the demands of particular tasks (Huttenlocher et al., 1991; Newcombe et al., 1999). Our hypothesis is that, for more complex configurations, people would still use a polar coordinate system with eight categories at each radial distance, but they would add rings at other radial distances as needed.

Modeling How Egocentric and Allocentric Information Is Aligned

Considerable evidence supports the conclusion that information about spatial layouts is stored in long-term memory using allocentric representations, in which bearings and distances to objects are coded with respect to each other (an intrinsic reference frame) or to a fixed, external reference frame (Burgess et al., 2004; Holmes & Sholl, 2005; Mou, McNamera, Valiquette, & Rump, 2004). However, as mentioned above (e.g., Sholl, 2001), information in VSTM is often thought to be coded egocentrically, with the viewer's body as the reference frame. An important question for our model concerned how information in these two distinct reference frames is coordinated. Cardinal direction judgments are a good task for investigating this question, because they require people to extract allocentric information about their current heading from the map as well as information about a bearing in the 3D view that is probably represented egocentrically, and then to coordinate these two types of information.

We made some important modeling decisions regarding how people coordinate allocentric and egocentric information based on a behavioral study in which participants performed some of the key steps of the heading referencing strategy as separate tasks (Gugerty & Brooks, 2004). In this study, participants identified the heading of the aircraft on the map (Step 1), identified bearings to the far lots in the forward view given the cardinal direction aligned with the forward-view ahead vector (Step 3), and identified bearings to the near lots given bearings to the far lots (Step 4).[1] Data analysis focused on determining which of these heading referencing steps was the source of the misalignment effect shown in the overall cardinal direction task, that is, the increase in errors and response time as the aircraft heading moved away from north. Steps 1 and 4 did not show misalignment effects; but for Step 3—identifying bearings to far lots given the cardinal direction aligned with ahead—errors and response times increased as the cardinal direction label at the top of the 3D view differed more from north. In line with other researchers who have interpreted misalignment effects in navigational tasks as evidence for a mental rotation process (Aretz, 1991; Hintzman, O'Dell, & Arndt, 1981; Shepard & Hurwitz, 1984), we think that the misalignment effect in Step 3 of heading referencing also suggests mental rotation. In particular, we hypothesized that people were identifying bearings to far lots by retrieving a mental compass in its canonical, north-up orientation into VSTM, overlaying the compass on the perceived forward view, rotating the mental compass until it aligned with ahead, and then reading off the bearings to the far lots from the mental compass. This process of mental-compass rotation was implemented in our heading referencing model.

Modeling Covert vs. Overt Attention Shifts

Another question concerned whether to model rotation of the mental compass via covert or overt attention shifts. A number of researchers have suggested that the same attentional mechanisms are used during mental transformations of VSTM as during visual perception (Awh et al., 1998; Ganis, Thompson, & Kosslyn, 2005; Jonides, Lacey, & Nee, 2005). According to these researchers, mental rotation of VSTM information involves covert shifts of visual attention and possibly overt eye movements. However, research by Brockmole and colleagues (Brockmole et al., 2003; Brockmole & Irwin, 2005) suggests that in a memory-percept integration task people use covert visual attention shifts but not overt eye movements to rehearse the location of VSTM information. Also, Gunzelmann et al. (2004) found that participants tended to fixate near the vertex of rotation throughout the mental rotation step of their cardinal direction strategy. Therefore, in our heading referencing model, we modeled mental-compass rotation via covert shifts of attention in VSTM, with the eye fixated on the location corresponding to the center of the mental compass.

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[1] A separate task corresponding to Step 2 of heading referencing (aligning the map heading with 3D ahead) was omitted from this study, because, in isolation, this step involves little difficulty.

Finally, another finding from our part-task study (Gugerty & Brooks, 2004) guided the development of our heading referencing model. In Step 1 of the heading referencing strategy, compound directions such as “northeast” were identified on the map more slowly than simple cardinal directions such as “east.” Therefore, our model implemented a multi-stage process for identifying compound directions and a single-stage process for simple cardinal directions.

A Cognitive Model of Cardinal Direction Judgments

Based on the verbal-protocol and behavioral studies described above, we assumed that the heading referencing strategy involves shifts of overt focal attention, an egocentrically coded VSTM buffer that stores categorical cardinal-direction labels and is spatially integrated with the visual perception buffer, and shifts of covert spatial attention to accomplish rotation of a mental compass in VSTM. One novel aspect of this project is that the model combines a number of cognitive processes used in spatial tasks—such as memory-percept integration, coordination of allocentric and egocentric information, and coordination of categorical and coordinate information—to a task that has not been used much in studying these processes, and which is more complex than some of the spatial tasks previously used to study these processes. Thus, this project gives information about the generality of these cognitive processes, and about how spatial sub-processes interact during a complex task.

We implemented a model with the characteristics described above using the ACT-R architecture (Anderson et al., 2004). ACT-R models executive control processes (e.g., strategies) using a set of production rules that interact with a long-term declarative memory and with working memories (e.g., a goal buffer and a long-term-memory retrieval buffer). Based on Meyer and Kieras’ (1997) EPIC model, ACT-R contains modules that model perceptual-motor processes. The important perceptual-motor modules for the cardinal direction task are the visual-location module, which models the parallel attentional mechanisms of ambient vision, and the visual module, which models the serial attentional mechanisms (including eye movements) of focal vision. The end products of these modules are representations stored in a visual-location buffer and a visual-recognition buffer that can be accessed by the production system.

By default, ACT-R does not contain a VSTM buffer. However, ACT-R does allow users to add working memory buffers; so we added a simple VSTM buffer. In the VSTM buffer in our model, categorical spatial information (e.g., the name of a cardinal direction) is stored in slots that represent coarsely-coded and egocentrically-referenced locations. The VSTM locations, which are shown in Figure 2, were: origin (center); eight slots representing a ring around the center location (far center, far right, right, near right, near center, near left, left, and far left); and ahead (very far center). These VSTM slots have a spatial character in our model because a production can only transform (e.g., rotate) information in VSTM by shifting the contents of a slot to the spatially adjacent slot.

Since we wanted a model that could solve cardinal direction problems at any map heading, we included in our model the variety of strategies people use to handle different map headings. Thus, we included a north-heading strategy for north headings and a south-reversal strategy for south headings. For headings between north and south, we modeled the heading referencing strategy, since our verbal protocols had shown this as the most common strategy used for these headings. In the model presented here, each of these strategies always solved the cardinal direction problems accurately. Thus, we modeled expert performance. A goal for future work is to model the effects of heading misalignment on accuracy during early stages of learning the cardinal direction task.

