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A Dynamic Field Model of Location Memory

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Abstract

One of the fundamental questions in cognitive science is how people remember the locations of important objects in the world with enough accuracy to find these objects when they are no longer in view. Evidence from a variety of studies suggests that people rely on visible reference axes—streets, walls, the edges of a table—to help them remember the locations of target objects. Use of such perceptual information can help stabilize memory, but there is a cost: when people are asked to reproduce the location of a hidden object, they exaggerate the distance between the reference axis and the actual location of the object. These memory errors increase in magnitude as memory delays increase. Thus, errors away from reference axes may provide a window into the second-to-second processes that serve to maintain location information in memory. In the present report, we describe a dynamic field model that captures in quantitative detail how information is maintained in memory near reference axes. This model explains the time-dependent integration of memory and perceptual processes, thereby moving beyond current models of location memory.

Introduction

To interact successfully with the world, people must remember the locations of important objects with enough fidelity to find these objects when they are no longer visible. This is relatively easy when the target object shares a clear relationship with a visible landmark (e.g., under the landmark). In more challenging situations, however, there may be long delays between perception of the location and action toward it, and the target object may be hidden within a continuously varying scene or a field of view with relatively few perceptual landmarks. In these situations, how do people accurately maintain location information in memory?

Research on the short-term characteristics of location memory has generally focused on what people represent in memory when asked to remember the location of a hidden object. For instance, Smyth and colleagues have demonstrated that people represent locations relative to both egocentric body position and an allocentric reference frame (Smyth, Pearson, & Pendleton, 1988). Other data suggest that humans and non-human primates encode locations in retinotopic coordinates, head-centered coordinates, and shoulder or body-centered coordinates (e.g., Feigenbaum &

Rolls, 1991; Graziano, Hu, & Gross, 1997; Woodin & Allport, 1998).

Although the question “what is represented” is central to the study of location memory, it is equally important to understand how represented information is maintained in memory over short-term delays. In the past decade, this issue has been the focus of several neurophysiological studies (e.g., Constantinidis & Steinmetz, 1996; Rao, Rainer, & Miller, 1997). These studies have demonstrated that the sustained activation of neurons in prefrontal cortex, premotor cortex, and posterior parietal cortex underlie the maintenance of location information over short-term delays. Nevertheless, there have been relatively few behavioral studies investigating the short-term characteristics of location memory. The small number of behavioral studies is surprising given that virtually all of the studies examining what people represent in memory ask participants to reproduce remembered locations following a delay. A prerequisite for understanding the effects in many of these studies, then, is to understand how information about one location is maintained for several seconds.

The relative lack of behavioral data on maintenance processes has also led to a de-emphasis on time-dependent models of location memory. The goal of the present report is to introduce a dynamic model of location memory. This model represents the first attempt to explicitly capture how location information is maintained in memory over short-term delays.

How Is Location Information Maintained?

One way to help maintain an accurate memory of location over delays is to encode locations relative to visible reference cues in the environment. People might, for instance, encode locations relative to salient perceptual landmarks. This can help stabilize memory, particularly if the landmark is visible from a variety of vantage points (e.g., the Eiffel Tower).

Although the use of landmarks has been well documented (e.g., Sadalla, Burroughs, & Staplin, 1980), the present report emphasizes people’s use of a different, but equally prevalent type of reference cue—visible reference axes. The environments in which people typically act are naturally sub-divided by visible reference axes. Reference axes such

as streets, rivers, and walls sub-divide far spaces, while axes such as the edges of tables, the edges of a computer screen, and the edges of a counter top sub-divide near spaces. Data from a variety of spatial memory studies suggest that, as with visible landmarks, people use reference axes to help them remember locations (e.g., McNamara, Hardy, & Hirtle, 1989). However, the use of reference axes may have a cost. Specifically, when people are asked to reproduce the location of a target object near a reference axis after different delays, responses become systematically distorted away from the reference axis on a second-by-second basis (Spencer, 2000). These delay-dependent effects are central to the present report because they provide insights into the processes that serve to maintain location information in memory.

