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The Development of Nonverbal Working Memory and Executive Control Processes in Adolescents

Monica Luciana, Heather M. Conklin, Catalina J. Hooper, and Rebecca S. Yarger
University of Minnesota

The prefrontal cortex modulates executive control processes and structurally matures throughout adolescence. Consistent with these events, prefrontal functions that demand high levels of executive control may mature later than those that require working memory but decreased control. To test this hypothesis, adolescents (9 to 20 years old) completed nonverbal working memory tasks with varying levels of executive demands. Findings suggest that recall-guided action for single units of spatial information develops until 11 to 12 years. The ability to maintain and manipulate multiple spatial units develops until 13 to 15 years. Strategic self-organization develops until ages 16 to 17 years. Recognition memory did not appear to develop over this age range. Implications for prefrontal cortex organization by level of processing are discussed.

Interest in the development of the prefrontal cortex has intensified in recent years, because the prefrontal cortex orchestrates high-level cognitive functions that support responsible adult behavior. Among these functions are inhibitory control (Diamond, 1990), the ability to integrate past knowledge with future goals (Fuster, 1997), and behavioral flexibility (Dias, Robbins, & Roberts, 1996). It is presumed that in healthy people, these functions interact cooperatively to promote adaptive future-directed behavior. Future-directed behavior is by definition integrative. It requires that one is able to represent pertinent information in mind, ignore extraneous distractions, and translate goal-related representations into behavioral actions at appropriate times, using recall to guide those actions. It is often assumed to require working memory. When Baddeley and Hitch (1974) introduced their tripartite model of working memory to the psychology community, they described a central executive system and two subordinate (visuospatial and phonological) systems that collectively allowed for the temporary storage and manipulation of information. The subordinate systems were hypothesized to encode information according to domain of processing and maintain it over time. The central executive allocated attentional resources, manipulated information that was maintained by the subordinate systems, and implemented strategies relevant for the use of that information. Emerging as it did from the cognitive psychology tradition, this model made no assumptions regarding the neurobiological substrates of these functions (Baddeley, 1992; Baddeley & Hitch, 1974). It was left to neuroscientists interested in the brain substrates of cognition to investigate the neural dynamics of working memory processes, initially through the use of delayed response tasks.

When Jacobsen (1935) demonstrated that spatial delayed response performance was impaired in nonhuman primates following bilateral prefrontal lesions, delayed response tasks became the preferred means of examining the integrity of prefrontal functions, particularly those mediated by the dorsolateral region (Goldman & Rosvold, 1970; Goldman-Rakic, 1987). Numerous studies confirmed that dorsolateral prefrontal cortex cells are active during the delay phase of task performance in behaving animals (Funahashi, Bruce, & Goldman-Rakic, 1989; Fuster & Alexander, 1971; Niki, 1974) and that dorsolateral prefrontal lesions impair performance (Diamond & Goldman-Rakic, 1989; Goldman-Rakic, 1987). Notably, virtually all of the paradigms used to derive these conclusions involved the assessment of spatial delayed response (also referred to as spatial working memory) using paradigms that required animals to make recall-guided responses to retrieve desired objects. According to neurobiologically based models of spatial working memory, the use of recall to guide future actions is a fundamental

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Correspondence concerning this article should be addressed to Monica Luciana, Department of Psychology, 75 East River Road, University of Minnesota, Minneapolis, MN 55455. Electronic mail may be sent to lucia003@tc.umn.edu.

function of the prefrontal cortex during situations that require working memory (Fuster, 1997; Goldman-Rakic, 1987). If recall is not integrated with a requirement for future-directed action, the demands on the prefrontal cortex decrease. Thus, not all recall-based tasks require working memory or the prefrontal cortex. The active representational nature of the response is critical to the definition of prefrontally mediated working memory functions that we adopt herein.

Executive Versus Nonexecutive Working Memory Processes

With the advent of human neuroimaging capabilities, more recent studies have been devoted to validating the role of the dorsolateral prefrontal cortex in human spatial working memory (Fletcher & Henson, 2001). This work has yielded unexpected findings that suggest a dissociation between areas of the lateral prefrontal cortex that mediate information maintenance, which are more ventrally located, and those that facilitate the strategic self-monitoring that allows such information to be manipulated and subjected to executive control, which are more dorsally located (D'Esposito & Postle, 1999; Petrides, 1995; Smith & Jonides, 1995). Therefore, a distinction has been made at the neural level between spatial working memory processes that require online storage of information versus those that demand executive control over it, or what has been termed ''executive working memory'' (Perry et al., 2001).

Accordingly, spatial working memory processes can be conceptualized as lying along a continuum according to the extent to which these executive operations are required. At the highest level, there is *executive working memory*, a coherent constellation of processes that require cognitive multitasking, defined as the simultaneous recruitment of several control functions that are needed to allocate appropriately resources to direct behavior toward future goals. However, working memory need not require extensive levels of executive control. Working memory is demanded when one must hold single items in mind for brief periods before acting on them (i.e., delayed response; Goldman-Rakic, 1987), when one must remember the temporal order of multiple items presented in a sequence (i.e., span tasks; Milner, Corsi, & Leonard, 1991), and when one must self-organize behaviors without the benefit of external cues to achieve a goal (as demanded by self-ordered search tasks; Petrides & Milner, 1982). When putative working memory measures are deconstructed, they vary considerably in the extent to which they recruit not only recall-guided action but also executive control functions such as inhibition of extraneous information, trial-by-trial updating, strategy use, and stimulus reconfigurations that promote successful performance.

If executive versus nonexecutive aspects of working memory are represented differently at neural levels, perhaps they emerge differently in the course of prefrontal development. Although it has been demonstrated that recall requires greater processing capacity than recognition (Whiting & Smith, 1997), few studies have considered working memory development from the standpoint of executive processing demand. Recent work supports the notion that the basic modular structure of working memory (according to the Baddeley & Hitch, 1974, model) is present from age 6 years onward and that each tripartite component of the model increases its capacity until early adolescence (Gathercole, Pickering, Ambridge, & Wearing, 2004). Moreover, similar prefrontal regions appear to be activated by spatial working memory tasks (i.e., the spatial n-back; see Nelson et al., 2000) in prepubertal children as compared with young adults (Nelson et al., 2000; Thomas et al., 1999). However, age-related differences in working memory and executive control processes from childhood to young adulthood are unexplored.