Heading-Referencing Model. In the following, we describe the heading referencing model, using a schematic problem in Figure 3 to show eye fixations and information in VSTM for key model substeps. Some of the heading referencing substeps involve recognizing the two configurations of parking lots in the 3D view in these problems. For problems where the plane is headed northeast, southeast, southwest or northwest (like in Figure 3), the parking lots form an X configuration, with lots in the far-left, far-right, near-left and near-right portions of the 3D view. For problems where the plane is headed north, east, south or west, the parking lots form a plus configuration, with lots in the far-center, near-center, right, and left portions of the 3D view. The complete ACT-R model is available at www.gugerty.net/cdirmodel.htm.

In Step 1 of the heading referencing strategy (reading the plane heading from the map), the model completes the following sub-steps, in sequence:

1.1 Saccades to the aircraft icon on the map. Stores the location coordinates of the plane in the "origin" (center) slot in VSTM. (View A, Figure 3)
1.2 Saccades to the target icon on the map. (View B)
1.3 Compares the plane location coordinates (in VSTM) with the target location coordinates (in the perceptual visual-location buffer) and determines the plane's heading. For plane headings towards a simple cardinal direction, this process is completed in a single production. For plane headings towards a compound direction such as southeast, which take longer to identify, four productions fire: two to code the north-south (e.g., *southerly* in Figure 3) and east-west orientation (e.g., *easterly*) from the plane to the target, and two to retrieve from long-term memory the compound cardinal direction corresponding to these orientations. These productions classify map headings that vary continuously between

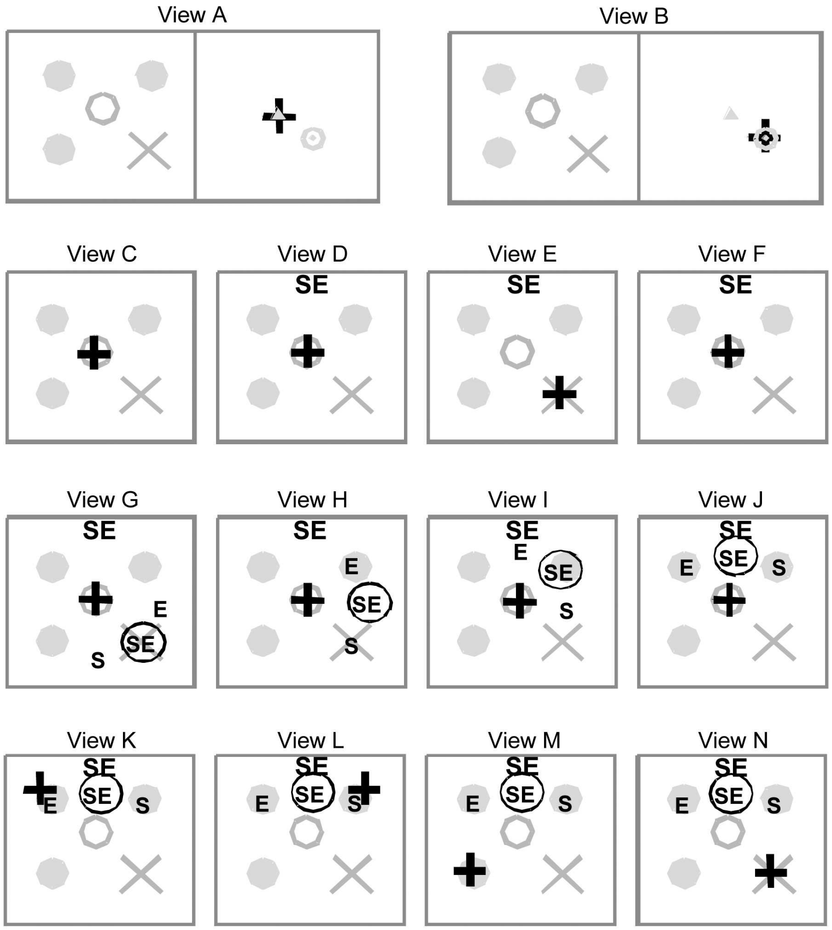

Figure 3. Depiction of the sequence of eye fixations and information in VSTM for the heading referencing model for a representative problem. Icons perceived by the model on the map and 3D displays are in gray: Filled circles are empty parking lots; X is the lot with cars; unfilled circle is the central building; triangle is the plane; and bulls-eye is the map target. Model eye fixations and VSTM information are in black: The + shows an eye fixation; the circle shows the locus of covert visual attention in VSTM; the text (e.g. SE) shows categorical labels stored at particular locations in VSTM. The map display is attended to by the model only on the first two views, so it is not shown in later views.

0 and 360° into eight heading categories; headings between 337.5 and 22.5° are classified as north, those between 22.5 and 67.5° as northeast, and so forth.[2]

1.4 Stores the plane heading in goal working memory as a categorical label.

In Step 2 of the heading referencing strategy (encoding the plane heading as aligned with ahead in the forward view), the model sub-steps are:

2.1 Saccades to the center building in the forward view. Stores the location coordinates of the building in the "origin" (center) slot of VSTM. (View C)
2.2 Stores the plane heading as a categorical cardinal-direction label in the VSTM slot "ahead" (very far center). (View D)
2.3 Saccades to the parking lot with the cars. Stores in goal memory the egocentric location of this lot (e.g., *near-right* in Figure 3) and whether the lots form a plus or an X configuration. (View E)
2.4 Saccades to the center building in the forward view. (View F) The eye remains fixated on this location during mental compass rotation in Step 3.

In Step 3 of the heading referencing strategy (determining the bearings to the far lots), the model sub-steps depend upon the type of problem. For most problems, including the one in Figure 3, the model steps are:

3.1 Mental compass retrieval: Retrieves from declarative memory the egocentric location (e.g., "near right" in Figure 3) associated with the current plane heading (e.g., *southeast*) and stores the current plane heading in VSTM in this location (e.g., stores *southeast* in the "near-right" VSTM slot). Shifts covert visual attention to this VSTM location. Also retrieves and stores in VSTM the cardinal directions 45° to the right and left of the current heading for X-configuration problems, and 90° to the right and left for plus problems (e.g., for Figure 3, stores *south* in the "near-center" slot and *east* in the "right" slot). (View G)
3.2 Mental rotation: Retrieves from declarative memory the location of the next VSTM location to rotate the current heading to (e.g., the "right" slot); moves all three cardinal directions just retrieved to the appropriate new VSTM location (e.g., one location counterclockwise); and shifts covert visual attention to the new location holding the plane heading (e.g., "right"). Stops rotating when the plane headings in the VSTM "far center" and "ahead" slots are the same. (Views H, I, J)

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[2] The mechanism by which ACT-R accomplishes this categorical perception of heading involves mathematically calculating a numerical heading from two spatial coordinates. This mathematical mechanism may not be psychologically plausible. Our hypothesis here is about the categorical nature of heading perception, not this particular mechanism.

