The Real-Time and Developmental Dynamics of Position Discrimination

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Abstract – The Dynamic Field Theory (DFT) has been used to account for spatial recall biases in children and adults. This paper extends the DFT to a second spatial working memory task, position discrimination. The DFT captures details of adults’ discrimination performance, as well as predicting developmental changes in discrimination. We conclude by discussing the dynamic field approach to developmental change in spatial working memory and how future theoretical and empirical work can help us understand the dynamics of development, while remaining committed to the real-time dynamics of behavior.

Index Terms – spatial working memory, neural networks, child development

I. INTRODUCTION

For the past several years, research from our lab has focused on understanding both the real-time and developmental dynamics of spatial working memory (SWM). This research program began by studying two classes of effects in spatial recall. First, children and adults show systematic biases in recall responses: young children’s responses are biased toward the center of a task space [1], whereas older children’s and adults’ responses are biased away from the center of the task space [2, 3]. Spencer, Schöner, and colleagues have proposed a Dynamic Field Theory (DFT) of SWM to account for these biases in recall responses [4, 5]. The DFT can also capture a second class of effects from studies of spatial recall: biases toward previously-remembered locations [1-3, 6].

More recent work has expanded the scope of the DFT to incorporate a second SWM task, position discrimination. We extended our work to capture the dynamics of position discrimination because it is viewed in the literature as a more perceptual task than spatial recall, but is still within the domain of SWM. Additionally, the shorter time scale of discrimination allows for closer examination of how frames of reference impact the initial formation of spatial memories. The model presented here is an extension of the DFT that captures position discrimination in adults. The central goal of the present report was to use this model—in conjunction with our developmental work on spatial recall performance—to predict developmental changes in discrimination performance. Empirical results support our predictions. Thus, we conclude by discussing how these results may be captured by the DFT, and what these findings indicate about our understanding of developmental process.

II. DYNAMIC FIELD THEORY

The DFT is a process-based theory of spatial working memory (SWM) instantiated in a neural network model, originally developed to account for spatial recall biases [4, 5]. Here we present an extension of this model that captures position discrimination performance. In this task, two stimuli are presented in quick succession (e.g., 500 ms apart) and the participant judges whether the stimuli were in the same or different locations. Fig.1 shows a DFT simulation of a position discrimination trial. In each of the panels in Fig.1, the x-axis consists of a collection of spatially-tuned neurons, and the y-axis shows each neuron’s activation level.

The left column of Fig.1 shows activation in the SWM field; this field actively maintains location information in working memory in the absence of target-specific input [4, 5]. The right column is a “novelty” field, which is critical to our approach to the same/different decisions required by the position discrimination task. In particular, the novelty field detects changes along the spatial dimension (i.e., differences in the positions of stimuli). The SWM and novelty fields are reciprocally coupled such that strong activation in SWM locally inhibits the associated sites in the novelty field, while strong activation in the novelty field globally inhibits all sites in SWM. Note that both fields receive perceptual inputs that capture the events in the task.

The rows of Fig.1 show how activation evolves over time in the model during a single discrimination trial. The first stimulus (S1) is presented for 500 ms (top row), then removed for a 500 ms delay (second row). Then, the second stimulus (S2) is presented for 500 ms either near (third row) or far (fifth row) from S1. After S2 is removed, the fields compete to form a same (fourth row) or different (sixth row) decision.

In the top row of Fig.1, S1 is presented to the model, that is, we presented a Gaussian input centered at the location of S1 to both the SWM and novelty fields (see arrows in Fig.1). This input led to the creation of an activation “peak” in the SWM field (see top left panel of Fig.1) due to strong locally excitatory
and laterally inhibitory interactions among neurons in this field. In addition, this activation in SWM created a trough of inhibition at the location of S1 in the novelty field. After S1 is removed, local excitation and lateral inhibition among neurons in the SWM field maintain the S1 peak throughout the delay. Consequently, there is continued local inhibition projected to the novelty field, thereby maintaining the inhibitory trough (see second row of Fig.1).