Behavioral Development of Working Memory

Studies of very young children have been informative regarding when working memory processes first emerge. The ability to direct one's actions into the future emerges late in infancy, coincident with the capacity for independent locomotion (Diamond, 1990). Performance gradually improves during the preschool period and into middle childhood on simple set-shifting tasks that require children to keep multiple response dimensions in mind and shift responses among them (Zelazo, Frye, & Rapus, 1996; Zelazo & Resnick, 1991). During middle childhood, executive control over information that is held in memory appears to develop with increasing precision (Luciana & Nelson, 1998; Passler, Isaac, & Hynd, 1985; Welsh, Pennington, & Groisser, 1991). Welsh et al. (1991) studied 3- to 12-year-olds using a battery of executive function measures. On tasks including the Wisconsin Card Sort and 4-disk Tower of Hanoi tasks, an adult level of performance was reached between 10 years and adolescence depending on the task. Luciana and Nelson (2002) used the Cambridge Neuropsychological Testing Automated Battery (CANTAB; Sahakian & Owen, 1992) to study working memory functions in 4- to 12-year-old

children as compared with young adults. Using measures of spatial memory span, a spatial self-ordered search task, and a modified Tower of London (Shallice, 1982) task, they reported that 12-year olds were significantly inferior to young adults on tasks that required increasing levels of executive control. Specifically, although young children and preteens were able to perform all three tasks at low levels of demand, their performance remained inferior to adults when problem sets became more complex. Luciana and Nelson (1998) suggested that the demands exerted by more complex task items were due to those items' demands for cognitive multitasking, the ability to perform multiple simultaneous operations in working memory. They also suggested that future studies should focus on cohorts of adolescents, as compared with adults, to identify when adult levels of competence are reached under conditions that demand increasing levels of executive control.

There are few comprehensive studies that have assessed working memory and cognitive control processes in adolescents between the ages of 12 and 20 years. The frequently cited conclusion that these functions reach maturity during adolescence is largely derived from studies such as the Welsh et al. (1991) and Luciana and Nelson (2002) studies that report performance differences between prepubescent children and young adults. A recent study (Luna, Garver, Urban, Lazar, & Sweeney, 2004) used oculomotor working memory and cognitive control tasks to demonstrate continued development of processing speed, working memory, and inhibitory control from late childhood to young adulthood. Additional knowledge is derived from neuroimaging investigations that reveal several brain changes occurring during adolescence. These changes are important to describe because they suggest that improvements in executive control (presumed to be prefrontally mediated in adults) might co-occur. Accordingly, although the current study does not incorporate neuroimaging techniques to examine prefrontal development, a brief review of this literature is provided to orient the reader to changes in brain structure that may underlie behavioral changes that occur during adolescence.

Prefrontal Cortex Maturation During Adolescence

The prefrontal cortex undergoes continued structural and neurochemical refinement throughout childhood and into adolescence (Chugani, 1998; Spear, 2000). Although gross structure and overall brain volume are relatively stable by the age of 5 postnatal years (Giedd et al., 1996; Paus et al., 2001; Reiss, Abrams, Singer, Ross, & Denckla, 1996), neuroimaging studies in humans and histological studies of animals consistently indicate that adolescence is characterized by gray matter loss in numerous areas of the cortex and that such loss is consistent with synaptic pruning (Giedd et al., 1999; Pfefferbaum et al., 1994; Sowell, Thompson, Tessner, & Toga, 2001). Sowell and colleagues (Sowell et al., 2003; Sowell, Thompson, et al., 2001) have demonstrated that gray matter loss in the prefrontal cortex occurs at a more protracted rate than similar loss in the parietal cortex. At the same time, white matter development, particularly myelination, also continues throughout adolescence (Caviness, Kennedy, Richelme, Rademacher, & Filipek, 1996; Klingberg, Vaidya, Gabrieli, Moseley, & Hedehus, 1999; Paus et al., 2001; Pfefferbaum et al., 1994) and may be particularly pronounced in the frontal lobe (Reiss et al., 1996).

Evidence of Structure–Function Links?

Unfortunately, there have been few attempts to link directly these structural changes with functional developments. Sowell, Delis, Stiles, and Jernigan (2001) reported that frontal gray matter decline predicted delayed verbal memory performance and visuospatial memory in 35 children ages 7 to 16 years. In addition, recent functional neuroimaging studies suggest that changes in prefrontal cortical activity and metabolism might underlie working memory improvements. For instance, Klingberg, Forssberg, and Westerberg (2002) measured brain activity in fourteen 9- to 18-year-olds while they performed a spatial delayed recognition task under low versus high memory load conditions. They reported activation in superior and middle frontal regions, as well as regions of the parietal lobe, that increased with age and working memory capacity. Similarly, Kwon, Reiss, and Menon (2002) reported age-related increases in prefrontal cortical activation associated with visuospatial two-back performance in a small group of twenty-three 7- to 22-year-olds.

A Need for More Behavioral Work

Despite these intriguing reports, few studies have comprehensively examined the normative development of executive working memory processes in larger samples of individuals from early adolescence to young adulthood. This void is addressed by the current study.

The purpose of the current study was to examine neurocognitive development in healthy adolescents as compared with young adults, using spatial working memory tasks that have established brain correlates and that vary in their demands for executive control. It was hypothesized that adolescents would demonstrate a progressive ability to integrate multiple sources of information on tasks requiring memory, cross-temporal response selection, and strategic self-monitoring. Tasks that were nonverbal in their demands and that could be hierarchically ordered, as depicted in Table 1, according to their demands for executive control were used. This ordering scheme was rationally derived but informed by animal and neuroimaging studies.

At the low end of the hierarchy was a passive recognition memory task, implemented here for discriminant validity purposes, that required indi-

Table 1
Nonverbal Working Memory Tasks Hierarchically Organized by Multitasking Demand

Task	Paradigm	Processes required for success
Nonverbal face recognition memory	Delayed match to sample: Recognize single units of information (facial identities) after brief delays; categorical response; computerized	Attend to each stimulus when presented. Encode each stimulus according to facial identity. Remember each identity over a brief delay interval. Compare each face with a second one that is simultaneously presented. Select the face that is familiar.
Spatial delayed response	Delayed recall-guided response: Recall single units of spatial information after brief delays; execute a precise recall-guided response; computerized	Attend to each stimulus dot as it is presented. Encode the dot's location (vertical and horizontal coordinates) in extrapersonal space. Hold the location information in mind for delays of 0 ms, 500 ms, or 8 s. Inhibit shifting attention to internal or external distractors during the delay interval. When cued to respond, touch with precision the remembered location of the dot. Erase this information from short-term memory before the start of the next trial.
Spatial memory span: Forward	Sequential recall of multiple units of spatial information after brief delay; manual response; three-dimensional, noncomputerized display	Attend as the experimenter taps a sequence of locations. Encode and remember which locations were tapped. Encode and remember the order in which each location was tapped. Respond by reproducing the sequence in order.
Spatial memory span: Backward	Sequential recall plus manipulation of multiple units of spatial information; manual response; three-dimensional, noncomputerized display	Attend as the experimenter taps a sequence of locations. Encode and remember which locations were tapped. Encode and remember the order in which each location was tapped. Mentally reverse this order. Respond by reproducing the sequence in backward order.
Spatial self-ordered search	Recall plus manipulation of multiple units of information and strategic self-organization of that information; computerized	View an array of locations on screen. Touch locations one at a time to search for hidden tokens. If a token is not found, keep that location active as a possible response alternative. If a token is found, eliminate that location from possible response alternatives. Update this information as each token is found. Develop and execute an organized search strategy to minimize the task's mnemonic demands.