3.3 For each of the far lots, saccades to the lot and transfers the bearing for that lot from VSTM (e.g., *east* in "far-left" slot) to the corresponding slot in goal memory. If multiple far lots are present, as in Figure 3, saccades to them in either order. For each lot, responds immediately if this is the lot with the cars. (Views K, L)

For plus-configuration problems where the lot with the cars is in the far-center or near-center lot, retrieving and rotating a mental compass is not needed because the participant can determine the bearing to the far-center lot by making inferences from the nearby "ahead" vector in VSTM (as in Step 3.1, next), and can determine the bearing to the near-center lot by retrieving cardinal-direction facts from memory (in Step 4). We assumed that people would not do the difficult task of rotating a mental compass when it is not needed, so retrieving and rotating the compass is not done in Step 3 for these far-center or near-center problems. For these problems, the model sub-steps for Step 3 are:

3.1 Saccades to the far center lot and transfers the bearing for that lot from VSTM (e.g., *east* in "ahead" slot) to the "far-center" slot in goal memory. Responds immediately if this is the lot with the cars.

In Step 4 of the heading referencing strategy (determining the bearings to the near lots), the model sub-steps are:

4.1 For each near lot (in either order), determines its cardinal direction by retrieving an opposite fact from declarative memory and using the known cardinal direction for the far lot opposite from it (e.g., determines that the "near-right" lot is *west* given that the "far-left" lot is *east*, or that the "near-center" lot is *west* given that the "far-center" lot is *east*). Also saccades to each near lot. For each lot, responds immediately if this is the lot with the cars. (Views M, N)
4.2 (This step is only needed in plus-configuration problems where the cars are in the right or left lot.) Saccades to the right and the left lot (in either order) and transfers the bearing for that lot from the VSTM mental compass (e.g., *south* in "right" slot) to the corresponding slot in goal memory. For each lot, responds immediately if this is the lot with the cars.

North-Heading and South-Reversal Models. Since verbal protocol data showed that people used different strategies than heading referencing when the map heading was north or south—i.e., they used the north-heading and south-reversal strategies, respectively—the ACT-R cardinal direction model also used a north-heading and a south-reversal strategy when appropriate. The north-heading model involves retrieving an un-rotated mental compass into VSTM overlaid on the 3D scene and then reading the cardinal direction from VSTM. The south-reversal strategy uses the north-heading strategy and then reverses the answer by retrieving a cardinal-direction opposite fact from declarative memory.

Integrated Cardinal Direction Model. The heading referencing, north-heading and south-reversal strategy models were integrated in a single ACT-R model that chose the appropriate strategy based on the map heading. This integrated model was run with the default human-performance parameters for ACT-R 5.0, which are based on an extensive database of empirical studies in experimental psychology, except for two parameters noted here. The parameter for the time required to retrieve a chunk of information from declarative memory, which does not have an agreed upon default value, was set at 350 ms based on another ACT-R model of a visuospatial task (Lyon, Gunzelmann, & Gluck, 2004); but this parameter was not varied to best fit the data from the empirical study presented here. The single parameter that was varied to fit the data from this empirical study was the procedural cycle time parameter (the time to fire a production); and this parameter was varied only for a single production, the production that rotates cardinal directions in VSTM. The cycle time for this production was set at 150 ms because of the assumed high cognitive load of rotating a complex, three-part knowledge structure. All other productions used the ACT-R default cycle time of 50 ms. Also, the productions and declarative memory knowledge structures (e.g., cardinal direction opposite facts) included in the model were based on prior empirical studies of cardinal direction judgments and on prior research in spatial cognition, as outlined previously. These productions and knowledge structures were not developed after looking at the data from the current empirical study.

This cardinal direction model makes specific predictions about how human performance will vary with the aircraft heading and the 3D location of the lot with the cars (the target lot). All model predictions were based on having the model complete four blocks of 32 cardinal direction problems for each of 20 modeled participants, and averaging across the resulting data. The 32 problems per block given to the model included the 12 map headings and the 4 target locations given to participants in the empirical study. Since the model always correctly solved the problems, predictions are only given for response times. The predictions for the effect of aircraft heading for all three strategies are shown in Figure 4. Predicted response times are fastest for a north heading, increase as heading moves away from north, and then decrease some for a south heading.

For the heading referencing model, more detailed predictions are shown in Figure 5 regarding how aircraft heading and target lot location might interact (see the white bars labeled first model). The model's predictions regarding this interaction differ depending on the configuration of lots in the 3D view, i.e., the X configuration associated with headings of northeast, southeast, southwest and northwest, and the plus configuration associated with headings

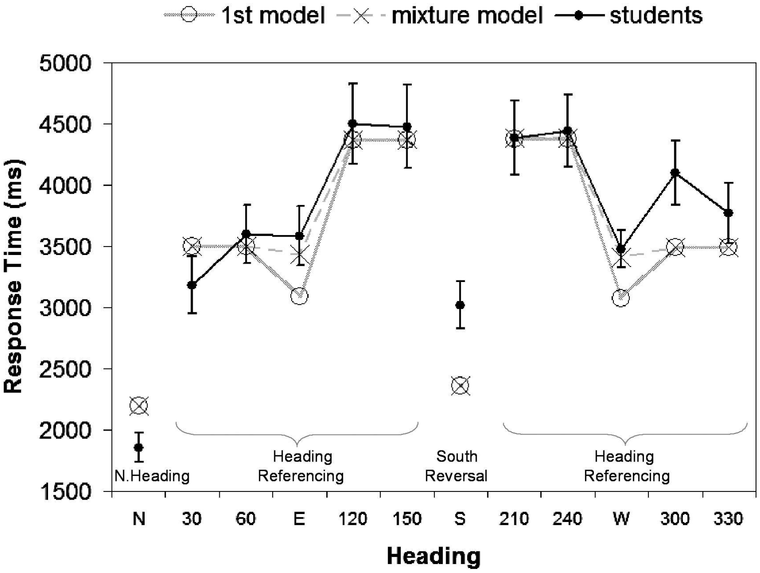

Figure 4. Effect of aircraft heading on response time for the 20 college students; and heading effects predicted by two heading referencing models (the first model and the mixture model), and by the north heading and south reversal models. The north heading model only makes predictions for an aircraft heading of north; the south heading model only makes predictions for south headings; and the heading referencing models make predictions for all other headings. Standard error bars shown for data.

of east and west. Regarding effects of heading for the X-configuration problems, the model predicts that problems with headings of northwest or northeast will be completed faster than those with headings of southeast or southwest, because less rotation of the mental compass is needed in the former problems. Regarding effects of target location for the X problems, the model predicts that problems with cars in the far lots will be completed faster than those in the near lots, because Step 4 of heading referencing is only needed when the cars are in the near lots. Since these effects of heading and target location are caused by different stages of the model, additive main effects are predicted, as shown on the right side of Figure 5.

