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Developmental relations between working memory and inhibitory control

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Abstract

Working memory (WM) and inhibitory control (IC) are general-purpose resources that guide cognition and behavior. In this study, the developmental relations between WM and IC were investigated in 96 typically developing children aged 6 to 17 years in an experimental task paradigm using an efficiency metric that combined speed and accuracy performance. The ability to activate and process information in WM showed protracted age-related growth. Performance involving WM and IC together was empirically distinguishable from that involving WM alone. The results indicate that developmental improvements in WM are attributable to increased processing efficiency in activation, suppression, and strategic resource deployment, and that WM and IC are best studied in novel, complex situations that elicit competition among those resources (*JINS*, 2007, *13*, 59–67.)

Keywords: Memory, Inhibition, Child development, Prefrontal cortex, Speed-accuracy tradeoff measurement, Cognitive science

INTRODUCTION

Many theories of cognition account for individual and age-related differences in terms of general-purpose functional resources (Richardson, 1996). Working memory (WM) and inhibitory control (IC) are two such resources that can be applied to a number of domain-specific representational systems. WM is a capacity-limited activation resource for processing information (Awh et al., 1995; Roberts et al., 1994). IC, in its intentional form, is a suppression resource that prevents the entry or maintenance of irrelevant information in WM. The protracted growth of WM in childhood has been well documented (e.g., Bayliss et al., 2003; Cowan, 1997), although it is unclear exactly which underlying components of WM are responsible for the developmental change. This study addresses the nature of developmental improvement in WM and the relation between activation and suppression resources during childhood and adolescence.

At any age, WM is optimized under conditions that activate only task-relevant information and cognitive functions (Pascual-Leone, 1984; 1987; 1995). Tasks given in this context are operationalized in terms of *span*, the number of activated units that can be held within WM at one time (e.g., Cowan, 2001; Oberauer & Kliegl, 2001). The prototypical example is the backward digit span task, in which single digits are presented in strings of increasing length that must be repeated back in reverse order. WM span tasks involve a trade-off between demands for storing *versus* operating on presented information (Johnson et al., 2003; Pascual-Leone, 2001). Conlin et al. (2005) showed, for example, that children's span performance is compromised when processing activities, such as carrying out concurrent mental arithmetic operations, divert WM resources from storage. In addition, specific, age-related storage and processing abilities associated with number and rate may make independent contributions to WM performance (Bayliss et al., 2005).

WM span can also be altered by strategic processes that functionally reduce the WM capacity consumed by items and operations. For instance, children who are chess experts have superior memory for meaningful chess positions compared to adult novices, even though the adults outperform

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the same children on other memory tasks (Schneider et al., 1993). Domain-specific expertise enables these children to process chess positions as meaningful patterns, and superior memory in this context depicts greater efficiency in the use of WM capacity rather than a larger WM span. Thus, strategic processes allow more information to be stored, essentially increasing capacity. This implies that novel tasks designed to prevent intratask learning should be used for the most reliable measurements of WM capacity.

The application of WM in complex situations might involve IC to keep irrelevant information from consuming WM's limited capacity (Dempster, 1993; Engle et al., 1995; Harnishfeger & Bjorklund, 1993). In some formulations, WM growth during childhood is at least partly attributable to increases in IC resources (Bjorklund & Harnishfeger, 1990; Dempster, 1993; Wilson et al., 2003). Correspondingly, WM declines associated with aging have been attributed to decreased IC efficiency; specifically, weakened IC processes co-opt WM resources, which reduces the availability of WM for task-relevant information and operations (Hasher & Zacks, 1988; Hasher et al., 1999).

Resistance to various types of interference changes during child development (Dempster, 1993; Tipper et al., 1989). Infants' initial susceptibility to motoric interference declines rapidly during the first five years (Diamond, 1990; Espy et al., 1999). Sensitivity to perceptual forms of interference declines more gradually in childhood and adolescence (Band et al., 2000; Dempster, 1993). For example, the size of the Simon effect (i.e., poorer performance when there is response conflict created by the propensity to respond motorically on the same side as a perceptual cue; Simon & Berbaum, 1990; Umilta, 1994) diminishes steadily throughout childhood and adolescence (Davidson et al., 2006). The Stroop effect, which involves cognitive control over stimulus-stimulus conflict once reading has become an automatic process (Liu et al., 2004), also decreases over a protracted developmental period (Leon-Carrion et al., 2004).