viduals to encode then recognize neutrally posed human faces after a brief delay interval. Next was a spatial delayed response task based on the seminal work of Goldman-Rakic and colleagues (Goldman-Rakic, 1987) and known to be associated with prefrontal activation in primates. Spatial memory span, using the Corsi Block Task (Milner, 1971), was implemented next because its backward response condition requires the maintenance plus manipulation of multiple spatial locations in memory. Finally, a computerized self-ordered search task was implemented to assess strategic self-monitoring in the context of visuospatial memory (Owen, Downes, Sahakian, Polkey, & Robbins, 1990; Owen, Doyon, Petrides, & Evans, 1996; Owen, Evans, & Petrides, 1996). Because executive control processes have been linked with fluid aspects of global intellectual function (IQ) in some studies (Gray, Chabris, & Braver, 2003), IQ was also measured.

One initial hypothesis was that adolescents would succeed at passively recognizing information before they succeed at recall-guided action. Indeed, it was expected that recognition memory would not show pronounced development during adolescence, consistent with findings from other studies (Luciana & Nelson, 1998; Nelson, 1995). Within the domain of recall, execution of an action based on the recall of a single unit of information was hypothesized to stabilize in development before the execution of actions based on the recall of multiple units. Recall-guided actions that occur in a fixed sequence would precede actions that must be recalled then reordered. Finally, recall-guided reordering of information would precede the ability to self-organize responses to multiple units of information in a more flexible manner.

It was expected that IQ would be unrelated to these developmental trends. Thus, consistent with our view of executive working memory as a dimensional hierarchical construct, it was expected that within the domain of nonverbal working memory, passive recognition memory would cease to show pronounced age-related change before adolescence, followed, in a staggered fashion, by the more active recall-guided tasks of simple delayed response, forward spatial memory span, backward spatial memory span, and strategic spatial self-organization.

Method

Participants

This study relied on a convenience sample. Participants were recruited from a database maintained by the University of Minnesota's Institute of Child Development (ICD). When their children were born, parents were identified through published birth announcements. Parents were then sent letters by ICD administrative staff and asked whether they would be interested in participating in ICD-sponsored research projects. The names, addresses, and telephone numbers of interested participants are maintained in an ongoing research database. Families with children between the ages of 9 and 17 years ($N = 106$) were identified, contacted by telephone, and invited to participate in a study of adolescent cognitive development. Inclusion criteria included being in the desired age range, being a native English speaker, having normal or corrected-to-normal vision and hearing, and having no current or past history of neurological illness, psychological illness, mental retardation, or learning difficulties. Approximately two thirds of the possible participants who were approached were eligible and interested in the study. The child and a parent made one visit to our laboratory where informed consent (parent) and assent (minor child under age 18) were obtained according to the requirements of the University of Minnesota's Institutional Review Board.

A separate group of 18- to 20-year-olds ($N = 27$) was recruited from the undergraduate student population at the University of Minnesota using the same inclusion and exclusion criteria as required of the minor participants. These participants completed the same task battery as did the 9- to 17-year-olds; the Wechsler Adult Intelligence Scale–3rd Revision (WAIS–III: Wechsler, 1997b) was used to derive IQ estimates.

The demographic characteristics of both samples are presented in Table 2. As indicated, younger participants ranged in age from 9 to 17 years ($M = 13.52$, $SD = 2.82$ years) and were roughly balanced by gender (47 males, 59 females). This sample was largely Caucasian (91%) and middle to upper middle class based on levels of parental education (sample $Mdn = 16$ years for both the mother and father) and total family income (sample $Mdn =$ US$80,000). General intelligence, estimated from the Vocabulary and Block Design subtasks of the age-appropriate version of the Wechsler Intelligence Scales (Wechsler, 1991, 1997b), indicates that the sample is above average in verbal and nonverbal abilities that contribute to overall IQ.

The 18- to 20-year-olds (M age $= 19.5 \pm 0.73$ years; 10 males, 17 females) were demographically comparable to the younger cohort. This subgroup was also mostly Caucasian (93%) and middle to upper middle class in socioeconomic status, based on reports of their parents' educational levels (sample

Table 2
Participant Characteristics

Group	Ages 9–10	Ages 11–12	Ages 13–15	Ages 16–17	Ages 18–20
n	25	26	30	25	27
Males:females	13:12	10:16	13:17	11:14	10:17
% Caucasian	92%	89%	97%	88%	93%
% right-handed[a]	96%	85%	90%	84%	93%
Mother's education (years)	15.9 (2.6)	16.6 (2.2)	16.8 (2.1)	16.3 (2.8)	15.3 (2.7)
Father's education (years)	16.6 (3.2)	15.6 (2.2)	16.3 (3.2)	16.8 (2.8)	15.9 (2.6)
Family income (US$)	117,875.0	83,269.2	93,413.8	91,041.7	111,958.3
Vocabulary scaled score[b]	12.9 (2.9)	12.6 (2.5)	11.6 (2.1)	14.1 (2.8)	13.5 (2.3)
Block Design scaled score	12.7(3.5)	13.0 (2.8)	12.5 (3.8)	12.9 (2.3)	12.6 (2.8)

[a]Handedness was determined using the Edinburgh Inventory (Oldfield, 1971).
[b]Vocabulary scaled scores were significantly different between groups, $F(4, 131) = 3.80$, $p < .01$, based on one-way analyses of variance (ANOVAs). This effect was due to higher scores in 16- to 17-year-olds versus 13- to 15-year-olds. Block Design scores did not vary between groups, $F(4, 131) = 0.14$, *ns*. No other demographic or sample characteristics significantly distinguished the groups.

Mdn = 16 years for both the mother and the father) and total family income (sample *Mdn* = US$95,000). General intelligence was in the high average range for both the Vocabulary and Block Design subtests of the WAIS–III.

Because this is a study in which data collection is expected to continue for a number of years, equal numbers of participants have not been studied in all age groups between ages 9 and 20. Accordingly, for this series of analyses, the sample was grouped to yield comparable sample sizes within each group as follows: 9- to 10-year-olds ($n = 25$), 11- to 12-year-olds ($n = 26$), 13- to 15-year-olds ($n = 30$), 16- to 17-year-olds ($n = 25$), and 18- to 20-year-olds ($n = 27$).