For the plus configuration problems, the heading referencing model determines the cardinal directions of lots in the following order: far-center, then near-center, then right or left. Also, the model does not perform mental rotation in VSTM when the target is in the far-center or near-center lots, which saves considerable time. These factors lead to the prediction that far-center and near-center targets will be responded to much faster than right or left targets, and that far-center targets will be responded to slightly faster than near-center problems. See the left side of Figure 5 (white bars).

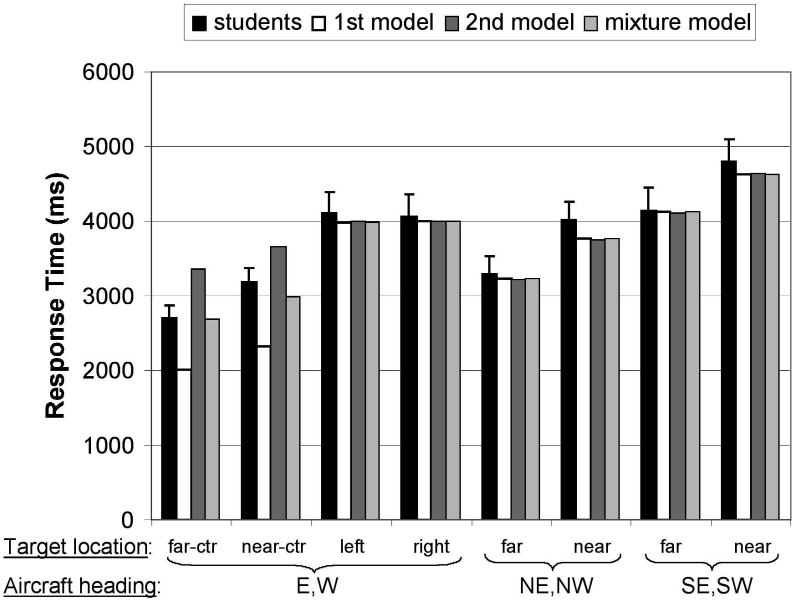

Figure 5. Effect of aircraft heading and 3D target location on response time for 20 college students (black bars, with standard errors), the first heading referencing model that avoids use of mental rotation on far-center- and near-center-lot problems (white bars), the second heading referencing model that maximizes use of mental rotation on far-center- and near-center-lot problems (dark gray bars), and a mixture model that uses the first and second model 50% of the time on far-center- and near-center-lot problems (light gray bars).

Empirical Study

Next we describe an empirical study in which we collected human performance data that was compared to the model predictions. The participants in this study, college students, completed cardinal direction problems like the modeled task, with the aircraft map heading varying from 0° (north) to 330° (north-northwest) in 30° increments and the bearings to the target lot in the 3D view varying among north, east, south and west. Since the model used the heading referencing, north heading and south reversal strategies at an expert level, i.e., without errors, we wanted the human performance data to also reflect expert performance using these same strategies. Therefore, we gave the students training and practice on these three strategies and required them to use the strategies. In order to obtain appropriate data to compare with the model, data from students who reported not using the trained strategies regularly and students who performed poorly on the initial cardinal direction problems were dropped, based on predetermined thresholds.

METHOD

Participants

The 30 participants in this study were university students at the undergraduate or graduate level. Six participants were dropped because they failed to meet predetermined criteria: 3 of these got less than 86% of the cardinal direction problems correct in the first block of 48 trials; and 3 reported using the trained strategies less than 90% of the time in at least one of the three sessions. One participant was dropped due to computer-related data loss. Three participants were not included because it was discovered after collecting their data that they had prior knowledge of expected experimental results. The remaining 20 participants, 4 males and 16 females, ranged in age from about 19 to 36. We expected that this imbalanced gender ratio would not be misrepresentative because we gave participants explicit training and considerable practice before collecting the data that were fit to the model. Data presented in the results section documents that this expectation was warranted.

Materials and Tasks

On each cardinal-direction problem, a forward-view (3D) scene and a map were presented simultaneously on a personal computer screen. These were like the ones shown in Figure 1, except that the figures in the experiment were in color. The north-up map shows the location of the participants' aircraft and the current ground target; from these icons, the aircraft's heading can be determined. The forward view shows a central building surrounded by four parking lots. The task was to determine the bearing from the central building to the parking lot with the cars. The figures remained visible until the participants responded by pressing a key on the number pad labeled N (8 key), S (2 key), E (6 key), or W (4 key), for north, south, east, west, respectively. After responding, participants received feedback about whether the response was correct, their response time, and the correct answer. Then they pressed the 5 key to start the next trial. Across trials, the plane heading shown on the map varied from 0 to 330°, in 30° increments. The other factor that was varied was the parking lot where the vehicles were located, which was either north, south, east, or west of the building. Crossing these two factors yielded 48 trials, which were presented in random order in blocks of 48.

Procedure

In Session 1, participants received strategy training and practice. In each of Sessions 2 and 3, they completed three blocks of 48 cardinal direction problems. Session 1 took about 60 minutes, and Sessions 2 and 3 about 25 minutes each. Each session was separated by a break of at least 1 hour. The total time span from Session 1 to 3 ranged from 5 hours to 6 days.

In Session 1, participants first received initial training on the elements of the map and 3D display, the response keys, and the overall cardinal direction task, without receiving any strategy training, and then performed 6 practice problems. Then the strategy training was administered first for the heading referencing strategy (called the "map heading strategy" for participants), then the north heading strategy (called the "north strategy"), and finally the south reversal strategy (called the "south strategy"). For the heading referencing strategy, the experimenter verbally explained the strategy using a cardinal direction problem display enhanced with icons (e.g., arrows) and text, and also using appropriate pointing gestures. The experimenter gave these explanations for two problems and then the participants tried to apply the strategy for two problems while speaking aloud. If participants made errors in applying the strategy on either practice problem, the experimenter gave verbal feedback on their error and went though a complete strategy explanation for that problem. Then participants were given a diagram showing how to use the heading referencing strategy, which they could refer to during the rest of the study. The strategy training for the north heading and south reversal strategy was very similar, expect that the experimenter explained and participants practiced only one problem. Participants were asked to use these strategies when appropriate on each problem during the rest of the study.

Following the strategy explanations, participants completed a practice block of 24 cardinal direction problems, which required all three strategies, while giving a verbal protocol. After each problem where participants gave the correct answer and used the appropriate strategy correctly, the experiment said "OK continue." Otherwise, the experimenter gave feedback on the correctness of the participant's answer and explained how to apply the appropriate strategy for that problem. Following these practice problems, participants completed another block of 48 cardinal direction problems, with instructions to use the strategies, but without speaking aloud. Finally, participants estimated how frequently (0 to 100%) they used the trained strategies on the last block of 48 problems.