Location Memory Biases Near Reference Axes

Spatial priming and free recall studies have shown that adults use reference axes to help them remember locations. Specifically, adults group locations in memory relative to reference axes. McNamara and colleagues, for example, asked adults to learn the locations of multiple objects in a room subdivided by tape on the floor (McNamara et al., 1989). After the layout of objects was learned, participants read pairs of object names presented sequentially on a computer screen and judged if the second object was present in the original layout of objects. Adults responded more quickly when the two objects were in the same spatial region than when they were in different regions. This occurred even if the objects in different regions were physically closer than the objects in the same region. Similarly, free recall of objects and places is ordered relative to reference axes (McNamara et al., 1989). For example, adults use reference axes such as streets and rivers, recalling buildings and businesses from one region before recalling items in adjoining regions.

Although these data demonstrate that people use reference axes to organize location memory, it is difficult to isolate how such axes are used in these tasks because people are asked to remember multiple locations in the presence of many reference cues. Other studies have used much simpler tasks in which people remember a single location on each trial in the context of simple reference cues. In these studies, participants are typically shown a dot inside a geometrical figure. The dot is then covered up, there is a short delay, and participants are asked to reproduce the dot's location in a second, blank figure (e.g., Huttenlocher, Hedges, & Duncan, 1991; Huttenlocher, Newcombe, & Sandberg, 1994).

These studies allow a more complete view of the processes that maintain location information in memory, because factors central to these processes can be directly manipulated. For instance, the length of memory delays and the separation between the target location and the axes of the geometrical figure can be manipulated across trials. In addition, two types of error can be measured—the mean or constant error across responses to the same location, and the variability of these responses. These two measures provide complementary views of how location information is maintained. Constant error indicates both the direction and

magnitude of memory biases. Variable error indicates how stably location information is maintained.

Data from several location reproduction studies demonstrate that location memory is systematically distorted near reference axes. Specifically, memory is biased away from visible reference axes when the to-be-remembered locations are close to these axes. Huttenlocher and colleagues (1994) asked children and adults to reproduce the locations of dots within a rectangular frame. Responses in this study were biased away from the left and right edges of the frame. Similarly, when older children and adults were asked to reproduce the locations of dots within a circle, they made errors away from the edges of the circle (Huttenlocher et al., 1991; Sandberg, Huttenlocher, & Newcombe, 1996). Finally, Engbretson and Huttenlocher (1996) asked adults to reproduce the direction of a line within a “V” frame. Responses were once again biased away from the edges of the frame (see also, Schiano & Tversky, 1992).

In addition to biases away from visible reference axes, responses in these studies were biased away from “mentally imposed” axes. For example, participants made errors away from the vertical midline axis of the rectangular and V frames (Engbretson & Huttenlocher, 1996; Huttenlocher et al., 1994). Similarly, in the circle task, adults made errors away from both vertical and horizontal axes, suggesting they mentally sub-divided the circle into quadrants (Huttenlocher et al., 1991; Sandberg et al., 1996).

Finally, data from a recent study demonstrate that biases away from reference axes increase systematically over short-term delays. Spencer and Hund (2000) asked adults to reproduce the location of targets at different angular distances from the midline axis of a large, homogeneous task space. Participants moved to these remembered locations after delays that ranged from 0 to 20 s. As the delay increased, participants' responses were biased away from midline and became more variable. These delay-dependent effects suggest that errors away from reference axes may be a product of the processes that maintain information in memory. As such, these errors may offer unique insights into how location information is maintained over short-term delays.

Perceptual Processes and Reference Repulsion

Although delay-dependent results from Spencer and Hund (2000) indicate that memory decay plays a key role in response biases near reference axes, data from several studies suggest that memory processes are not the sole cause of these biases. Instead, perceptual processes contribute to biases near reference axes. Specifically, perceptual judgements of dot location and line orientation are biased away from reference axes. Importantly, these biases occur even though, in many studies, reference and target displays are presented simultaneously. Thus, errors away from reference axes in these studies cannot be caused by memory processes.