Procedure

All assessments were completed within a single experimental session. Experimenters were graduate students or volunteer research staff members, all of whom had at least 1 year of training in the fundamentals of clinical neuropsychology. Upon each participant's arrival, a medical and demographic history was obtained from the parent (if the participant was younger than age 18) or from the participant (if age 18 or older) through use of a structured interview questionnaire designed for use in this study. All participants completed a comprehensive cognitive testing battery that included the following measures.

Nonverbal face recognition memory. Nonverbal face recognition memory was tested through a delayed match to sample procedure. Participants viewed a series of faces derived from the MacBrain Stimulus Set (developed by Nim Tottenham at the University of Minnesota) that were presented one at a time on a computer screen. Two blocks of trials were presented. In each block, 12 faces were presented for 3 s each, followed by a 5-s pause. Then pairs of stimuli were presented. One face in the pair was previously seen and one was novel. The task was to select the face that was previously seen. The percentage of correct responses, out of a total of 24 stimuli, was the primary variable of interest. Because this task demanded recognition versus recall of information using a forced-choice matching procedure, it was hypothesized to exert a relatively low level of executive control and multitasking demand. The critical cognitive requirement is to attend to each stimulus as it is presented. Stimuli do not have to be actively maintained in memory because when a response is required, that response is facilitated by the presence of the target stimulus.

Spatial delayed response. In contrast, a spatial delayed response task was employed to measure the capacity for online maintenance and recall of information (Luciana & Collins, 1997). On each trial, the participant viewed a fixation point in the center of a computer monitor. During the viewing interval, a dot flashed in the periphery of the fixation point for 200 ms, after which both the dot and fixation point disappeared from view. The screen was masked for a delay interval of 500 ms or 8 s, randomly interspersed across trials. Following the delay interval, the participant indicated the exact location of the target stimulus using a touch pen input device (FTG Data Systems Inc.). For each trial, response accuracy (in millimeters) and response latency (in milliseconds) was recorded. A group of trials using the same stimulus locations but no delay interval was administered to assure that error rate was not attributable to basic perceptual or motor inefficiencies.

Spatial memory span. This test measured the recall of sequences (multiple items) of visually presented information (Wechsler, 1997a). Participants were presented with a board on which a number of three-dimensional blocks were affixed. An experimenter, seated across from the participant, tapped sequences of blocks, and the participant was asked to reproduce the sequence by touching the blocks in the same order (forward spatial span). The sequence started with two items (taps) and was incremented by one item following a correct response until the individual's maximum span was reached. Two sequences were presented at each level. If an individual succeeded on at least one of the sequences, the length of the sequence incremented by one item until the individual failed both trials at a given level. Similarly, a second trial block required the participant to recall the same set of sequences (although in a different order) but in backward order (backward spatial span). Forward spatial span is regarded as a measure of immediate spatial recall and attention because it requires that each sequence is encoded then recalled in the correct order. Backward spatial span is regarded as a measure of nonverbal working memory because not only must multiple units of information be recalled, but they must be reverse-ordered in memory before response initiation.

Spatial self-ordered search. This test, from the CANTAB battery (Cambridge Cognition, 2004; Sahakian & Owen, 1992), is an adaptation of the radial arm maze task that has been used for decades to measure spatial working memory in animals. As depicted in Figure 1, it measures the participant's ability to conduct an organized search of locations to obtain tokens hidden at each one. Search complexity varied in this study from searches of three locations to searches of eight locations. If a participant searches a location where he or she has previously found a token, a "forgetting error" is recorded. Additionally, a strategy score is tabulated (Owen, Morris, Sahakian, Polkey, & Robbins, 1996). The strategy score, which is based on responses to six- and eight-item searches, reflects the participant's tendency to search through available locations in an organized fashion. For example, an organized strategy might be to order conceptually the stimuli for any given trial from left to right or from top to bottom, and once a token is found, to resume searching from the same initial starting point, eliminating already-baited locations along the way.

This self-ordering tendency, which is not necessarily conscious on the part of the examinee but is typical in healthy adults (Owen, Morris, et al., 1996), is automatically recorded by the CANTAB program as an individual works through the task. Thus, this task yields error scores for each level of search complexity as well as a strategy score computed from responses to the six- and eight-location searches.

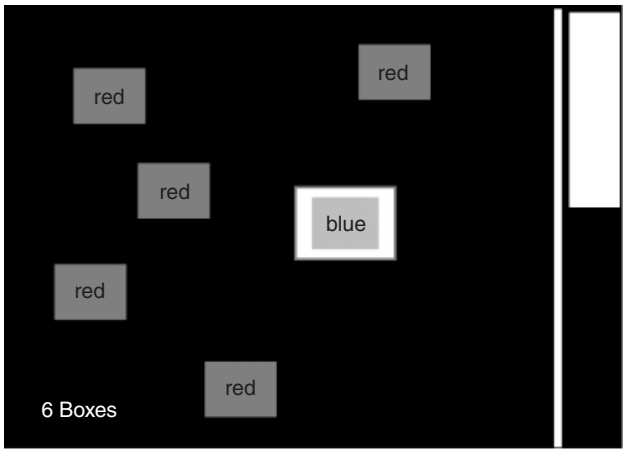

Figure 1. Spatial self-ordered search task. An example problem is presented. Color names are presented for clarity but are not part of the actual stimulus display. For each problem, colored squares are presented at different locations on the screen. The participant must touch a colored square to "open" it. When a blue token is found at that location, the participant must place it in the black column at the right of the screen. The colored square then "closes" (e.g., returns to its original [red] color). When the participant begins to search for other tokens, he or she must ignore locations where tokens have been found. If the participant returns to search a location where a square has been found, he or she has made a "forgetting error."

In contrast to the spatial memory span task, this task requires strategic self-monitoring and organization of behavior plus an ongoing demand for information updating as each trial progresses. Thus, this task is hypothesized to place a heavy demand on executive control.

The tasks that were implemented also vary in other important ways. In addition to the working memory and executive control functions that are required by each task, each measure varies in the type of stimulus presented and in the precision of the motor response demanded for successful performance. To present a more comprehensive view of each measure and to allow for alternative explanations of the findings, Table 1 lists processes that are required by each task, expanding on what was described earlier.

Task order was varied between participants. Three configurations were implemented. Task order did not significantly affect performance on any of the reported measures, nor did it interact with age group to affect performance on any measure. For these reasons, it is not considered further as a task variable. The task battery also included measures of fluency,

inhibitory control, personality function, and reward-related decision making. These tasks are the subjects of additional reports (Conklin, Luciana, Hooper, & Yarger, 2004; Hooper, Luciana, Conklin, & Yarger, 2004).