Next, the second stimulus (S2) is presented to the model. The effect of this input depends on the location of S2 relative to S1. If S2 is near S1 (third row of Fig.1), then the S2 input will overlap with the existing peak in the SWM field. Activation grows and, in turn, broadens the inhibitory trough in the novelty field. Thus, when S2 is removed, the peak in SWM remains, leading to a same decision (fourth row of Fig.1).

When S2 is far from S1 (fifth row of Fig.1), however, input enters the SWM field at a strongly inhibited site, specifically, within the lateral inhibition created by the S1 peak. This causes activation to grow slowly at the spatial position of S2. In the novelty field, on the other hand, S2 is outside of the strong inhibitory trough created by input from the SWM field, so activation builds more quickly. After S2 is removed (sixth row of Fig.1), this slight advantage in the novelty field allows a peak to build at S2. Above-threshold activation in the novelty field then passes global inhibition to SWM, which squashes the S1 peak. Thus, at the end of the trial, the peak in the novelty field leads to a different decision.

According to this account, then, discrimination performance depends on whether S2 is presented in a location that overlaps with the S1 peak. Critically, several aspects of the DFT that capture performance in spatial recall also influence the degree of overlap in a discrimination context. In particular, adults' biases away from reference frames in spatial recall tasks arise from inhibition associated with the reference axis. This reference-related inhibition has two predicted consequences for discrimination performance.

First, greater inhibition near the reference results in narrower peak width near midline. Because narrower peaks are less likely to overlap, this produces enhanced discrimination performance in the DFT (i.e., different responses at smaller separations between S1 and S2). Second, greater inhibition near reference frames leads to directional drift. Fig.2 shows how directional drift should influence position discrimination in the DFT. When S1 is presented, a peak forms in SWM and self-sustains during the delay before S2 is presented. During this delay, reference-related inhibition repels the peak away from midline (as seen in spatial recall). If S2 is presented in the direction that S1 has drifted (left side of Fig.2), the peaks are more likely to overlap, leading to more same responses at larger separations (i.e., impaired performance). On the other hand, if S2 is presented in the opposite direction (right side of Fig.2), then the peaks are less likely to overlap and will lead to more different responses at smaller separations (i.e., enhanced performance). Thus, the DFT predicts that discrimination will be impaired when S2 is presented in the direction of drift, or away from midline for adults. Moreover, directional drift should affect discrimination performance most at spatial locations where recall biases are greatest, around 20-30° [3].

In summary, the DFT predicts two novel effects of reference-related inhibition on position discrimination: enhanced performance near midline and impaired performance when S2 is presented away from midline. These effects are illustrated schematically in Fig.3. Based on peak width, performance should be enhanced (i.e., lower discrimination thresholds) near versus far from midline, regardless of the direction of S2 (see Panel 1). At these same locations, directional drift should not influence performance near midline.

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Fig.1. DFT simulation of a position discrimination trial.

Fig.2. Effect of directional drift of S1 on discrimination when S2 is presented in the same (left panel) or opposite (right panel) direction of
where drift is minimal (see Panel 2). By contrast, around 20-30° from midline, drift should impair performance when S2 is presented away from midline, but improve performance if S2 is toward midline (as shown in Fig.2). Because these two effects arise through the same mechanism in the DFT, they should combine to form the pattern of performance shown in Panel 3: comparable performance across locations when S2 is presented toward midline, but impaired performance far from midline when S2 is away from midline. Panel 4 shows data with adults confirming this predicted pattern of performance [7].

III. DEVELOPMENT OF POSITION DISCRIMINATION

A. Developmental Predictions

Previous work from our lab has shown continuity in the processes underlying spatial working memory over development [2]. If the same processes underlie SWM over development, then we should be able to use the factors central to our theory of position discrimination to predict developmental change in position discrimination. The dynamic field account of position discrimination in adults highlights two important factors: peak width and directional drift. How might we expect these factors to change over development?