Brain imaging has helped to clarify the relation between WM and IC described in behavioral research. In adults, a subset of the neural circuitry supporting WM is activated for IC processes (Bunge et al., 2001; Konishi et al., 1999; 2002), and increased demand for top-down control over the deployment of WM and IC resources (e.g., in the Simon and Stroop tasks) further enhances this neural activation (Gazzaley et al., 2005; Liu et al., 2004; Mecklinger et al., 2003). Recent *in vivo* studies have shown that activation in this common neural area fluctuates during cognitive performance in concert with the demands of particular phases of a given task (e.g., encoding, delay, and response; Constantinidis et al., 2002; Knight et al., 1999; Manoach et al., 2001). Thus, both behavioral and brain research indicate that IC is part of the WM system when applied in complex situations that involve multiple or competing cognitive resources.

Although neuroimaging and behavioral studies reveal that WM and IC overlap in the mature brain, the way in which this interrelationship develops over the course of childhood and adolescence is unknown. We examined the performance of 96 children aged 6 through 17 years in three tasks that varied in WM and IC processing requirements to address two specific questions:

1. What is the nature of developmental change in WM and IC, respectively?
2. What is the nature of the relation between WM and IC during development?

METHOD

Participants

After approval was obtained from York University's Human Participants Review Committee and The Hospital for Sick Children's Research Ethics Board, 96 typically developing children and adolescents (4 boys and 4 girls at each age from 6 to 17 years old) were recruited from local schools in southern Ontario, Canada. All participants spoke English as their primary language and obtained a Full-Scale IQ score above 70 ($M = 104.80$, $SD = 10.16$, Range = 79–128) on the Wechsler Abbreviated Scale of Intelligence two-subtest form (Wechsler, 1999). Participants were excluded if they had been identified for special education services, had a disorder known to be associated with cerebral dysfunction and/or cognitive deficit (e.g., epilepsy, diagnosed learning disability, etc.), or had a history of head injury.

Materials and Procedure

Participants completed three experimental tasks that permitted simultaneous and separate measurements of WM and IC in a common paradigm. All tasks were administered using a Macintosh 1400cs laptop computer positioned on a table in front of the participant. Responses were made using two keys identified by white stickers located equidistant from the center of the keyboard ("d" and "l"). Internal task conditions were counterbalanced across participants to control for response bias to one side (i.e., half of the time a stimulus was assigned to the left button and *vice versa*).

Activation

The Activation task was adapted from part of the Directional Stroop Task (Davidson et al., 2006; Diamond et al., 1998). In this task, associations are established between visual stimuli (abstract shapes) presented individually in the middle of the computer screen and manual responses (press on left side/right side). Task performance provides a baseline measure of efficiency in recalling and actively maintaining newly learned information in WM. We replaced Diamond et al.'s shapes with different abstract shapes to reduce the likelihood of verbal encoding, and set both the stimulus exposure time and the interstimulus interval at 750 ms. Participants were told that shapes would appear in the middle of the screen one at a time, and that they would need to remember the button that goes with each shape. Three shapes were assigned to each response side, counterbalanced across participants. After a training set in which the stimulus-response associations were taught and practiced, there were three practice runs of the six shapes, two in the same order and one in a different order. The test set consisted of 22 trials using the six shapes in random order. The first two trials were not analyzed.