Results

Data were analyzed using the Statistical Package for the Social Sciences, Windows version 11.5 (SPSS Inc., Chicago, IL). Between-group comparisons were made by one-way, univariate, or multivariate repeated measures analyses of variance (ANOVA), depending on which dependent variable or set of variables was being analyzed. An alpha level of .05 is used to classify findings as significant; a level of .10 is used to describe trends. The nature of significant group effects was conservatively assessed post hoc using the Bonferroni procedure. When post hoc comparisons were made, each age group was compared with the four other age groups in the sample to ascertain the nature of the effect. Effect sizes (η_p^2) are also provided and range from values of 0 to 1.0, with a 1.0 indicating the strongest effect. Descriptive statistics, including means and standard deviations, for all cognitive task variables for each age group are presented in Table 3.

Age-Related Differences in Performance

Recognition memory. Performance accuracy (percentage of correct trials) on the facial recognition memory task revealed no significant main effect of age group, $F(4, 131) = 1.97$, *ns*; $\eta_p^2 = .06$. The mean level of performance was $\sim 78\%$ correct.

Spatial delayed response. The accuracy in locating and touching a spatial target when it remained on screen (no delay) was examined first, yielding a main effect of age group, $F(4, 131) = 9.46$, $p < .01$; $\eta_p^2 = .23$. The oldest group (18- to 20-year-olds) performed significantly better than 9- to 10-year-olds, 11- to 12-year-olds, and 13- to 15-year-olds (all $ps < .01$) but no differently from 16- to 17-year-olds. The 16- to 17-year-olds performed better than 9- to 10-year-olds and 11- to 12-year-olds, but only marginally better ($p < .07$) than 13- to 15-year-olds. There were no performance distinctions among 9- to 10-year-olds, 11- to 12-year-olds, and 13- to 15-year-olds. Reaction times did not vary by group, $F(4, 131) = 1.16$, *ns*; $\eta_p^2 = .04$. Thus, it appears that motor control processes are still developing during adolescence, independent of any mnemonic demand exerted by this task.

As indicated in Table 4, error scores on no-delay trials were negatively (and significantly) correlated with no-delay response times for 11- to 12-year-olds

Table 3
Cognitive Task Performance Across Age Groups

	Ages 9–10	Ages 11–12	Ages 13–15	Ages 16–17	Ages 18–20
Recognition memory					
Face recognition (% correct)	76.5 (16.4)	74.8 (16.0)	74.9 (16.3)	79.3 (11.7)	83.8 (6.3)
Spatial delayed response					
Error scores (millimeters)					
No delay	2.67 (0.77)	2.35 (0.96)	2.27 (1.12)	1.62 (0.64)	1.42 (0.76)
500-ms delay	8.14 (2.92)	6.21 (2.54)	6.10 (1.97)	5.21 (2.10)	5.38 (1.84)
8-s delay	12.84 (4.35)	9.31 (3.69)	8.30 (3.00)	7.75 (3.22)	7.79 (3.54)
Response latencies (milliseconds)					
No delay	1,722.14 (631.34)	1,504.53 (464.09)	1,557.72 (443.81)	1,622.83 (494.09)	1,789.51 (707.69)
500-ms delay	1,743.08 (515.29)	1,839.00 (455.33)	1,742.32 (367.02)	1,796.54 (412.83)	1,634.03 (395.77)
8-s delay	1,983.84 (429.98)	1,963.96 (523.41)	1,856.18 (392.94)	1,903.69 (438.14)	1,765.79 (460.04)
Memory span					
No. of spatial forward	5.08 (1.06)	5.77 (1.03)	6.57 (1.28)	6.48 (1.01)	6.93 (1.14)
No. of spatial backward	5.00 (0.83)	5.50 (1.36)	5.90 (1.00)	6.44 (1.08)	6.59 (1.25)
Spatial self-ordered search					
Forgetting errors					
3-location searches	0.12 (0.33)	0.04 (0.20)	0.07 (0.25)	0.08 (0.28)	0.04 (0.19)
4-location searches	1.20 (1.78)	0.68 (1.60)	0.47 (1.25)	0.38 (0.82)	0.26 (0.76)
6-location searches	13.20 (5.57)	10.20 (6.71)	4.30 (3.66)	2.25 (2.45)	3.81 (3.71)
8-location searches	27.36 (10.47)	23.88 (9.80)	15.63 (8.48)	9.71 (6.92)	9.30 (7.91)
Strategy score	36.16 (5.17)	35.64 (3.81)	33.10 (3.95)	28.67 (5.88)	29.89 (5.30)

Note. Values represent raw score means (± *SD*s).

Table 4
Spatial Delayed Response Task: Intercorrelations Among Task Variables

Variables	Ages 9–10	Ages 11–12	Ages 13–15	Ages 16–17	Ages 18–20
Err0/Err500	0.10	0.18	−0.14	−0.07	0.35†
Err0/Err8000	0.15	0.08	−0.04	−0.11	0.08
Err500/Err8000	0.45*	0.43*	0.32†	0.65**	0.50**
RT0/RT500	0.41*	0.37†	0.32†	0.27	0.71**
RT0/RT8000	0.45*	0.53**	0.58**	0.42*	0.63**
RT500/RT8000	0.64**	0.82**	0.88**	0.86**	0.90**
Err0/RT0	0.02	0.63**	−0.16	−0.57**	−0.27
Err500/RT500	−0.03	0.12	0.01	0.18	0.38*
Err8000/RT8000	−0.17	0.21	−0.19	0.17	0.28

Note. Values represent Pearson product–moment correlations; Err0 = error no delay; Err500 = error 500-ms delay; Err8000 = error 8,000-ms delay; RT0 = reaction time no delay; RT500 = reaction time 500-ms delay; RT8000 = reaction time 8,000-ms delay.
†$p < .10$. *$p < .05$. **$p < .01$.

($r = -0.63$, $p < .01$) and 16- to 17-year-olds ($r = -0.57$, $p < .01$), suggesting that a speed–accuracy trade-off might have operated to influence performance on the task's non-mnemonic trials for some groups.

Because differences in simply touching the stimulus dot under no-delay conditions could affect performance on memory trials and because an analysis of covariance would be inappropriate given the significant group differences in performance (Miller & Chapman, 2001), correlations among the task's no-delay and delay trials were examined within each age group to ascertain the amount of shared variance between mnemonic and non-mnemonic aspects of performance. These correlations, presented in Table 4, indicate that performance accuracy under no-delay conditions was not consistently associated with performance under delayed response conditions. In contrast, performance accuracies under 500-ms and 8-s delay conditions were strongly intercorrelated within most age groups. Thus, at the level of accuracy, the motor demands of the task appear to be distinct from its mnemonic demands.