For instance, when a test line abuts a visible reference line forming an acute angle, people report the angle is larger than it actually is. This *acute-angle expansion* or *tilt contrast* effect is maximized at small angles and if the

reference line is horizontal or vertical (e.g., Blakemore, Carpenter, & Georgeson, 1970). Judgements of line orientation are also repelled from “virtual” reference axes (e.g., Beh, Wenderoth, & Purcell, 1971). Virtual reference axes result from the symmetry properties of geometrical figures. A square, for example, has four virtual reference axes—two diagonals and horizontal and vertical axes. Beh et al. (1971) showed that when adults are asked to judge the orientation of a rod in the context of a square frame, adults’ judgements are repelled from the closest axis of symmetry defined by the square frame. Such repulsion is particularly strong near horizontal and vertical axes.

Finally, adults’ judgements of dot position are repelled from visible reference axes. Rauber and Treue (1998) asked adults to judge if two sequentially presented locations were identical. When these locations were close to a vertical reference line, adults’ judgements were repelled from the reference line. This effect decreased as the separation between the target location and the reference line increased.

To summarize, data suggest that both memory processes and perceptual processes contribute to response biases near visible reference axes. Response biases increase systematically over delays, suggesting that these errors are caused, in part, by how location information is maintained in memory. However, responses are also biased away from reference axes when reference and target displays are presented simultaneously, suggesting that perceptual processes play an important role.

Here we present a formal model that brings together perceptual and memory processes to explain the origin of response biases near reference axes. Central to this account is the proposal that initial biases in perceptual processes are amplified in memory over short-term delays. Specifically, our model demonstrates how enhanced perceptual processing of visual information near reference axes can produce both biases in perceptual judgements and biases in how information is maintained in memory.

Empirical Results to be Modeled

The model we propose here was designed to capture data from several experiments that have explicitly investigated the time-dependent processes that underlie reference repulsion (Spencer & Hund, 2000). In these experiments, participants pointed to target locations projected on a large, opaque tabletop. Pointing movements were tracked using an optical-electronic motion-analysis system (Optotrak, Northern Digital, Inc.). Importantly, the layout of all visible

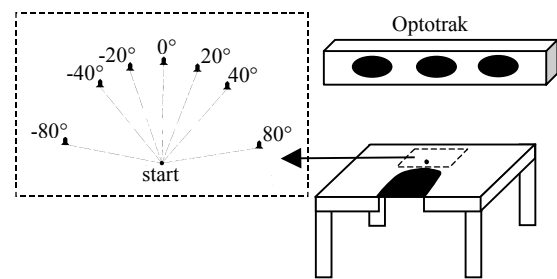


Figure 1. Schematic of apparatus. Targets projected on tabletop from below. Movements recorded using an Optotrak motion analysis system. Inset shows sample target positions relative to starting point.

reference cues were explicitly controlled (Figure 1). The experimental table was quite large (4' x 5') and the surface was homogeneous. Experimental sessions were conducted in dim lighting in a room with black curtains covering the walls and ceiling. This prevented participants from using external landmarks. Nevertheless, the hand, body, and table were clearly visible. Participants sat in a chair positioned within an arc cut out from one edge of the table (Figure 1). This limited their ability to use the front edge of the table as a reference location. Thus, in this task setting, visible reference cues included the edges of the table and its axes of symmetry, the location of the participant’s body and hand, and any reference locations projected onto the surface of the table.

In the first experiment (Spencer & Hund, 2000), participants moved to three target locations—a left, center, and right location—15 cm from a starting position located on the midline axis of the table. The delay (0-20 s) between the offset of a target light and a “go” signal was varied as was the angular distance of the targets from midline (10°, 20°, 40°, 60°, 80°; see Figure 1). Based on the results of studies by Huttenlocher and colleagues, we expected participants to make errors away from the midline reference axis, particularly when targets were close to 0°. The key question was how these errors would change as a function of delay. As the delay increased in the 10°, 20°, and 40° conditions, constant directional errors to the left target became significantly more negative (larger counterclockwise errors), and errors to the right target became significantly more positive (larger clockwise errors) (Figure 2a). Errors to the center target remained small across all delays. At larger target separations, the magnitude