Working memory

In this task, which we created, the same stimuli as used in the Activation task were presented individually in the middle of the screen in strings ranging from two to four shapes. Immediately following the last shape in the string, a two-alternative, forced-choice probe (see Fig. 1, top panel) appeared, and participants chose the shape that was presented earliest in the sequence. The stimulus exposure time and interstimulus interval were set at 1000 ms for presentation and 2000 ms for the recency judgment component. The particular shapes used and the order in which they were presented and tested were randomized once and then fixed across individuals. Participants completed three practice runs with two shapes and then three runs with three shapes, followed by four unprompted practice runs (two with two shapes and two with three shapes). In the test set, five trials were administered in blocks corresponding to the three string lengths for a total of 15 trials. The first trial in each block was not included in the data analysis.

We used a progressively ordered design to model the prototypical span task, which fosters intratask learning, in a context involving WM for item and temporal source memory, the latter of which is particularly demanding of prefrontal cortical regions (Cabeza et al., 1997; Marshuetz, 2005; Marshuetz et al., 2000). The first set of items (Block 1) was expected to be performed easily by all participants using immediate recognition of the two shapes to make the recency judgment. By contrast, the second string length (Block 2; three shapes) requires item and order recognition to make the recency judgment, thus providing a measure of WM with sufficient cognitive demand to challenge its limited capacity during childhood. The last string length (Block 3; four shapes) provides a measure of WM moderated by intratask learning, in that strategic processes could counteract the expected rise in WM demand imposed by increasing the string length by an additional item in older children with more WM capacity. We opted not to use longer string lengths because they would be confounded not only by intratask learning but also by the effects of item position (e.g., magnitude coding; Marshuetz, 2005).

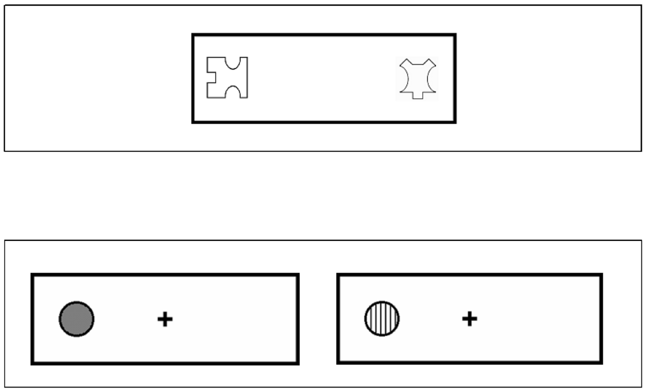

Fig. 1. Sample stimuli. The top panel shows a stimulus with two of the shapes used in the Activation and WM tasks as they are presented for the recency judgment portion of the latter task. The bottom panel shows two stimuli used in the WM+IC task. The cross appears in the middle of the screen just prior to the dot as a prompt to attend to the trial.

Working memory plus inhibitory control

This task, which was taken from part of the Directional Stroop Task (Davidson et al., 2006; Diamond et al., 1998), requires responses to individually presented dots (see Fig. 1, bottom panel) using either ipsilateral or contralateral manual responses according to a response rule. The task has three parts, each with a test set of 22 randomized trials. In the first part, an association between one dot type (e.g., solid dot) and an ipsilateral manual response is established. Next, an association between the other dot type (e.g., striped dot) and a contralateral manual response is established. This portion of the task measures IC over a prepotent motor response (Inhibition). Finally, a mixed set of stimuli (half ipsilateral, half contralateral) is presented. The mixed set provides a measure of WM+IC because performance involves activation of the two possible responses associated with each dot type (which have been well-learned and consolidated in memory by this point in the task), response selection based on the actual dot type presented in the trial, and response inhibition of the unselected dot-response association while executing the selected motor response.

Both the stimulus exposure time and the interstimulus interval were set at 750 ms. The first two trials of each test set were not analyzed. Assignment of dot type to ipsilateral or contralateral response was counterbalanced across individuals.

