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Probing the early development of visual working memory capacity with functional near-infrared spectroscopy

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ABSTRACT

Visual working memory (VWM) is a core cognitive system with a highly limited capacity. The present study is the first to examine VWM capacity limits in early development using functional neuroimaging. We recorded optical neuroimaging data while 3- and 4-year-olds completed a change detection task where they detected changes in the shapes of objects after a brief delay. Near-infrared sources and detectors were placed over the following 10–20 positions: F3 and F5 in left frontal cortex, F4 and F6 in right frontal cortex, P3 and P5 in left parietal cortex, and P4 and P6 in right parietal cortex. The first question was whether we would see robust task-specific activation of the frontal–parietal network identified in the adult fMRI literature. This was indeed the case: three left frontal channels and 11 of 12 parietal channels showed a statistically robust difference between the concentration of oxygenated and deoxygenated hemoglobin following the presentation of the sample array. Moreover, four channels in the left hemisphere near P3, P5, and F5 showed a robust increase as the working memory load increased from 1 to 3 items. Notably, the hemodynamic response did not asymptote at 1–2 items as expected from previous fMRI studies with adults. Finally, 4-year-olds showed a more robust parietal response relative to 3-year-olds, and an increasing sensitivity to the memory load manipulation. These results demonstrate that fNIRS is an effective tool to study the neural processes that underlie the early development of VWM capacity.

Introduction

Working memory has been called the heart of intelligent behavior (N cka, 1992), and a core property of this cognitive system is its highly limited capacity. Working memory capacity limitations are reliably predictive of individual differences in a host of cognitive functions including fluid intelligence, language comprehension, and scholastic achievement (e.g., Conway et al., 2003). This predictive relationship appears to be particularly strong for visual working memory (VWM). VWM plays a key role in much of visual cognition, comparing percepts that cannot be simultaneously foveated and identifying changes in the world when they occur (for review, see Luck and Vogel, 1997; Vogel et al., 2001). By some estimates, individual differences in VWM capacity account for up to 40% of the variance in global fluid intelligence (Fukuda et al., 2010). VWM capacity limitations also have a profound influence on cognitive development across a range of domains (e.g., Oakes et al., 2008), and visuo-spatial WM deficits have been observed in clinical populations, including children diagnosed with attention-deficit/hyperactivity disorder (ADHD; Willcutt et al., 2005), autism (Steele et al., 2007), developmental coordination disorder (Alloway, 2007), and schizophrenia (Cullen et al., 2010), as well as children born preterm (Vicari et al., 2004). Given these pervasive influences, understanding the development of VWM and the nature of VWM capacity limits has broad implications and may be central to develop early interventions for atypically developing populations.

The method of choice for probing VWM capacity is the change detection task (Luck and Vogel, 1997). Here, participants are shown a memory array (100–500 ms), there is a brief delay (250–1000 ms), and then a test array appears in which either all of the objects match the memory array, or the feature(s) of one object is changed to a new value. Participants report whether they detected a change in the second array or whether the arrays were the same. This task has several advantages over other visuo-spatial tasks. For instance, the brief presentation and short delay reduce the likelihood of verbal recoding and rehearsal (Vogel et al., 2001), and location is typically not a relevant dimension in the task—items in both arrays are generally in the same positions—so the influence of spatial memory is minimized. Thus, change detection provides a relatively direct probe of the VWM system.

Recent work using fMRI has revealed a distributed network of frontal and posterior cortical regions that underlies VWM and change detection. VWM representations are actively maintained in the intraparietal sulcus (IPS), the dorso-lateral prefrontal cortex (DLPFC), the ventral–occipital (VO) cortex for color stimuli, and the lateral–occipital complex (LOC) for shape stimuli (Todd and Marois, 2004, 2005). Many of these regions

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show a key signature of VWM capacity: the BOLD signal increases as more items must be remembered, and this increase asymptotes near the capacity of the VWM system. For instance, Todd and Marois (2004) reported an increase in the BOLD signal in IPS as the number of items in the change detection task (the set size) increased from 1 to 3. This neural signal reached an asymptote at set sizes 4, 6, and 8, consistent with behavioral estimates of VWM capacity using Pashler's capacity measure, *k* (Pashler, 1988). Other data have revealed a suppression of the temporo-parietal junction (TPJ) during the delay interval of the change detection task (Todd et al., 2005), and activation of the anterior cingulate cortex (ACC) during the comparison phase (Mitchell and Cusack, 2007; Todd et al., 2005). Moreover, there is greater activation of this network on change versus no change trials, and the hemodynamic response on error trials tends to be less robust (Pessoa and Ungerleider, 2004; Pessoa et al., 2002).