Accordingly, error scores on 500-ms and 8-s delay trials were next evaluated between groups in a repeated measures ANOVA with two levels of delay interval. This analysis revealed a main effect of delay, $F(1, 127) = 112.32$, $p < .01$; $\eta_P^2 = .47$; a main effect of age group, $F(4, 127) = 10.71$, $p < .01$; $\eta_P^2 = .25$; and a significant Delay × Age Group interaction, $F(4, 127) = 2.56$, $p < .05$; $\eta_P^2 = .08$. Performance was less accurate on long (8-s) delay trials. In general, 9- to 10-year-olds were significantly less accurate than the other four age groups, who did not differ from each other. This pattern was similar for the omnibus analysis and for one-way ANOVAs in which the 500-ms and 8-second delay intervals were separately evaluated between groups. The nature of the Delay × Group interaction was difficult to ascertain. When evaluated separately, each age group exhibited a significant main effect of delay, and for all age groups, this was due to worse performance on 8-s delay trials. However, the effect size was largest for 9- to 10-year-olds ($\eta_P^2 = 0.59$) versus 11- to 12-year-olds ($\eta_P^2 = 0.45$), 13- to 15-year-olds ($\eta_P^2 = 0.36$), 16- to 17-year-olds ($\eta_P^2 = 0.53$), and 18- to 20-year-olds ($\eta_P^2 = 0.39$). These findings suggest that younger children may be most sensitive to the task's memory load manipulations (delay increases). However, in general, the ability to remember a single piece of information across brief delays, and to execute a spatially precise response based on this memory, appears to stabilize in development by age 11. Counterintuitively, the ability to execute an equally precise response under no-delay conditions continues to improve until age 16.

Developmental differences in mnemonic accuracy were not paralleled by changes in reaction times. Analyses of delay reaction times indicate a significant main effect of delay, $F(1, 127) = 36.31$, $p < .01$; $\eta_P^2 = 0.22$, but no significant main effects or interactions by age group. Responses were generally slower on longer delay trials. As indicted in Table 4, there was no evidence for a speed–accuracy trade-off for delayed response (500-ms and 8-s) trials.

Spatial memory span. Spatial memory span performance was evaluated by a repeated measures ANOVA with two levels of task (forward, backward) as a within-subjects factor. This analysis revealed significant main effects of task, $F(1, 127) = 7.24$, $p < .01$; $\eta_P^2 = .05$, and age group, $F(4, 127) = 13.25$, $p < .01$; $\eta_P^2 = .29$, but no significant Age Group × Task

interaction, $F(4, 127) = 1.23$, *ns*; $\eta_P^2 = .04$. Across age groups, performance was superior on forward versus backward span trials. Nine- to 10-year-olds performed worse than 13- to 15-year-olds, 16- to 17-year-olds, and 18- to 20-year-olds ($ps < .01$). Eleven- to 12-year-olds performed worse than 16- to 17-year-olds ($p < .05$) and 18- to 20-year-olds ($p < .01$). The oldest three age groups (13- to 15-year-olds, 16- to 17-year-olds, and 18- to 20-year-olds) did not differ from one another. Thus, nonverbal memory span continues to improve up to 13 to 15 years old; counter to prediction, this developmental course appears to be similar for forward and backward spatial memory span.

Spatial self-ordered search. The number of forgetting errors was separately tabulated for each level of search complexity (3-, 4-, 6-, and 8-location searches) and compared between age groups in a repeated measures ANOVA, yielding a main effect of search length, $F(3, 378) = 395.82$, $p < .01$; $\eta_P^2 = .77$; age group, $F(4, 126) = 28.61$, $p < .01$; $\eta_P^2 = .48$; and a Search Length × Age Group interaction, $F(12, 378) = 18.71$, $p < .01$; $\eta_P^2 = .37$. Forgetting errors generally increased as search length increased. Overall, 9- to 10-year-olds and 11- to 12-year-olds performed similarly, but both groups performed worse than 13- to 15-year-olds, 16- to 17-year-olds, and 18- to 20-year-olds ($ps < .01$). The oldest three age groups did not differ from one another.

The Search Length × Age Group interaction was investigated by a series of one-way ANOVAs, with errors at each level separately evaluated as dependent variables between age groups. For three- and four-location searches, the age groups did not differ in their performance. For six-location searches, a main effect of age group was observed, $F(4, 130) = 25.97$, $p < .01$; $\eta_P^2 = .45$. For this difficulty level, 9- to 10-year-olds and 11- to 12-year-olds performed comparably but were both worse than 13- to 15-year-olds, 16- to 17-year-olds, and 18- to 20-year-olds, who did not differ from one another. For the most complex eight-location searches, a main effect of age group was also observed, $F(4, 130) = 21.97$, $p < .01$; $\eta_P^2 = .41$. The same pattern was observed as for the six-location searches, although 13- to 15-year-olds performed marginally worse ($p = .08$) than 18- to 20-year-olds. Thus, consistent with what was found for spatial memory span, mnemonic functions recruited by this task continue to improve at least until ages 13 to 15 years and may continue to improve up to ages 18 to 20 years or beyond.

The task's strategy score was then evaluated. A high score reflects poor use of strategy. Strategy use was significantly different between age groups, $F(4, 130) = 11.93$, $p < .01$; $\eta_P^2 = .28$. Sixteen- to 17-year-olds obtained significantly better strategy scores than all younger age groups (all $ps < .01$) but did not differ from 18- to 20-year-olds. The younger age groups (9- to 10-year-olds, 11- to 12-year-olds, and 13- to 15-year-olds) did not differ from one another. Therefore, the ability to strategically self-organize behavior, an executive working memory function, is still developing through middle to late adolescence until roughly age 16.

Effects of Gender

Main effects of gender and Gender × Age Group interactions were examined post hoc for all task variables. Gender significantly affected face recognition memory performance, $F(1, 132) = 3.99$, $p < .05$, with females outperforming males. Otherwise, no significant main effects or interactions by gender were observed.

Relations Among Working Memory Variables and General Intelligence

One alternative explanation for the current pattern of findings is that the ability to perform demanding working memory processes is associated with general intelligence factors that are differentially expressed across age groups. Although estimates of general intelligence did not vary systematically or strongly between age groups in this study (see Table 2), it is possible that intelligence is more associated with working memory tasks that demand high versus low levels of executive control. To address this possibility, correlations between task performance variables and raw scores on subtests from the Wechsler Intelligence Scales were computed for the sample as a whole, partialing out the effect of age. Values are presented in Table 5. Based on these data, it does not appear that the ability to use executive control in increasingly demanding contexts is a function of general intelligence.