Dependent measure

Because latency and accuracy measures contain inversely related information about task difficulty, analyzing them separately does not allow for the evaluation of overall efficiency in performance across tasks and between groups, in which these components might contribute differently to performance. As seen in adults (Kane & Engle, 2003), typically developing children are assumed to follow a performance efficiency rule in which they speed up on easy tasks but slow down on difficult tasks that are more demanding of their cognitive resources (Diamond & Kirkham, 2005; Leon-Carrion et al., 2004). In this view, optimal performance efficiency is calibrated throughout a task by slowing down just enough to ensure response accuracy, and a per-

Table 1. Task-Specific calculations of the *n* coefficient used in the Derivation of Efficiency Scores

Task	Minimum RT (ms)	Maximum Proportion correct	*n* Coefficient
Activation	424	100	2.120
WM	324	100	1.620
WM+IC	665	95	3.500

formance measure that combines average latency and accuracy can represent overall task efficiency. To this end, we formulated an efficiency score that merges latency and accuracy data and provides a generic metric of performance efficiency in tasks involving a trade-off between speed and precision:

$$\text{Efficiency} = [\text{RT}\,(\text{RT} - 100 * n)/(\text{RT} + 100 * n)]/$$
$$[\text{RT}\,(\text{RT} - \text{PC} * n)/(\text{RT} + \text{PC} * n)],$$

where *RT* is the individual's mean latency, *PC* is the individual's mean proportion correct, and *n* is the sample's minimum latency divided by twice the sample's maximum proportion correct (see Table 1 for task-specific calculations of the *n* coefficient). The value of *n* was derived to correct for scale unit differences between latency and accuracy, as well as the differences between tasks associated with task-specific strategic processes that influence the ranges of latency and accuracy units.

The distribution of this efficiency score is bounded at its upper end by 1 (i.e., perfect performance) and at its lower end by the value of the efficiency formula when proportion correct is 0 (i.e., $[\text{RT} - 100 * n]/[\text{RT} + 100 * n]$). As such, an individual's efficiency score reflects performance in terms of both speed and precision, with higher scores representing more efficient performance regardless of the individual's RT characteristics (e.g., an overall slower, reflective response style). The efficiency score can be interpreted relative to the upper bound as a distance measure from optimal performance, or as a metric representing the relative contribution of accuracy to overall performance efficiency. Both comparisons are conceptually meaningful for the appraisal of developmental differences in efficiency of responding within and between tasks. It is our hope that others will use this efficiency formula in future studies involving cognitive tasks with inversely related speed and accuracy measurements.

Task order

All participants completed the tasks in the following order: WM+IC (all three parts in sequence), Activation, WM. A given task was discontinued if mastery was not achieved within three repetitions of the full practice set. Participants were told to go as fast as possible for all test sets.

RESULTS

Developmental Improvement in Cognitive Processes

We used ANOVA and MANOVA models to evaluate differences in performance efficiency among four age groups ($N = 24$ in each group): 6- to 8-year-olds (6–8), 9- to 11-year-olds (9–11), 12- to 14-year-olds (12–14), and 15- to 17-year-olds (15–17). After three unsuccessful attempts at the practice set, the WM task was discontinued with one 6-year-old participant, and the WM+IC task was discontinued with another 6-year-old participant. For group effects with an alpha below .05, we performed Tukey pairwise comparisons between noncontiguous age groups using a Bonferroni familywise probability level of .02 to identify significant developmental improvements in performance efficiency. Table 2 shows descriptive statistics of the efficiency scores for each task. There were no significant differences between girls and boys in efficiency scores.

Activation

An ANOVA performed on efficiency scores revealed a main effect of age group, $F(3, 91) = 5.44$, $p = .002$, partial $\eta^2 = .152$. As shown in Figure 2 and confirmed by post hoc comparisons, the youngest age group was less efficient than the oldest age group.

Working Memory

A 3 (Block) × 4 (Age Group) repeated-measures MANOVA was performed on efficiency scores in the WM task. The

Table 2. Mean (SE of the Mean) of Efficiency Scores across Tasks by Age Group

		Tasks			
Age Group	Activation	WM (Block 1)	WM (Block 2)	WM (Block 3)	WM+IC
6–8	.896 (.016)	.955 (.023)	.801 (.020)	.841 (.015)	.858 (.013)
9–11	.944 (.011)	.918 (.025)	.851 (.021)	.874 (.019)	.904 (.015)
12–14	.935 (.012)	.990 (.010)	.869 (.028)	.838 (.025)	.922 (.012)
15–17	.964 (.009)	.957 (.027)	.921 (.019)	.909 (.023)	.943 (.010)