In each of Sessions 2 and 3, participants first were shown cardinal direction problems requiring each of the three strategies and asked to explain the appropriate strategy for that problem. Incorrect strategy explanations were corrected by the experimenter. Then participants were given the strategy training diagrams from Session 1 and encouraged to use the strategies on every problem. Then participants completed three blocks of 48 problems, with the opportunity for a break after each block. Finally, participants estimated their frequency of strategy use for the three blocks.

RESULTS AND DISCUSSION

After receiving training and practice in the strategies in Sessions 1 and 2, participants' data for the last three blocks (Session 3) were compared to the model predictions. During each of the last three blocks, the average percent correct was 97.2 ($SE = 0.60$). This accuracy level was similar to that of a group of six male and one female jet pilots ($M = 94\%$ correct) from a prior study (Gugerty & Brooks, 2004), which will be discussed in more detail later. Thus, the training and practice succeeded in bringing participants in this study to near-optimal accuracy. Also, given the similar performance of the predominantly female participants in this study and the predominantly male participants in the jet pilot group, the imbalance in gender ratio in the current study did not seem to affect performance much.

Main Effects of Heading

Figure 4 shows the effect of aircraft heading on response time for correct responses averaged over the last three blocks. Heading significantly affected participants' response time, $F(11, 209) = 16.8$, $MSE = 2483696$, $p < .01$. The overall pattern of how heading affected participants' response time was very similar to that predicted by the model, that is, shortest response times for a north heading, increasing response times as heading diverged from north, and then decreasing times near south.

Although three strategies were modeled, two of them—north heading and south reversal—are special-case strategies that apply only to a few types of problems and allow fairly accurate performance even for unpracticed participants. We do not provide quantitative evaluation of model fits for these special-case strategies, beyond noting that, as shown in Figure 4, the modeled north-heading strategy fit participants' response time data well and the modeled south-reversal strategy underestimated response time by about 750 ms. This underestimation could have occurred because participants did not use the south-reversal strategy on all south heading problems, but instead intermixed this strategy with the more time-consuming heading-referencing strategy.

To evaluate how well the heading referencing model fit participants' response times, the root mean squared deviation (RMSD) between the participant data and model predictions for the ten data points in Figure 4 where heading referencing was used (headings of 30°, 60°, E, 120°, 150°, S, 210°, 240°, W, 300°, and 330°)—314 ms—can be compared to the average standard error of the participants' data for these points—264 ms (see Table 1). Reasons why this RMSD is greater than the standard error will be discussed later. The correlation between model and data for these ten points was .87.

The model categorized any plane heading that was about 45° from a cardinal direction into a compound cardinal direction category (e.g., headings between 22.5 and 67.5° as northeast), and it performed this categorization at the same speed regardless of the plane heading. Therefore, the model predicted that actual plane headings 30 or 60° from a cardinal direction would lead to the same response time. Figure 4 shows that this prediction

Table 1
Data Relevant to Fit Between Heading Referencing Models and the Response Time Data of the 20 College Students and of the 4 Jet Pilots Classified as Using Heading Referencing

	First model		Mixture model		Mixture model & fast compass	
	RMSD	*r*	RMSD	*r*	RMSD	*r*
Heading effect for all headings but N, S						
Students ($SE = 264$ ms)	314	.87	247	.89		
4 jet pilots ($SE = 354$ ms)			460	.80	285	.84
Lot location effect for headings NE, NW, SE, SW (X-configuration)						
Students ($SE = 272$ ms)	161	.98	161	.98		
4 jet pilots ($SE = 285$ ms)					213	.97
Lot location effect for headings E, W (plus configuration)						
Students ($SE = 232$ ms)	558	.98	122	.99		
4 jet pilots ($SE = 411$ ms)					601	.65

RMSD = root mean squared deviation between model and data, in units of ms.

was accurate for headings near southeast (120 vs. 150°) and southwest (210 vs. 240°), where participant response times were very similar, $t(19) < 1.0$, $p > .5$, but inaccurate for headings near northeast and northwest, where response times were faster for headings closer to north, $t(19) > 3.0$, $p < .01$. These findings suggest that these participants used categories like southeast and southwest, as assumed by the model, for the southern hemisphere of their mental compass, but may have used finer-grained categories for the compass' northern hemisphere.

Additive Effects of Heading and Target Lot Location

Figure 5 shows how participants' response time was affected by both aircraft heading and target location in the 3D view. For X-configuration problems, where heading varied between northeast or northwest and southeast or southwest, and target location varied between the far and near lots, participants showed the additive main effects predicted by the model (see the white bars labeled first model on the right side of Figure 5). That is, participants were faster for northeast or northwest than for southeast or southwest headings, probably because less mental rotation was needed, and faster for far than near lots, probably because Step 4 of heading referencing was not needed. This conclusion was supported by significant main effects of heading, $F(1, 19) = 63.6$, $MSE = 1737991$, $p < .05$, and of target location, $F(1, 19) = 16.8$, $MSE = 150639$, $p < .01$, and no interaction effect, $F(1, 19) < 1$, for these problems. The RMSD between the participant data and model predictions for the four data points on the right side of Figure 5—161 ms—was less than the average standard error of the participant data for these points—272 ms (see Table 1). This along with the correlation between model and data of .98 suggests a good model fit for the X configuration problems.

For plus configuration problems, where heading was always east or west and target location varied between far-center, near-center, left and right, participants showed the qualitative effects predicted by the model, with response times fastest for the far-center lots, slower for the near-center lot, and slowest for the left or right lots (see the left side of Figure 5). Planned contrasts confirmed these impressions. Response times to far-center lots were faster than to near-center lots, $t(19) = 4.24$, $p < .01$; response times to near-center lots were faster than to the average of left and right lots, $t(19) = 4.26$, $p < .01$; and response times for right and left lots did not differ much, $t(19) = 0.16$, $p > .5$. The RMSD between the participant data and model predictions for the four data points on the left side Figure 5—558 ms—was considerably greater than the average standard error for the participant data—232 ms, although the correlation between model and data was .98 (see Table 1). This discrepancy between the model RMSD and the participant standard error is primarily due to participants performing slower than the model predictions for the far-center and near-center lots. The model fit for the right and left lots was quite good.

The main reason that the model was much faster than participants when the cars were in the far-center or near-center lots was probably that the model does not retrieve or rotate a mental compass on these problems, but instead determines cardinal directions by mapping the direction in the "ahead" location in VSTM to the "far-center" location and by retrieving facts concerning opposite cardinal directions. We assumed that people would not perform the difficult operation of retrieving and rotating a mental compass on problems such as these where they could use simpler operations. However, it could be that, since people were in the habit of using a mental compass on many other cardinal-direction problems during the experiment, they sometimes used a mental compass when the target was in the far-center or near-center lot even though it was not necessary. To test this possibility, we created a second version of the model, identical to the first except that it retrieved and rotated a mental compass on all far-center and near-center problems.