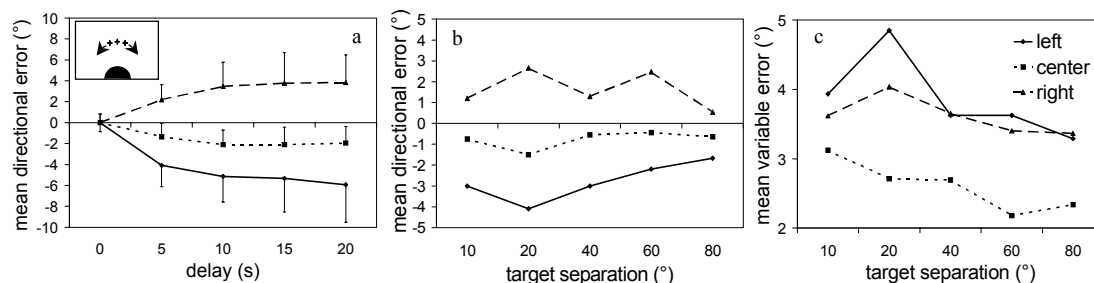


Figure 2. (a) Mean directional errors over delays for movements to the left, center, and right targets in the 20° condition. Inset shows a schematic of target locations and mean directional error. Error bars = 1/2 standard deviation. (b) Constant (mean) and (c) variable (standard deviation) directional errors for movements to each target location across target separation conditions.

of the errors away from midline decreased (Figure 2b) and no longer depended on delay. Variable (standard deviation) directional errors also increased over delays (see errors bars in Figure 2a). As with the constant errors, this effect was larger for movements to the left and right targets than to the center. Variability was largest in the 20° condition and decreased significantly at the other target separations (Figure 2c).

Results from this study indicate that location memory decays over short-term delays. More importantly, however, these results reveal a specific pattern of decay near a reference axis. Both constant and variable error increased over delay when participants moved to the left and right locations, and both types of error remained small when participants moved to midline. In addition, errors were largest at 20°, and decreased as the left and right targets were moved farther from midline. Thus, reference repulsion decreased for targets far from midline. Finally, there was a reduction in both constant and variable error very close to midline (at 10°).

In a second experiment, we found similar delay-dependent effects near reference axes, demonstrating that decay effects generalize to conditions in which the three targets are not symmetrically positioned around the midline axis of the table (Spencer & Hund, 2000). Specifically, we rotated the three targets clockwise and counterclockwise around the midline axis. For example, in one condition, targets were located at -60°, -40°, and -20°, while in another condition, targets were located at -40°, -20°, and 0°. Across all modified layout conditions, participants' responses to non-0° targets were repelled from midline as delays increased. In addition, the magnitude of these errors decreased as the targets were rotated away from midline (e.g., from -20° to -40° to -60°). Finally, participants' responses to targets along the midline axis were accurate with low variability.

The Model

To explain the pattern of memory decay near reference axes, we propose the following dynamic field model. This model specifies how perceptual and memory processes are integrated over delays to produce reference repulsion. Although this model represents a new approach to location memory, several of the concepts we discuss here have been used to capture how adults plan reaching movements to visually specified target locations (Schöner, Dose, & Engels, 1995).

The starting point for our dynamic field model is the concept of an activation field, where “activation” indicates the likelihood that a participant will move to a specific location at a particular moment in time. Plans to move to a target can be thought of as distributions of activation values across all possible target locations, with higher values indicating that a person is more likely to move to these locations than to others.

Two different types of information are integrated within the activation or action planning field. The first input—target input—captures the appearance and disappearance of the target light. The second input—P-ACT input—represents a participant's memory of previously activated

locations. The integration of these inputs in the planning field is governed by an interaction function that determines how activation at one site in the field influences activation at other sites. We use a local excitation and lateral inhibition interaction function. Thus, activation at one site increases the activation of its neighbors and decreases the activation of sites far away. One consequence of this function is that strong input can produce “self-sustaining” activation. Such patterns of activation maintain themselves, even after input is removed. In this way, *the planning field can maintain a memory of the input*.