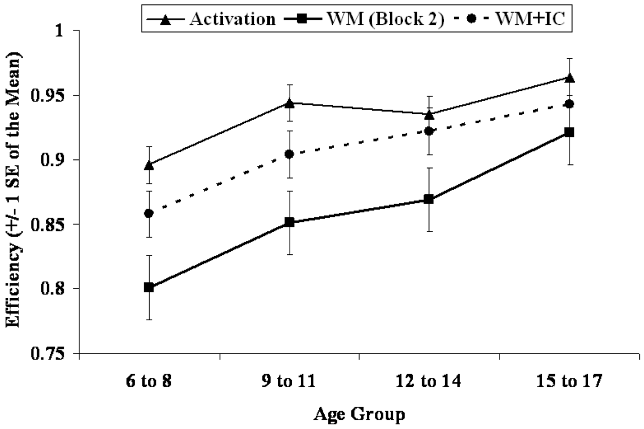

Fig. 2. Efficiency in Activation, WM (Block 2), and WM+IC by age group.

interaction was significant, $\Lambda = .85$, $F(6,180) = 2.60$, $p = .019$, partial $\eta^2 = .080$. Follow-up univariate analyses revealed that efficiency was significantly higher in Block 1 compared to Block 2 for all but the oldest group, in which efficiency was equally high across the three blocks. In addition, efficiency was superior in Block 1 relative to Block 3 in the 6–8 and 12–14 groups. As predicted, in Block 1 there were no age group differences. In Block 2, which required the application of WM for item and order recognition, the youngest group was less efficient than the 12–14 and 15–17 groups, and the 9–11 group was less efficient than the oldest group (see Fig. 2). In Block 3, efficiency was superior in the oldest group relative to the 6–8 and 12–14 groups, indicating a general developmental improvement in intratask learning efficiency.

Working memory plus inhibitory control

An ANOVA revealed a significant effect of age group in efficiency scores, $F(3,92) = 8.32$, $p < .001$, partial $\eta^2 = .213$. This was because of lower efficiency scores in the youngest group compared to the 12–14 and 15–17 groups (see Figure 2).

Developmental Relations Among Cognitive Processes

We computed Pearson coefficients within each age group to examine the intercorrelations of efficiency scores during different periods of development (see Table 3). In addition to the three main outcome measures, Activation, WM (Block 2), and WM+IC (i.e., the third part of the task involving a mixed set of stimuli), we also analyzed the inhibition measure taken from the second part of the WM+IC task in which only contralateral responses were required.

In all age groups WM+IC efficiency was unrelated to efficiency in WM, suggesting that the former is not simply a more complex form of the latter. WM efficiency was unrelated to activation efficiency in all groups, and it was unrelated to inhibition efficiency in all but the youngest age group. A different correlational pattern was produced for WM+IC across development: Efficiency correlated positively with activation efficiency in children aged 6 through 11 years, and with inhibition efficiency in children aged 12 through 17 years. These differential findings imply that the relation between WM and IC changes over the course of development.

Table 3. Intercorrelations of Efficiency Scores by Age Group

Age Group	Tasks	Activation	Inhibition	WM (Block 2)	WM +IC
6–8	Activation	—	.06	−.16	.56**
	Inhibition		—	.47*	.10
	WM (Block 2)			—	.07
	WM+IC				—
9–11	Activation	—	.44*	.04	.49**
	Inhibition		—	−.16	.36
	WM (Block 2)			—	.27
	WM+IC				—
12–14	Activation	—	.38	.10	.17
	Inhibition		—	.11	.49**
	WM (Block 2)			—	−.01
	WM+IC				—
15–17	Activation	—	.14	−.12	.15
	Inhibition		—	.22	.46*
	WM (Block 2)			—	.19
	WM+IC				—

*$p \leq .05$; **$p \leq .01$.