One well-documented effect in SWM is a shift in spatial recall biases over development: young children show drift toward midline [1], whereas older children show adult-like patterns of drift away from midline [2]. This shift in directional drift occurs gradually between the ages of 3 and 6 years [8]. Given this developmental shift in recall biases, the DFT predicts that the advantage shown in adults’ discrimination performance based on the direction of S2 should “flip” with children who show drift toward midline (i.e., 3-year-olds): performance should now be better when S2 is presented away from midline. Moreover, because recall biases shift gradually between the ages of 3 and 6, this S2-away advantage should gradually shift to an S2-toward advantage by 6 years of age.

B. Empirical Tests of Predictions

1) Method: Participants in this experiment were 40 3-year-olds, 42 4-year-olds, 39 5-year-olds, and 39 6-year-olds from the Iowa City community, and 19 University of Iowa undergraduates. Participants were seated at a large, homogeneous table, with stimuli projected onto the surface from below. Each trial began with a 100 ms warning tone, followed by a 1 s delay and then a 1 s presentation of S1 (7 pixels in diameter). Next came a 500 ms delay, then a 1 s presentation of S2. After S2 disappeared, participants reported “same” or “different” to the experiment, who then entered the response by pressing corresponding buttons on a keypad. Across trials, S1 was presented at two target locations: 10° and 30° to the right of the midline symmetry axis of the table. For children, S2 could then appear 0-20 pixels from S1, in steps of 4 pixels. For adults, S2 could appear 0-10 pixels from S1, in steps of 1 pixel. Children were randomly assigned to S2-toward or S2-away conditions; adults completed both within a single session, with trials blocked by S2-direction. Trials were presented according to a stair-casing procedure that effectively estimated discrimination thresholds in relatively few trials (see [9] for details).

2) Results: Fig.4 shows mean discrimination thresholds across targets and ages separately for each S2-direction. As this figure shows, the pattern of results changed systematically across ages. Three-year-olds showed the expected reversal relative to adults’ performance based on S2-direction with better performance in the S2-away condition at the far target. Across 4-, 5-, and 6-year-olds’ data, thresholds in the S2-toward condition decreased, eventually leading to adult-like performance by 6 years. Adults’ data replicated the results of Experiment 1, with no difference at the near target, and better performance for S2-toward at the far target. Lastly, across development, we observed an overall decrease in discrimination thresholds.

IV. CONCLUSIONS AND FUTURE DIRECTIONS

The model presented here extended the DFT to capture adults’ position discrimination performance. Based on the same processes, we were able to predict developmental changes in discrimination that mirrored known developmental changes in spatial recall biases. The next step in this line of research is to use what we have learned about development from these data to examine how the processes of the DFT can account for developmental change.

In our previous developmental work, we proposed the Spatial Precision Hypothesis (SPH) to capture developmental changes in SWM [2, 6, 8]. The SPH posits a gradual, quantitative change in the interaction among neurons in SWM. Specifically, neural interactions in SWM become stronger and more precise over development. Fig.5 illustrates this change. Early in development, local excitation is broad and weak, with weak lateral inhibition (black line in Fig.5). Later in development, local excitation is strong and focused with precise lateral inhibition (gray line in Fig.5). We have tested this account of developmental change by capturing a number
of developmental changes in SWM including enhanced precision of long-term spatial memories [6], enhanced precision of choice selection in spatial recognition tasks [10] and the developmental changes in reference-related recall biases discussed previously [8].

The developmental effects in position discrimination reported here mirror the changes in directional drift captured in our model of spatial recall using the SPH. As such, this developmental hypothesis is likely to capture developmental changes in this task. Moreover, because peak width is important for position discrimination and peak width changes systematically over development according to the SPH, this hypothesis should capture the gradual reduction in discrimination thresholds between 3 and 6 years. We are currently working on model simulations that explore how developmental changes in spatial precision affect both peak width and directional drift in position discrimination.

In conclusion, the SPH is a promising approach to developmental change in SWM tasks, and it seems well-positioned to capture the empirical results reported here. To our knowledge, the DFT is the only process model that can capture both real-time and developmental dynamics in a variety of SWM tasks. Future theoretical and empirical work aims to address how changes in spatial precision arise, and how these changes might relate to other changes in brain-behavior relations over development [11].

REFERENCES