Developmental studies using the change detection task have revealed that 3-year-olds have a capacity between 1.5 and 2 items (Simmering, 2012). Capacity increases to 2–3 items by 5 years and to roughly 4 items by 7 years (Cowan et al., 2005; Riggs et al., 2006; Simmering, 2012). What neural systems underlie these changes in VWM capacity? Previous studies have reported activation across frontal (DLPFC, VLPFC) and parietal (intra and inferior parietal regions) regions in VWM tasks across a range of ages from 6 to 23 years (Bunge and Wright, 2007; Edin et al., 2007; Fair et al., 2007; Geier et al., 2009; Klingberg, 2006; Klingberg et al., 2002; Kwon et al., 2002; Nelson et al., 2000; Olesen et al., 2007; Scherf et al., 2006; Thomas et al., 1999; Vuontela et al., 2009). Frontal–parietal activation becomes stronger (Kwon et al., 2002; Olesen et al., 2007; Thomas et al., 1999) and, in some cases, more localized (Geier et al., 2009; Scherf et al., 2006) over development. Additionally, some studies have reported involvement of the caudate nucleus (Bunge and Wright, 2007; Olesen et al., 2007; Scherf et al., 2006), precuneus (Scherf et al., 2006), and parts of the premotor cortex (Scherf et al., 2006; Thomas et al., 1999) in VWM tasks, but these effects have been inconsistent across age groups. Finally, several studies reported a decrease in the activation of Broca's area as a function of age which may be linked to verbal reasoning strategies employed by children during the task (Kwon et al., 2002).

Although these data have shed light on the neural systems that underlie changes in VWM over development, technical barriers have prevented an extension of this work into early development. fMRI is extremely sensitive to movement of the head—an obvious limitation when working with infants and young children—and the background noise created by MRI is quite loud. Such technical barriers are unfortunate given that individual differences in cognitive performance in the first two years of life are predictive of later performance (Rose et al., 2009, 2012), and recent analyses suggesting that investments and intervention efforts in early development are among the wisest (Heckman, 2006).

An alternative to fMRI is to use functional Near-Infrared Spectroscopy. fNIRS uses light in the near infrared range (695–1000 nm) which passes through the skull and brain tissue. fNIRS systems measure the absorption and scattering of photons as light passes through, allowing for the quantitative measurement of changes in cerebral blood volume and oxygenation resulting from functional activation. Because fNIRS uses light-weight and quiet light emitters and receivers directly attached to the head, this technology is much more resistant to head movements. With respect to spatial resolution, fNIRS is better than EEG but poorer than fMRI. Its greatest limitation is its inability to examine relatively deep areas of the cortex (infrared light generally penetrates up to 2 cm into the brain depending on the separation between the source and the detector). Given that infants and young children have relatively thin skulls and small brains, however, this limitation is much less severe. Moreover, a large proportion of the frontal–parietal network central to VWM is located close to the cortical surface and can be measured using fNIRS even with adults (Cutini et al., 2011). Thus, fNIRS is ideally suited as a cognitive neuroscientific technique to study the VWM system early in development (Aslin and Mehler, 2005).

In this report, we present data from the first functional neuroimaging study to examine the neural basis of VWM capacity in early development. Three- and 4-year-old children participated in a change detection task where we varied the number of items they had to remember from 1 item to 3 items while we simultaneously recorded neural activity using a 24-channel fNIRS system with sources and detectors positioned over frontal and parietal cortical areas in both the left and right hemispheres. Our central question was whether the frontal–parietal network identified using fMRI would show task-specific neural activity, and how this network would change between 3 and 4 years. We also examined whether the same neural signature of VWM capacity—the asymptote of neural activity at capacity (Todd and Marois, 2004)—would be evident early in development.

Method

Participants

Twenty-eight 3.5-year-olds (17 females; *M* age = 3.5 years, *SD* = 1.5 months) and 19 4.5-year-olds (7 females; *M* age = 4.5 years, *SD* = 2.5 months) participated in the two-session study. Children were recruited from a participant registry maintained by the Department of Psychology. Parents were sent a letter inviting them to participate and then received a follow-up phone call. All children had normal or corrected-to-normal vision. Seven children were Asian or African-American; the remaining participants were Caucasian. Nine additional 3.5-year-olds were enrolled in the study but were excluded from further analysis: 6 completed only one session, 2 had noisy NIRS signals, and 1 took the NIRS cap off during a session. Two additional 4.5-year-olds were enrolled in the study but were excluded from further analysis because they only completed one session.

The final sample contributing behavioral data included 18 3.5-year-olds and 18 4.5-year-olds. As we discuss below, several children were excluded from the behavioral analysis for poor behavioral performance (<50% correct on set size 1 trial for 2 or more runs). fNIRS data from 3 additional 3.5-year-olds and 1 additional 4.5-year-old were excluded from fNIRS analyses after motion-rejection and outlier removal because they failed to contribute data to every cell in the experimental design (see below).

Stimuli and apparatus

We used the change detection task from Simmering (2012). The task was explained to children using 3 × 3 inch flashcards that contained a set size of 1 (SS1), 2, or 3 items. The task proper was completed on a 46 inch LCD television monitor that was connected to a PC running E-Prime 2.0 software (Psychology Software Tools, Pittsburgh, PA). Children were seated approximately 25 in. from the screen. The stimulus arrays were composed of a subset of 8 different white shapes (see Fig. 1) presented on a virtual gray card on a black background. The shapes subtended approximately 1 by 1 in. and the virtual gray card subtended a 6.25 by 6.25 inch area. Shapes were presented in any of six randomly selected and evenly spaced locations 3 in. from the center of the gray rectangle. On a given trial, an array of 1 to 3 items was presented. On same trials, the second array contained the same shapes in the same configuration as the sample array. On a change trial, the second array contained a new shape at a location previously occupied on the sample array.

Procedure and design

At the start of the first session, an experimenter described the task to the child as a 'matching' game. The experimenter first demonstrated the task using the flash cards which were placed on a large piece of