Given that WM and WM+IC were uncorrelated, we wished to explore whether the tasks were empirically distinguishable in terms of the factors involved in producing performance. To this end, we tested two parallel hierarchical regression models. Efficiency in Block 2 of the WM task served as a measure of WM involving item and order recognition. WM+IC efficiency (i.e., the part with the mixed set of stimuli) provided a measure of WM applied in a more complex context involving competition between activation and suppression resources. The regressors were: (a) chronological age (CA); (b) activation efficiency (i.e., activation of relevant information only); and (c) inhibition efficiency (i.e., intentional suppression of a prepotent motor response activated by the perceptual situation). The regressors' variance inflation factors were 1.708, 1.250, and 1.486, respectively, indicating no substantial multicollinearity in the two models. The regression statistics are presented in Table 4.

Efficiency in WM (Block 2) was predicted by CA alone; activation and inhibition did not contribute significantly to the final model, $F(3,90) = 4.88$, $p = .003$, adjusted $R^2 = .11$. By contrast, efficiency in WM+IC was best predicted by the combination of CA, activation, and inhibition, $F(3,91) = 20.60$, $p < .001$, adjusted $R^2 = .39$. All three regressors made significant contributions to the final model.

Table 4. Summary of Hierarchical Regression Analyses predicting WM (Block 2) and WM+IC

Step	Variable	Standardized Beta	*t*	*p*	Increment R^2
		WM (Block 2)			
1	Chronological Age	.46	3.60	.001	.12*
2	Activation	−.06	−.56	.580	.00
3	Inhibition	.19	1.56	.123	.02
		WM+IC			
1	Chronological Age	.55	5.20	<.001	.22*
2	Activation	.26	2.91	.004	.11*
3	Inhibition	.33	3.38	.001	.08*

$^*p \leq .001$.

DISCUSSION

Contemporary models have moved away from conceptualizing WM in terms of isolated short-term storage buffers and rehearsal loops in favor of relating aspects of WM to other general-purpose resources that together serve complex cognition (e.g., Miyake & Shah, 1999). In this study, the developmental relations between WM and IC were investigated in an experimental paradigm that contrasted WM performance in tasks that varied the requirements for activation of items and order, IC, and strategic processes. The utility of this design was twofold: (a) it enabled direct comparisons of task performances both within the same individuals and between age groups; and (b) it allowed an appraisal of the constitution of WM.

Our WM task used recency judgments following serial learning to elicit active processing of items and their order, as well as intratask learning across item blocks to elicit strategic processes. A comparison of the Activation task, which involved only the maintenance of items, and Block 2 of the WM task, which involved maintenance of items as well as their order, revealed different developmental patterns: WM for item and order produced a steeper, stagewise developmental growth pattern compared to item maintenance alone. By contrast, there was parallel developmental improvement in WM and WM+IC performance up to mid-adolescence, suggesting that both tasks captured developmental improvement in frontally mediated WM to the extent that cognitive demands were made on the simultaneous activation and effortful processing of information. The results, then, provide support for WM models that attribute developmental change to increased processing efficiency of a limited-capacity activation resource (e.g., Case, 1987; 1995; Demetriou et al., 2002; Luciana & Nelson, 1998; Swanson, 1999), as opposed to greater WM span alone.

Importantly, this study also showed that the relation between WM and IC changes with development. Younger children (presumed to possess less WM capacity) were equally hindered by large item memory demands as by inhibition demands, and only activation resources were related to their WM+IC task performance. With increasing age, the relation between WM and IC seems to become stronger because increased WM capacity can accommodate the suppression of task-irrelevant information without affecting task-relevant processes. In this regard, improved WM efficiency was related to IC for older children only. These distinctions between different forms of WM and their relation to IC not only support and extend recent findings (e.g., Gathercole et al., 2004; Leon-Carrion et al., 2004; Vogel et al., 2005) but also contribute to theoretical accounts of these cognitive constructs in terms of age-related growth in multiple resources operating within a limited-capacity cognitive control system.