Discussion

These findings suggest that executive aspects of spatial working memory are developing well into adolescence in a dimensional hierarchical manner independent of general intellect. When recall must be used to strategically organize behavior (self-ordered search), development is evident up to the age of 16 years and remains stable through 18 to 20 years. A task that required relatively simplified spatial working memory demands, the spatial delayed response task, did not index developmental changes after ages 11 to 12. Recognition memory for non-

Table 5
Partial Correlations Among Working Memory Variables and Indexes of General Intelligence

	Vocabulary raw score	Block Design raw score
Face recognition	.03	.02
Delayed response no delay error	.14	.03
Delayed response 500-ms error	.21**	.04
Delayed response 8-s error	.17**	−.05
Delayed response no delay reaction time	−.00	.06
Delayed response 500-ms reaction time	−.00	−.09
Delayed response 8-s reaction time	−.05	−.09
Spatial span forward	−.19**	−.09
Spatial span backward	.03	.10
Self-ordered search errors: 3-location sequence	.01	.06
Self-ordered search errors: 4-location sequence	.01	−.06
Self-ordered search errors: 6-location sequence	−.03	−.08
Self-ordered search errors: 8-location sequence	.09	−.08
Self-ordered search strategy score	−.08	−.12

Note. Values represent partial correlations controlling for the effect of chronological age. Vocabulary and block design raw scores were computed from performance on the age-appropriate version of the Wechsler Intelligence Scale. *$p < .05$.

verbal (face) stimuli appears to mature early in that performance did not significantly change during this broad developmental period. This pattern suggests that this ability stabilizes before age 9, consistent with what has been reported for other forms of nonverbal recognition memory (Luciana & Nelson, 1998, 2002). Thus, when working memory is deconstructed into its relevant task demands, an orderly developmental progression in skill appears evident, and this progression is paralleled by findings from the neurodevelopment literature. These findings are not only important from a descriptive standpoint, but they have two major implications, one related to the maturation of distinct prefrontal regions and the other related to the organization of the prefrontal cortex by level of processing.

Prefrontal Regions Associated With Developmental Improvements in Task Performance

Nonverbal delayed match to sample. Recognition memory has been traditionally thought to be reliant on temporal lobe memory systems regardless of the type of information that must be processed (Nelson, 1995). However, recent studies indicate that, depending on the paradigm used, recognition memory might also recruit the prefrontal cortex. Petrides and colleagues (Petrides, 1995) recorded patterns of brain activation using positron emission tomography (PET) while adult humans performed a visual delayed match-to-sample recognition memory task. It was found that the ventrolateral frontal cortex was activated when participants were required to make active judgments about the familiarity of recently presented visual stimuli. The observed activation was enhanced relative to what was observed when either novel or familiar stimuli were presented and encoded in the absence of mnemonic judgments. Thus, the maintenance component of delayed match to sample tasks might depend partly on the ventrolateral prefrontal cortex. However, the working memory and executive demands of the face recognition task used in this study are low. Despite the fact that a delay interval is introduced, specific responses need not be held in mind over that delay. Instead, the major task is to encode correctly stimuli as they are presented because a range of possible alternatives, including the correct one, can be reviewed before retrieval and response selection.

Spatial delayed response. The spatial delayed response task appears to depend more distinctly on the dorsolateral prefrontal cortex in nonhuman primates (Goldman-Rakic, 1987). A network of structures including the inferior parietal lobe, the dorsomedial thalamus, the caudate nucleus, the superior colliculus, and the hippocampus promotes successful task performance (Selemon & Goldman-Rakic, 1988). In particular, the inferior parietal lobe has the role of mapping the coordinates of spatially relevant targets in extrapersonal space, and the dorsolateral prefrontal cortex not only maintains these coordinates over time but relays this information to motor output regions so that a response can be executed at the appropriate time. Unlike recognition memory tasks, this task requires accurate encoding of the target's location in space, formulating a response based on this location, holding this recall-guided response information in mind over a delay interval, then carefully executing the response. Performance accuracy is measured with precision at the pixel level. However, despite the animal literature, it is not possible to know whether this visuomanual task activates the prefrontal cortex in humans, and if so, which subregion is critical for performance.

This uncertainty is due to technical limitations imposed by neuroimaging. The task cannot be administered without a substantial modification that biases it in favor of a demand for recognition versus

recall. One commonly implemented paradigm is for human participants to view a spatial target, after which a delay interval is imposed. Then a second screen appears, consisting of the previously seen target as well as a number of distractors. One of the items on the second screen is highlighted, and the participant must indicate with a yes–no response whether the highlighted item is the same as what he or she previously saw (Belger et al., 1998; Jonides et al., 1993; Smith & Jonides, 1995). Thus, the mnemonic–motor integration that is demanded during the delay interval when the task is administered under visuomanual response conditions is absent. Whether spatial maintenance measured in this manner activates the dorsolateral prefrontal cortex is currently debated. Although the dorsolateral prefrontal cortex is activated in some studies (Belger et al., 1998), others have reported activations of ventral prefrontal regions (Fletcher & Henson, 2001). Some studies do not find prefrontal activation but instead report that the task relies on a network of structures in the posterior right hemisphere, including the inferior parietal lobe.

Despite the motoric demands that distinguish it from most similar tasks used in neuroimaging contexts, our spatial delayed response task is largely a maintenance-only (D'Esposito & Postle, 1999) task. That is, a single piece of information must be held in mind over a delay interval. As the delay increases, there is an increasing endogenous demand on inhibitory control mechanisms to resist distractions. The task should, as the animal literature suggests, recruit executive processing that is prefrontally mediated, particularly as delay intervals become longer. However, it appears possible that the task is more strongly associated with ventrolateral (vs. dorsolateral) prefrontal function in humans as opposed to animals.

The protracted development of non-mnemonic visuomotor skills, as assessed by the no-delay trials of the task, was unexpected. On the one hand, it may reflect the maturation of subcortical networks that mediate fine motor abilities during adolescence. More relevant to our interest in prefrontal function, an alternative (albeit speculative) suggestion is that it reflects the recruitment of inhibitory control mechanisms needed to executive a precise motor response with minimal error. Others have reported the continued development of inhibitory control functions in adolescence (Bunge, Dudokovic, Thomason, Vaidya, & Gabrieli, 2002; Luna et al., 2004; Luna et al., 2001). This explanation is not entirely satisfactory because inhibitory control over motor responding should also affect performance on delayed response trials.