The dark gray bars in Figure 5 show that this second version performed slightly slower than the participants on these problems. A mixture model that used mental rotation (i.e., the second model) on 50% of the far-center and near-center problems and no mental rotation (i.e., the first model) on the other

50% fit the human data well (see the light bars on Figure 5). The RMSD between this mixture model and the human data for the four data points on the left side of Figure 5—122 ms—was less than the average standard error of the human data for these points—232 ms; and the correlation between model and data was .99 (see Table 1). This suggests that, either within or across subjects, participants may have used a mixture of these two tactics on far-center and near-center problems, sometimes avoiding mental rotation (as in the first model) and sometimes doing it unnecessarily (as in the second model). The difference between the first and the second model—whether mental rotation is used on a small subset of the problems—is a minor one in the sense that both the first and second models follow closely the four main steps of heading referencing.

This more detailed analysis of how well the first heading referencing model fit the data regarding the additive effects of heading and 3D target location (in Figure 5) suggests that a primary reason for the relatively poor fit (RMSD = 314 ms) between the first model and the overall heading effect data (in Figure 4) is the poor performance of the first model on this subset of the problems—plus configurations problems with the cars in the far-center and near-center lots. Evidence for this explanation comes from the fact that the mixture model of heading referencing also fits the heading-effect data in Figure 4 much better than the first model. The RMSD between the mixture model and the participants' heading data—247 ms—was less than the average standard error for the ten headings where heading referencing was used—264 ms; and the correlation between model and data was .89 (see Table 1). Thus, the mixture model of heading referencing provides a good fit to both the overall heading effect data and the data on the additive effects of heading and target location.

Comparing These Data to Another Model

Although we did not develop and fit a cardinal direction model based on the mental rotation strategy, as Gunzelman et al. (2004) did; we were able to compare some of their model's predictions to the data from this study, since the tasks modeled were very similar. Their mental rotation model predicts a main effect of heading misalignment similar to the heading referencing model. Regarding effects of target lot location, for the plus-configuration problems (where heading is east or west), the mental rotation model again makes similar predictions to the heading referencing model; both models predict faster response times for near-center and far-center lots because mental rotation is not needed on these problems. However, for the X-configuration problems (where heading is northeast or northwest and southeast or southwest), the two models make opposite predictions.

The mental rotation model predicts faster responses on near than far lots because it takes more time to determine the direction of rotation for the larger angles associated with far lots; while the heading referencing model predicts faster responses on far lots because the last step of the strategy is not needed on these problems. Thus, the main effect of heading found in the current study is consistent with both heading referencing and mental rotation. However, the finding from this study that far lot problems were significantly faster than near lot problems cannot be explained by the mental rotation model.

To summarize the results of the empirical study, when only one departure from the ACT-R default parameters was made—a longer production execution time for mental rotation—the first heading referencing model matched the qualitative pattern of how participants' response times were affected by both heading and 3D target location. Also, this first heading referencing model matched the absolute magnitude of participants' response times well for most cardinal direction problems, with the exception of problems where the target location was the far-center or near-center lot. A mixture model that used mental rotation on half of the far-center or near-center problems and avoided rotation on the other half led to a good fit between the heading referencing model and the absolute magnitude of all of participants' response times. The mental rotation model of Gunzelmann et al. (2004) could explain some of these findings but not all of them

This empirical study suggests that heading referencing is an effective strategy for solving cardinal direction problems, since most participants with no prior navigation training were able to solve difficult cardinal direction problems with high accuracy after about an hour's training and practice. Also, the close fit of the heading referencing model to the response time data suggests that this model provides a good description of the specific cognitive processes and structures in the heading referencing strategy.

Fitting the Model to a Second Data Set

One potential criticism of this empirical study is that the participants were trained in and required to use the strategy that was modeled (although this has been done in other cardinal direction modeling studies, e.g., Gunzelmann et al., 2004). To deal with this criticism, we also compared the heading referencing model predictions to another group of participants who were not trained in any strategy for the cardinal direction problems. From a prior study (Gugerty and Brooks, 2004), we used data from seven Air National Guard jet pilots (6 males and 1 female) who solved the same cardinal direction problems used in the study just described. It is likely that these pilots had considerable expertise in spatial and navigation tasks that was based both on prior cognitive ability and on flight training and practice. These pilots were given brief instruction in how the cardinal direction problems worked, but no strategy training. Then they completed 3 blocks of 48 problems. We treated the first block of problems as practice and compared the pilots' performance on the last 2 blocks of problems to the heading referencing model and one alternative model.

The jet pilots averaged 94% correct ($SE = 1.9\%$) on the cardinal direction problems, similar to the trained college students in the last three blocks (97%). It did not seem that we would learn much about the validity of the heading referencing strategy model by fitting it to the aggregated performance data of participants who may have been using a variety of strategies. Therefore, before comparing the pilots' data to the model's predictions, we used the response time data of each pilot to estimate the strategy that he or she used. The two strategies we expected were the two frequent strategies found in our verbal protocol study (Gugerty et al., 2004), heading referencing and the mental rotation strategy modeled by Gunzelmann et al. (2004). Both of these models make the same prediction regarding the effect of heading, i.e., faster responses for plane headings closer to north. However, the two models make opposite predictions regarding the additive effects of heading and target lot location on X-configuration problems (where heading varied between northeast or northwest and southeast or southwest). The heading referencing model predicts faster response times for far lots than for near lots at all headings, while the mental rotation model predicts faster responses for near than far lots at all headings. Therefore, we classified a pilot as using heading referencing if he or she showed a heading misalignment main effect (faster for northerly than southerly headings) and a consistent lot location effect across both headings such that far lots were faster than near lots, and as using mental rotation if he or she showed the same heading misalignment effect and a consistent lot location effect across both headings such that near lots were faster than far lots. Four jet pilots fit this definition of heading referencing; two fit the mental rotation definition;[3] and one could not be classified.

Since the mixture model of heading referencing was the best fitting model for the college students' data, we fit this model to the response time data for the four jet pilots classified as using heading referencing. Figure 6 shows how the four heading referencing pilots fit the predictions of the mixture model

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[3] The conclusion that two of the pilots were using mental rotation is complicated by the fact that a variant of the heading referencing model makes the same predictions as the mental rotation model regarding additive heading and lot location effects. In this variant, the participant first identifies the cardinal direction the plane is coming from (instead of heading to) on the map, and then maps this heading onto a reference vector in the 3D view pointing towards the viewer (instead of ahead). In the absence of eye movement or verbal protocol data, we cannot be sure whether these two pilots were using mental rotation or this heading referencing variant. Since we did not want to classify participants as using heading referencing on the basis of equivocal evidence, we did not count these two pilots as using heading referencing. However, if these two pilots were added to the group of four heading referencing pilots, the findings from the following analyses of the four heading referencing pilots would remain unchanged.