The regression models helped to clarify the determinants of efficient cognitive performance. WM+IC efficiency depended upon increases in activation, intentional suppression, and age-related strategic processes, a finding that is consistent with recent empirical investigations of multiple determinants of complex WM performance (e.g., Bayliss et al., 2003; 2005; Gavens & Barrouillet, 2004). These results are also compatible with adult neuroimaging data showing that IC processes are part of the general WM circuitry in the mature brain. By contrast, activation and suppression efficiency did not contribute to variability in WM efficiency without IC demands, which implies that strategic processes acquired with age and experience (e.g., practice) are more important in determining performance in canonical WM tasks than are general-purpose resources.

Our paradigm and associated findings bear on the issue of measurement of WM. Most WM tasks assess how strategic processes increase the efficiency with which cognitive resources are deployed. For this reason, they might not reliably yield age-related differences other than learning efficiency. The results of our WM task highlight this point. The activation demands in the first block of items were easily met by all age groups and required little strategic knowledge; hence, performance efficiency in the first block of items was uniformly high. By contrast, the second block introduced a novel situation requiring increased activation demands on the items and their order as well as the application of strategic knowledge. Performance in this block yielded a clear developmental effect corresponding to age. The final block of items benefited from intratask learning because it followed the other two blocks, fostering more efficient use of strategic processes and obscuring developmental effects for all but the broadest comparison between the youngest and oldest participants. These behavioral findings are consistent with those obtained in previous studies in which practice-related EEG changes accompanied improved WM performance efficiency (Smith et al., 1999). Unless intratask learning is minimized or eliminated, the measurement of WM capacity and learning efficiency will be confounded in cognitive performance.

Our results have further implications for the neuroanatomy of WM. The empirical distinction we found between WM for items and for order is consistent with recent findings of distinct neural substrates of each of these forms of

WM (Slotnick et al., 2003), the latter of which relies on left prefrontal cortical activation, an area known to mature over an extended developmental period (Gogtay et al., 2004; Konishi et al., 2002). Similarly, the lack of relation between WM and WM+IC performance and the different sets of predictors of each imply that WM, intentional IC, and strategic processes mature concurrently but independently and become functionally connected in the brain over an extended period of development. Even in healthy young adults there is neurophysiological evidence of systematic interindividual variability in the efficiency with which the mature neurocognitive system functions in the face of multiple or competing demands on its limited capacity (Vogel et al., 2005).

A few caveats in the interpretation of our data are warranted. First, drawing inferences about development may be limited by the use of a cross-sectional, as opposed to a longitudinal study design. Second, rather than using separate WM span and IC tasks with independently documented validity, we employed an experimental paradigm designed for the present study to examine WM and IC during development. Furthermore, we developed a dependent measure that combined latency and accuracy information rather than conventionally analyzing these data separately. Other tasks and/or performance measures might yield a different pattern of results. For instance, tasks with higher demands for competition among cognitive resources might cause older children (and adults) to default to their activation resources, as the younger children did in our study. Finally, we subscribed to the notion that WM and IC are general-purpose cognitive resources. The generalizability of our findings to language-based task performance, for example, remains to be established.

Notwithstanding these qualifiers, our paradigm and dependent measures proved useful in studying the normal development of WM and IC in childhood and adolescence. They also provide the basis for understanding these cognitive issues in conditions of abnormal brain development. Diamond (2001) recognized this in her investigations of WM and IC deficits associated with phenylketonuria using her version of the Directional Stroop Task. Studying WM and IC in cases of developmental disorders with known underlying brain pathology by means of our paradigmatic approach might refine cognitive-developmental and neuropsychological models of these functions. In particular, the relation between WM and IC observed across developmental stages in this study might not hold in the context of abnormal brain development. For example, if the developing brain is damaged early in life, the WM-IC relation might be looser in later years. As a first step, we are continuing the investigation of the developmental relations between WM and IC using our paradigm in children with focal frontal lobe damage resulting from closed head injuries sustained in early childhood. Further research uniting brain-based and behavioral evidence will undoubtedly lead to a more parsimonious lifespan model of frontally mediated, top-down cognitive control over information processing in conditions of both normal and atypical development.

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