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Models provide specificity: Testing a proposed mechanism of visual working memory capacity development

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ABSTRACT

Numerous studies have established that visual working memory has a limited capacity that increases during childhood. However, debate continues over the source of capacity limits and its developmental increase. Simmering (2008) adapted a computational model of spatial cognitive development, the Dynamic Field Theory, to explain not only the source of capacity limitations but also the developmental mechanism. Capacity is limited by the balance between excitation and inhibition that maintains multiple neural representations simultaneously in the model. Development occurs according to the Spatial Precision Hypothesis, which proposes that excitatory and inhibitory connections strengthen throughout early childhood. These changes in connectivity result in increasing precision and stability of neural representations over development. Here we test this developmental mechanism by probing children's memory in a single-item change detection task. Results confirmed the model's predictions, providing further support for this account of visual working memory capacity development.

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Visual working memory (VWM) provides a critical foundation for our understanding of the visual world around us. Without the ability to represent visual information as we move our eyes around the world, our experience would be a series of disjointed snapshots. Decades of research on VWM have revealed its severely limited capacity, just 3–5 simple items in young adults (Cowan, 2010), as measured in the change detection task. In this task, a memory array containing a small number of

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simple objects—for example, colored squares—is presented briefly (100–500 ms), followed by a short delay (500–1000 ms). After the delay, a test array is presented in which all the colors are the same (on no-change trials) or one has changed to a new color (on change trials). Capacity is estimated based on how performance declines as the number of items increases (Pashler, 1988). Despite how well established capacity limits are empirically, there remains an active debate over the source of such limits in adults (Fukuda, Awh, & Vogel, 2010).

Multiple studies have demonstrated that VWM capacity increases early in development, but the mechanism(s) underlying this developmental improvement is also a source of debate (Simmering, submitted for publication; Simmering & Perone, submitted for publication). Simmering (2008) addressed the source of capacity limits and their developmental improvement by adapting Dynamic Field Theory (DFT; Spencer, Simmering, Schutte, & Schöner, 2007), a model of spatial cognition and development, to capture change detection performance in a neurally-grounded computational model. The core architecture of the model consists of three layers of neurons tuned along a continuous color dimension. Items are represented as localized “peaks” of activation in excitatory layers, which are supported through the local excitatory and lateral inhibitory connections within and between layers. Simmering demonstrated that the model could capture change detection performance and capacity limits from early childhood into adulthood through an established neuro-developmental mechanism, the Spatial Precision Hypothesis (SPH; first proposed by Schutte, Spencer, & Schöner, 2003).

A primary advantage of using computational models to explain behavior is the ability to generate and test novel predictions. Our goal here is to test Simmering’s (2008) account for developmental changes in VWM through such predictions. In the sections that follow, we first describe how Simmering’s model captures change detection performance through early childhood. Next, we discuss the implications of the DFT and the SPH and use the model to generate novel predictions for a color discrimination task. Then we present results from a new task we developed to test how memory representations change from early childhood to adulthood. We conclude by considering further questions raised by our results, how the DFT may address these in the future, and the implications for our understanding of developmental processes in general.

1. Modeling change detection performance over development

The three-layer architecture of the DFT was developed to account for performance across a number of spatial memory tasks (Spencer et al., 2007), and was recently extended to capture some characteristics of change detection performance (Johnson, Spencer, & Schöner, 2009; see Schöner & Spencer, in press, for details on development of this architecture and additional applications). Simmering (2008) built on these previous instantiations to test whether the DFT could provide a source of capacity limits in VWM (see also Johnson, Simmering, Buss, & Spencer, in preparation). The three layers of the model contribute different cognitive functions to the task. The first excitatory layer, the Perceptual Field (PF), serves as an encoding field; inputs are presented to the model as Gaussian distributions of activation centered at the relevant color values (e.g., red, blue, and green, along a continuous color dimension).[1] When these inputs are “on” (i.e., projecting activation into PF) localized peaks of activation form in PF; when the inputs turn “off” (i.e., the visual items disappear from the display and no activation is projected), the neurons in PF quickly return to their resting level. In this way, neurons in PF are tuned to respond only when visual stimuli are present in the array.

The second excitatory layer of the DFT, the Working Memory (WM) field, also receives weak input from the environment and strong input from PF. Thus, when visual stimuli are presented in the array, the peaks in PF and direct input to WM combine to form localized peaks in WM. Once peaks are established in WM, the items from the array have been encoded into memory. Although both PF and WM are excitatory layers, the excitatory connections within WM are tuned to be stronger than in PF. This allows WM to serve a maintenance function; when inputs are removed, the peaks in WM enter a self-sustaining state and are maintained in the absence of input, unlike activation in PF. Critically, this

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[1] This 360° color dimension is an approximation of the CIELAB 1976 perceptually-uniform color space (following Johnson, Spencer, Luck, & Schöner, 2009; Johnson, Spencer, & Schöner, 2009).