The main concepts of the dynamic field model are captured in Equation 1. This equation specifies how activation in the planning field changes from time step to time step. Specifically, the change in activation at the next time step is a function of the current activation, the current inputs (target, P-ACT), and the way current above-threshold activation at each site enhances or suppresses activation at all other sites (local excitation/lateral inhibition function). Once computed, the change in activation is added to the current activation to produce the activation in the planning field at the next time step.

$$\begin{aligned} \tau \dot{u}(x, t) = & -u(x, t) + h + \int dx' w(x, x') f(u(x', t)) \\ & + S_{tar}(x, t) + S_{pact}(x, t) + S_{noise}(x, t) \end{aligned}$$

Equation 1. Rate of change in field activation =
- current activation + base activation + sum(current thresholded activation weighted by the interaction function) + target input + P-ACT input + spatially-correlated noise

Central to our dynamic field model is the way the model integrates perceptual and memory processes. We propose that interaction is not identical across all sites in the field, i.e., interaction is inhomogeneous. Specifically, interaction is more precise at sites associated with visible reference axes due to enhanced spatial tuning of visual processes at these locations. Thus, local excitation will be narrowly distributed at sites associated with a reference axis—the focus of enhancement—and broadly distributed across sites associated with regions of “empty” space. This is depicted in Figure 3. This figure shows the local excitation/lateral inhibition functions (positive/negative values) at twelve different locations in a sample field. The focal point in this example is at location 150, reflecting the presence of a reference axis at this central location. Local excitation is

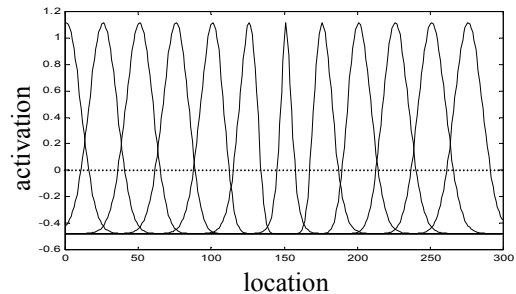


Figure 3. Sample modulation of local excitation/lateral inhibition function around the focal point x_0 (location 150).

most narrow at location 150, and expands to the left and right of this location.

The type of inhomogeneity we propose is conceptually similar to a proposal made by Suzuki and Cavanagh to account for repulsion effects in visual processing (1997); however, according to our proposal, inhomogeneities in visual processes couple directly into the processes that maintain location information in memory (via the interaction function). This has two effects on activation in the planning field over memory delays. First, activation peaks situated on or near the focus of enhancement will be attracted toward this focal point and remain stably positioned over delays. Second, activation peaks further from the focus of enhancement will be repelled from this focal point, because peaks gravitate toward sites with broader local excitation.

The form of inhomogeneous interaction we use is shown in Equations 2 and 3. We use an exponential form of inhomogeneity centered at the focal point x_0 —the site associated with the reference axis. The width of local excitation is modulated across the spatial range specified by σ_σ , and the magnitude of the modulation is specified by the amplitude parameter (A_σ).

$$w(x, x') = \frac{G_{\text{int}}}{\sqrt{2\pi}\sigma_{\text{int}}} \left\{ -w_i + \exp\left[-\frac{(x-x')^2}{2\sigma(x)^2}\right] \right\}$$

Equation 2. The interaction function is specified by $w(x, x')$, a local excitation/lateral inhibition function.

$$\sigma(x) = \sigma_{\text{int}}(1 - A_\sigma \exp[-(x - x_0)/\sigma_\sigma])$$

Equation 3. The interaction function (Equation 2) is inhomogeneous because the effective width of local excitation, $\sigma(x)$, depends on the field location x .

Model Results

Figure 4 shows a simulation of the dynamic field model that captures delay-dependent results from the 20° condition in Spencer and Hund (2000). Recall that in this condition, participants moved to three targets positioned symmetrically about midline. Figure 4 shows how activation in the planning field evolves from second to second during one trial in which the target is presented at -20°. The lower left

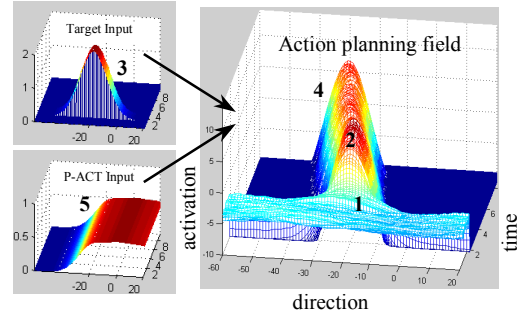


Figure 4. Simulation of the dynamic field model. “Input” axes are identical to axes in field graph. Numbers mark events during a single trial. See text for details.