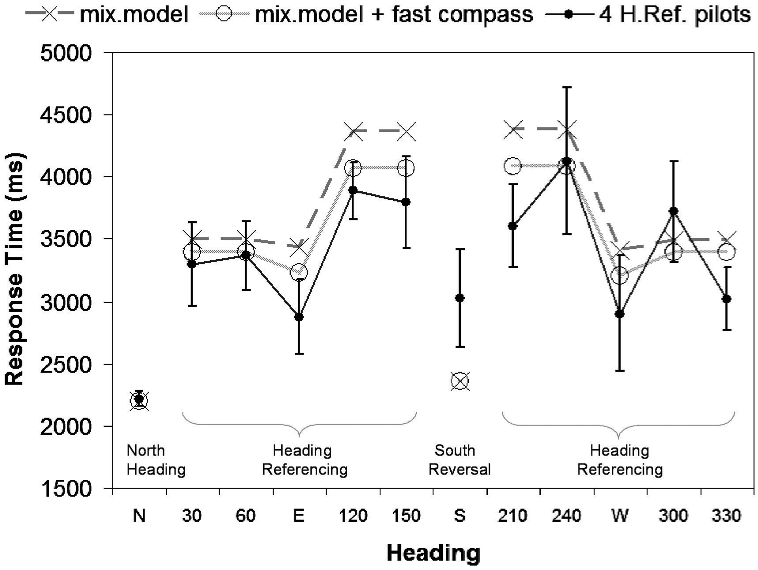

Figure 6. Effect of aircraft heading on response time for the four jet pilots classified as using heading referencing (labeled: 4 H. Ref. pilots); two heading referencing models (the mixture model, and the mixture model with speeded mental-compass rotation); and the north heading and south reversal models. Standard error bars shown for data.

regarding the effect of heading misalignment. The RMSD between the model and the four pilots' data was 460 ms, greater than the average *SE* for these pilots of 354 ms (see Table 1). The main discrepancy between the model and the data is at headings of east or west and southeast or southwest, where the pilots were faster than the model. This pattern suggests that the pilots were faster at mental rotation than the model. Recall that in order to fit the college student data, the mental rotation speed in the heading referencing models was slowed down by setting an execution time of 150 ms for the mental rotation production. Research by Gordon and Leighty (1988) suggests that aircraft pilots have better mental rotation ability than non-pilots. Therefore, to model the effects of possible faster mental rotation in pilots, we sped up the model's mental rotation by setting the execution time for the mental rotation production back to the default 50 ms. This "fast-compass" version of the mixture model of heading referencing fit the heading data of the four heading referencing pilots well (RMSD = 285 ms) as shown in Figure 6 and Table 1.

The fast-compass mixture model also fits these four pilots' data regarding the additive effects of heading and lot location for X-configuration problems (RMSD = 213; average *SE* = 285), as shown on the right side of Figure 7 and Table 1. The model fits the additive effects data for plus configuration

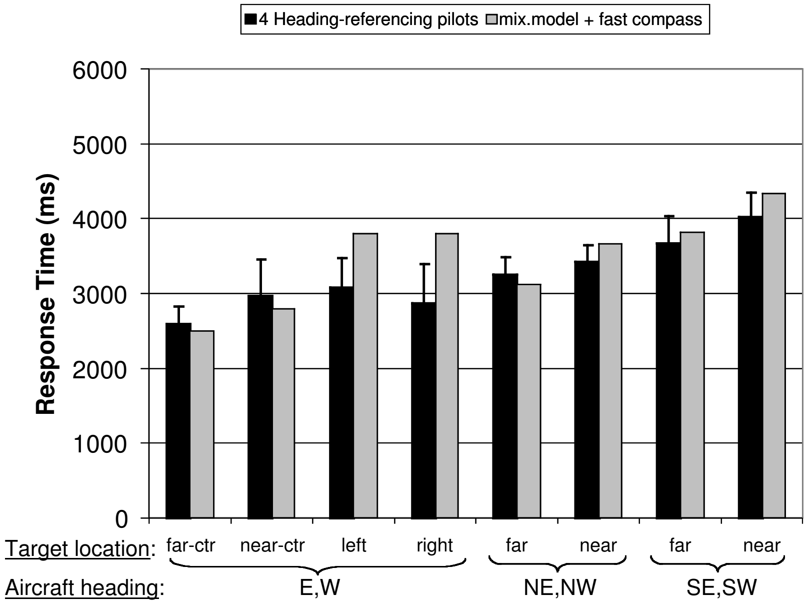

Figure 7. Effect of aircraft heading and 3D target location on response time for the four jet pilots classified as using heading referencing (black bars, with standard errors) and the mixture model of heading referencing with speeded mental-compass rotation.

problems less well (RMSD = 601, average *SE* = 411; see the left side of Figure 7 and Table 1), mainly because the jet pilots were faster than the model on right and left lot locations. The current heading referencing models are rather inefficient at determining the bearings to right and left lots. The reason for this is that, based on our verbal protocol studies, the model determines the bearings to top and bottom lots, even when these are not the target lots, before determining the bearing to the right or left lot. Perhaps the jet pilots were faster than the model on right and left lot problems because they developed a more efficient version of heading referencing for these problems that does not determine bearings to non-target lots. Finally, the right and left lot problems were the fast-compass mixture model fit poorly comprised only 14% of the different types of cardinal direction problems.

To summarize the jet pilot data, with the addition of a faster mental rotation parameter, the same heading referencing model that fit the college student data well also provided a good fit to the data of four experienced pilots classified as using heading referencing. For these pilots, the heading referencing model predicted the overall effect of heading misalignment and, for most of the cardinal direction problem types, the additive effects of heading and lot location. These findings suggest that this group of four jet pilots was using heading referencing.

GENERAL DISCUSSION

In this study, we used findings from our verbal-protocol and experimental studies (Gugerty et al., 2004; Gugerty & Brooks, 2001, 2004) to help specify an ACT-R cognitive model for some of the strategies people use for cardinal direction judgments. The verbal protocol studies suggested that people use at least three strategies in making cardinal direction judgments—north-heading, south-reversal, and heading referencing—with the particular strategy used depending on the heading of the navigator. The verbal-protocol studies also helped us identify and model the overall sequence of cognitive processes during each of these strategies. In addition, our part-task experiment (Gugerty & Brooks, 2004) suggested hypotheses regarding more detailed mechanisms for the heading referencing model, for example, that people align allocentric and egocentric information (and thereby determine bearings to objects in the 3D view) by rotating a mental compass overlaid on the perceived 3D view.