Other researchers have used similar tasks to measure spatial working memory in developmental samples. Recently, Luna and colleagues (Luna et al., 2004) reported that oculomotor delayed response performance matures around age 19, as evidenced by participants' accuracies in making memory-guided saccades to previously targeted spatial locations. That study incorporated delay intervals of 1, 2, 4, and 8 s, and no delay by age interactions were observed. Zald and Iacono (1998) used a variant of the visuomanual delayed response task to study an epidemiological sample of male twins. These individuals completed a block of no-delay trials as well as trials with delays of 500 ms, 8 s, and 14 s. As compared to 14-year-olds, 20-year-olds exhibited more accurate performance on all delayed response trials. The two groups did not differ in their performance on no-delay trials. Notably, the 14-year-olds in the Zald and Iacono sample performed comparably to the 9- to 10-year-olds in the current study on 500-ms and 8-s trials, whereas their sample of 20-year-olds performed worse than all groups in the current sample. In addition, both the 14- and 20-year-olds in their study, some of whom were from high-risk samples, performed worse on no-delay trials than individuals in all five groups tested in the current study. Thus, sampling differences or other idiosyncratic sources of variance may account for the discrepancies across studies.

Spatial memory span. PET has been used to demonstrate that forward spatial memory span activates a network of right hemisphere structures, including the ventrolateral prefrontal cortex (Owen, Evans, et al., 1996). In contrast, tasks that require backward memory span, whether the stimuli are verbal or spatial, appear to activate areas of the ventrolateral but also dorsolateral prefrontal cortex (Owen, 1997). Given these neural differences, it was unexpected to find similar age-related influences on forward and backward span in this study. It may be that finer task-related distinctions would have been observed had we had a large enough sample to attempt to distinguish performance among 13-, 14-, and 15-year-olds.

Spatial self-ordered search. The most demanding task described here is the spatial self-ordered search task, which requires response selection, memory, continuous updating of information, and a high degree of executive control. It also demands self-monitoring and formulation of a strategy, a task variable that has been shown to be specifically impaired in neurological patients with frontal, but not temporal, lobe lesions (Owen, Morris, et al., 1996). The development of these skills, when demanded simultane-

ously, shows a protracted and extended course up to age 16. Our sample of 16- to 17-year-olds did not differ from slightly older (18- 20-year-old) adults, consistent with findings from a recent study where 15- to 19-year-olds were reported to perform similarly to 20- to 29-year-olds on this task (DeLuca et al., 2003).

Because this type of task strongly recruits activity in the mid-dorsolateral prefrontal cortex based on recent neuroimaging (i.e., PET; Lee, Owen, Rogers, Sahakian & Robbins, 2000; Owen, Doyon, et al., 1996; Owen, Evans, et al., 1996) and lesion (Petrides, 2000) studies, executive control is thought to be primarily mediated by this region. This conclusion holds even when other types of executive control and self-monitoring tasks that cut across stimulus domains are implemented (Owen, 1997; Petrides, 2000; Petrides, Alivisatos, & Frey, 2000). Thus, the protracted developmental course observed here for strategy use (but not recall or recognition under delayed response conditions) may indicate that different prefrontal regions reach functional maturity at different rates, with the ventrolateral regions maturing before the dorsolateral region, which is responsible for the highest level of executive control over information processing.

If this finding can be replicated, it has clinical implications for conditions such as schizophrenia, which typically presents during adolescence (American Psychiatric Association, 1994) and has been associated with deviant patterns of organization and function of the dorsolateral prefrontal cortex (Callicott et al., 2003; Selemon & Rajkowska, 2003). Findings such as those reported in the current study may be helpful in designing neuroimaging or electrophysiological investigations that incorporate selective behavioral tasks to index activity within and across the multiple nodes that form prefrontally guided networks. This goal is not without methodological challenges.

It is clear that many tasks employed in experimental neuropsychology recruit activity in isolated sections of information-processing networks. These tasks permit main effects models to be examined, which is highly useful. It can be ascertained when it is that recognition memory develops independent of single-item recall versus multiple-item recall. But as the findings of the current study suggest, the developmental models derived from these tasks may limit the extent to which subtle changes in multitasking skills that underlie executive control are evident in emerging adulthood. Therefore, a major empirical task for researchers interested in executive function and working memory development is to devise a way to study parametrically cognitive integration (Keating, 2003) or multitasking (Luciana & Nelson, 1998). One assessment strategy that may prove useful would be to develop dual- or multi-task paradigms (e.g., D'Esposito et al., 1995) that are sensitive to developmental change and that can also be deconstructed into their component subdemands. Indeed, it must be acknowledged that interpretations from the current study would be more straightforward had we used a single task that built on itself to require increasing demands for executive control using similar stimuli and maximally similar response demands at each level of executive demand.

Other Limitations of the Current Study

As mentioned previously, data collection is ongoing, and it is our goal to report eventually on equal numbers of participants in each year of development from ages 9 to 25 years. A limitation of our current sample, which could be viewed as either a strength or a weakness, is that it is relatively advantaged socioeconomically as well as intellectually and may not be representative of the population as a whole. However, assuming that samples of this type represent optimal development under conditions where demographic variables are held relatively constant, age differences in performance across tasks suggest that executive control appears to increase dramatically during adolescence even under optimal circumstances.

Another potential limitation concerns the extent to which general conclusions can be drawn from single tasks or apparent similarities that seem to cut across tasks that are disparate in their stimulus and response configurations. For example, instead of using a recognition memory task that required the processing of faces, it might have been better for us to adapt the spatial delayed response task to include a recognition memory condition. Similarly, it is unclear whether the trends observed here for spatial processes will generalize to other (e.g., verbal) aspects of working memory. When the other end of the lifespan is considered, functional cognitive declines in healthy older adults are more pronounced for visuospatial tasks than for verbal tasks regardless of the type of task implemented (Jenkins, Myerson, Joerding, & Hale, 2000), perhaps suggesting that the emerging development of functions may differ across modalities as well. Finally, this report focuses on a cross-sectional analysis of working memory development, limiting the extent to which we are able to comment on developmental trajectories across time.

Implications for Prefrontal Organization According to Processing Demand

Early neurobiologically based models of working memory (Goldman-Rakic, 1988; Wilson, O'Scalaidhe, & Goldman-Rakic, 1993) proposed that the prefrontal cortex is organized to facilitate working memory according to stimulus modality (e.g., spatial, verbal). Other more recent views suggest that the prefrontal cortex is organized according to level of processing (e.g., areas that promote maintenance functions vs. manipulation; Owen, Evans, et al., 1996; Petrides, 1995, 2000). The data presented here support behavioral development of working memory functions within the spatial domain according to level of processing demand. If the prefrontal cortex is unified to promote working memory processes regardless of stimulus domain, similar developmental trajectories should be evident for verbal and spatial tasks that have equivalent processing demands. However, if level of processing is distinctly modulated by different prefrontal regions, tasks may dissociate across stimulus modalities according to their demands for executive control. These hypotheses remain to be tested in combined behavioral and neuroimaging protocols.

Prospective studies of this type, which incorporate working memory tasks that vary in their demands for executive control, will be highly informative regarding which prefrontal regions are maximally activated as processing demands increase and how activity in these regions matures within individuals across time.

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