panel of Figure 4 shows the P-ACT input. Activation in this panel is high near -20°, 0°, and 20°, reflecting a participant’s memory of activation at these sites on previous trials. For simplicity, we assume that this input is relatively constant during a 20 s trial. The upper panel shows the target input. Activation in this panel is zero at the start of the trial when the target is not visible, high at -20° when the target is turned on, and zero again when the target is turned off. The P-ACT and target inputs are integrated within the action planning field shown in the right panel. At the start of the trial, the planning field is slightly “pre-activated” at previously moved-to locations (1). This reflects the P-ACT input. Next, a target is turned on and a peak of activation builds up in the planning field at the target direction driven by the strong target input (2). This input generates a peak that is maintained even after the target is turned off (3). Finally, during the delay, the peak is repelled from the focus of enhanced interaction (0°) and drifts away from midline (4). This effect is partially counteracted by the P-ACT input which attracts the peak toward previously activated locations, in this case, toward 0° (5).

The model depicted in Figure 4 not only captures how information is maintained in memory on a single trial, but also the delay-dependent pattern of constant and variable errors reported in Spencer and Hund (2000). Figure 5 shows simulation results from 100 iterations of the model in which the location of maximal activation in the field was read-out at different delays. As can be seen in this figure, the constant and variable errors computed from simulations of the model capture the pattern of error shown in Figure 2 across both delays and target separations.

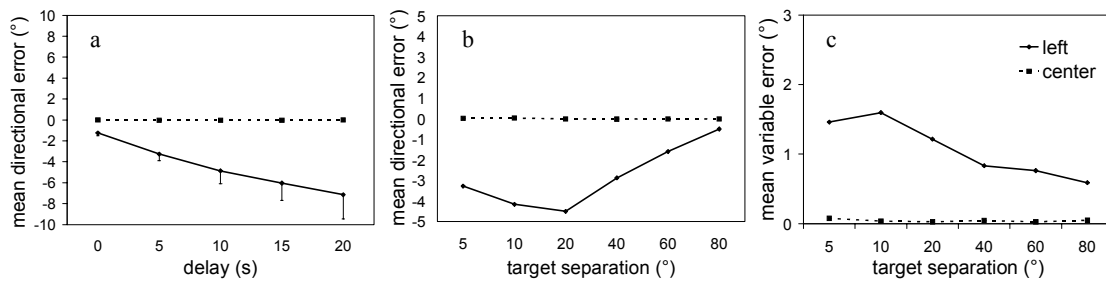


Figure 5. (a) Directional errors over delays for simulated trials to the left and center targets in the 20° condition. (b) Constant and (c) variable directional errors for simulated trials to these targets across target separation conditions.

Discussion

The dynamic field model effectively integrates the perceptual and memory processes that the literature suggests underlie biases away from reference axes. This model moves beyond the capabilities of previous location memory models in three fundamental ways. First, the field model proposes a specific integration mechanism that captures how location information is maintained from second-to-second over short-term delays. No current models of location memory are explicitly time-based. Second, the field model effectively reproduces time-dependent changes in both constant and variable errors near reference axes. Most models of location memory account for biases near reference axes; however, we know of no models that capture patterns of both bias and variability. Third, due to the “intrinsic” properties of the planning field, this field can generate its own activation in the *absence of input*. Thus, the field model can generate behavior that does not directly mirror the characteristics of input. Consequently, our model moves beyond models of location memory that posit that response biases are due to the relative weighting of inputs (e.g., Huttenlocher et al., 1991).

Finally, it is important to note that response biases in the dynamic field model are not solely a function of inhomogeneous interaction. As noted in Figure 4, the localization of activation peaks in the field is caused by the relative strength of repulsion effects (inhomogeneous interaction) and attraction effects (attraction toward P-ACT input). This has two important consequences. First, the field model may account for a second class of response biases prevalent in the spatial memory literature—attraction toward “prototypical” locations. We are currently exploring this possibility. Second, by changing the relative strength of repulsive and attractive effects, we may be able to capture striking differences in the performance of individuals. Consequently, the dynamic field model may offer insights not only into group effects, but also into the origins of individual differences in memory performance.

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