The process of developing our cardinal direction model was also guided by prior research in spatial cognition and navigation. The model presented here can be seen as an instantiation of the idea of memory-percept integration (Brockmole & Irwin, 2005) in the more complex and more realistic spatial task of making cardinal direction judgments. Data from our own and other labs suggested that people make cardinal direction judgments by integrating imagined visual information in VSTM with information in the visual-perception buffer, and then transforming the contents of VSTM and making inferences about it (Gugerty et al., 2004; Gunzelmann et al., 2004).

However, the general idea of memory-percept integration can be instantiated in multiple ways. For example, the VSTM representation can store coordinate or categorical spatial information, and it can use an egocentric or allocentric reference frame. Based on prior research showing the importance of categorical representations in spatial thinking (Huttenlocher et al., 1991; Tversky, 2003), we stored categorical cardinal direction labels in VSTM. In keeping with Sholl's (1996; 2001) model of short-term memory representations used in navigation tasks, we used egocentric coding of spatial locations in the VSTM buffer. In particular, VSTM locations in our cardinal direction model consisted of egocentric categories (e.g., "far-right") similar to those used in Moratz and Tenbrink's (2006) model of navigational communication.

The structures in the heading referencing model instantiating these psychological constructs—memory-percept integration, and categorical and egocentric spatial representations in VSTM—were developed before examining the empirical data in the college student and jet pilot studies. Therefore, to the extent that these empirical data support the model, they also provide evidence for the generality of these important constructs in spatial cognition by showing how they apply to a novel task domain. In the empirical data presented here, the response times predicted by the modeled heading referencing strategy provided a good fit to the response times of a group of well-practiced college students trained to use this strategy, and to four of seven experienced pilots who selected their own strategies. Thus, the heading-referencing model provides a specific example of how memory-percept integration, and categorical and egocentric spatial representations in VSTM can work together to accomplish a moderately complex spatial task.

Since heading referencing is used frequently by novice and experienced navigators (Gugerty et al., 2004), the empirical data in this study provide evidence that the heading referencing model is an accurate description of an important strategy for making cardinal direction judgments. Given the difficulty that many people experience in making cardinal direction judgments, many people need either training or improved interfaces in order to improve performance at this task. Staszewski (2006) has demonstrated how an accurate cognitive model can provide a basis for developing training that markedly improves performance of a spatial task (i.e., landmine search). We feel that the model presented here can be beneficial in developing training that will improve cardinal direction judgments (and the effectiveness of the model-based training in our college student study supports this conclusion). Further developing and testing this training is a goal for further research.

Comparison to other Cardinal Direction Models

In this project, we focused on heading referencing as a general strategy for making cardinal direction judgments when special-case strategies such as north heading and south reversal are not applicable. However, other general strategies are used for these judgments, such as the mental rotation strategy modeled by Gunzelmann et al. (2004) in which the angle in the 3D view formed by the viewer, the central building, and the target is translated to the map and then rotated. There are a number of differences between heading referencing and this mental rotation strategy. Heading referencing identifies allocentric cardinal direction information on its first step (map reading), stores this allocentric information as categorical labels in VSTM, and then transforms the categorical VSTM information. In contrast, the mental rotation strategy stores and transforms coordinate spatial information in VSTM, and does not identify categorical cardinal direction information until its last step. The heading referencing strategy involves some mental rotation of categorical cardinal-direction labels retrieved from long-term memory (i.e., the mental compass), but does not use mental rotation on all problem types. The mental rotation strategy rotates coordinate spatial information perceived from the 3D display, and always used mental rotation. Thus, while both strategies use both categorical and coordinate information, heading referencing makes more use of categorical information, and mental rotation of coordinate information.

Gunzelmann et al. (2004) developed an ACT-R model of how people use the mental rotation strategy just described for cardinal direction problems. Their model accurately predicted response times of people trained in the mental rotation strategy. The model of Gunzelmann et al. and our heading referencing model are complementary, since they describe two effective but different strategies for making cardinal direction judgments.

Earlier models of spatial thinking (e.g., Huttenlocher et al., 1991) emphasized that both categorical and coordinate spatial information are used in making common spatial judgments. These two main cardinal direction strategies—heading referencing and mental rotation—begin to elaborate some of the ways in which categorical and coordinate information is used in a complex spatial task. In our verbal protocol studies of novice and expert navigators (Gugerty et al., 2004), heading referencing was used twice as often as mental rotation strategies like the one modeled by Gunzelmann et al. (2004). We found a similar pattern in the current study, where four of seven jet pilots fit the response time predictions of heading referencing and two pilots fit the predictions of mental rotation. One hypothesis for why people prefer heading referencing is that this strategy emphasizes categorical information and people may prefer to use categorical over coordinate information in a complex spatial task, perhaps because maintaining and transforming spatial information in VSTM is easier (less mental demand) with categorical than with coordinate information.

Generality of the Current Model

Since the heading referencing strategy relies heavily on categorical representations of spatial information, the question arises about how widely these representations and this model can be generalized to cardinal direction judgments that differ from the particular task studied here. For example, how well would the heading referencing model generalize to judgments where the map heading varies continuously? Since the model currently categorizes any map heading into one of eight direction categories, it should generalize well to continuously varying map headings. However, more empirical testing needs to be done to ascertain whether this categorical perception of map headings matches with human behavior. The college-student data in this study suggests the tentative conclusion that people use heading categories such as east, southeast, and south (as used in this model) for the southern hemisphere, but use finer-grained categories for the northern hemisphere.

A related question concerns how well the heading referencing model would generalize to judgments of continuously varying 3D bearings. In the current task, participants identified the bearing from one object to another in the 3D view, but these bearings always fell clearly into one of four simple cardinal direction categories. How would heading referencing work if the bearings varied continuously between 0 and 360°? Some data from a prior study are relevant to this question. In Gugerty & Brooks (2004), we had participants perform three of the key substeps of heading referencing as separate tasks. In each of these tasks, there were always eight possible responses (north, northeast, and so forth) instead of the four responses on the task used in the current study. In each task, participants could perform the heading referencing sub-step about as well regardless of whether the response was a compound cardinal direction or a simple one. These findings suggest that the heading referencing model presented here would generalize to a task where there were eight bearings to be identified. Further research should assess how well the model generalizes to judgments of continuously varying bearings.

Finally, the cardinal direction model presented here should be generalized to other cardinal direction tasks and other types of participants. Regarding tasks, the current model can identify cardinal directions associated with a given bearing, but it cannot generate bearings associated with a given cardinal direction (as when following a route). Regarding participants, the current model only describes experts' accurate judgments. It should be generalized to describe the many errors in cardinal direction judgments made by novices.

In conclusion, the cognitive model of cardinal direction judgments presented and evaluated here demonstrates how basic spatial processes such as memory-percept integration and categorical coding in VSTM work together to accomplish a complex spatial task. In terms of applications, this cognitive model promises to be useful in guiding the development of training in cardinal direction judgments.

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