Context Processing and Cognitive Control in Children and Young Adults

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ABSTRACT. T. S. Braver and colleagues (e.g., T. S. Braver, J. D. Cohen, & D. M. Barch, 2002) have provided a theory of cognitive control that focuses on the role of context processing. According to their theory, an underlying context-processing mechanism is responsible for the cognitive control functions of attention, inhibition, and working memory. In the present study, the authors examined whether T. S. Braver et al.'s theory can account for developmental differences in cognitive control. The authors compared the performance of children (*M* age = 11.9 years, *SD* = 0.43 years) with that of young adults (*M* age = 21.7 years, *SD* = 3.61 years) on a continuous performance task (AX-CPT) that placed demands on context processing. The results suggest that developmental differences in the cognitive control functions of attention, inhibition, and working memory may be based on age-related changes in an underlying context-processing mechanism.

Keywords: attention, cognitive control, context processing, inhibition, working memory

THE DELIBERATE CONTROL of one's own thought and action is generally referred to as *cognitive control*. Researchers have used the term cognitive control interchangeably with a variety of terms in the literature (e.g., controlled processing, effort, and supervisory attention systems), and it may be considered synonymous with the construct executive function (Casey, 2005). Blair, Zelazo, and Greenberg (2005) noted that *executive function* refers to the psychological processes involved in cognitive control: the "maintenance of information in working memory, the inhibition of prepotent responding, and the appropriate shifting and sustaining of attention for the purposes of goal-directed action" (p. 561). A

basic challenge for developmental theorists is to identify and explain the functions of those mechanisms that are responsible for age-related improvements in cognitive control.

Scholars have offered a number of theories in an attempt to identify the cognitive mechanisms that are responsible for improvements in executive function during the course of child development (see review by Zelazo, Muller, Frye, & Marcovitch, 2003). For example, cognitive complexity and control theory (Frye, Zelazo, & Burack, 1998; Zelazo & Frye, 1997, 1998) attributes developmental improvements in executive function to age-related changes in the complexity of rules that children are able to generate and the degree to which they can reflect on those rules. Another leading explanation for age-related improvements in executive function concentrates on growth in the ability to actively maintain task-relevant information in working memory in the presence of competing information (e.g., Munakata, 2001). A third explanation for the development of executive function highlights the importance of inhibitory processes, particularly the ability to inhibit dominant response tendencies that were previously relevant for a given task (e.g., Diamond & Kirkham, 2005).

Recently, Braver, Cohen, and colleagues have constructed a theory of cognitive control in working memory that is expressed within a connectionist, computational framework (Botvinick, Braver, Barch, Carter, & Cohen, 2001; Braver & Cohen, 2000, 2001; O'Reilly, Braver, & Cohen, 1999). Although not intended to serve as a developmental theory, the framework has implications for the study of age-related improvements in cognitive control. The central hypothesis of their theory is that cognitive control depends on the ability to represent and actively maintain context information to prepare the system to respond appropriately to forthcoming events. Context is used in a general sense to include any form of "task-relevant information that is internally represented in such a form that it can bias processing in the pathways responsible for task performance" (Braver, Gray, & Burgess, 2007, p. 79). Braver and colleagues' context-processing theory is similar to Engle and colleagues' (Engle, 2002, 2004; Kane, Bleckley, Conway, & Engle, 2001; Kane & Engle, 2003) view of working memory capacity (executive attention), which Engle (2004) described as "the ability to maintain goal-relevant information in a highly active, accessible state under conditions of interference or competition" (p. 149). Examples of context include prior stimulus events, task instructions or goals, and any other task-relevant information. Representations of context are considered a subset of representations within working memory that regulate how other representations are used. Because the internal representation of task-relevant information guides the allocation of attention and the selection of an appropriate response, it forms the basis of controlled processing.

The theory of Braver and colleagues also distinguishes between forming an internal representation of context and the active maintenance of the representation across time (Braver & Barch, 2002; Braver, Satpute, Rush, Racine, & Barch, 2005). In some instances, the temporal delay between the predictive context cue

and the forthcoming event is long enough that it requires the active maintenance of the representation in working memory. The active maintenance of the context representation maintains the integrity of the informational cue over time and produces the same benefits and costs that were observed at shorter delays. In contrast, a failure to actively maintain context produces a transient representation of context that decays rapidly. Consequently, the benefits and costs that are associated with representation of context at brief delays between the predictive cue and the forthcoming target event are compromised at longer delays.

Braver and colleagues have suggested that their theory provides an important alternative to existing theories that propose separate cognitive functions (Diamond, 1990; Fuster, 1989; Goldman-Rakic, 1995). More specifically, they have suggested that a single underlying context-processing mechanism may explain three cognitive functions that are often considered independent: attention, inhibition, and active memory (Braver et al., 2002). Thus, context representations provide an attentional function by selecting task-relevant information for additional processing, instead of other competing sources of information. In addition, rather than invoking a separate inhibitory mechanism, Braver and colleagues have argued that context representations provide support for task-relevant responses and thereby allow these responses to compete more effectively with irrelevant ones. Conceptualizing inhibition in terms of the increased activation of goals is consistent with a number of other recent proposals (e.g., De Jong, Berendsen, & Cools, 1999; Kane et al., 2001; Roberts & Pennington, 1996). Also, there is no dedicated memory function in Braver and colleagues' model. Instead, the mechanism that represents context also maintains this information against the interfering effects of noise during a retention interval. In each of these conditions, only one context-processing mechanism is responsible for attention, inhibition, and active memory functions.

Scholars presume that cognitive control relies on distinct neurobiological mechanisms. Specifically, cognitive control is considered the result of the dynamic interaction of specific subsystems within the brain: the lateral prefrontal cortex (PFC), the anterior cingulate cortex (ACC), and the midbrain dopamine (DA) system. Because scholars believe that the PFC plays a central role in the representation and maintenance of context information, the PFC has particular importance within Braver and colleagues' model (Braver & Cohen, 2000, 2001; Braver et al., 2002). The processing of context in the PFC is aided by its interactive connectivity with the DA neurotransmitter system and the ACC. The ACC adjusts the responsiveness of the PFC through a performance-monitoring mechanism that continuously assesses the need for top-down control (Botvinick et al., 2001). The DA projection to the PFC serves a gating function, and regulates access of information so that only task-relevant context information is actively maintained. More specifically, the phasic bursts of DA are considered to exert a neuromodulatory effect on PFC neurons, thereby enabling the active maintenance and updating of inputs from other regions of the brain. Without such bursts of DA

at the time of external inputs, such inputs would be represented only in a transient manner within the PFC and would decay shortly after input. The DA system is considered to be involved in situations in which learning involves the prediction of anticipated rewards.

Researchers testing Braver and colleagues' theory primarily have used a continuous performance task known as the *AX-CPT paradigm* (see Figure 1 for a schematic overview; Braver et al., 2002). In the AX-CPT, sequences of letters are presented on a computer monitor one at a time as cue–probe pairs. The object

	Cue	
	Valid	Invalid
Target	AX (70%)	BX (10%)
Nontarget	AY (10%)	BY (10%)
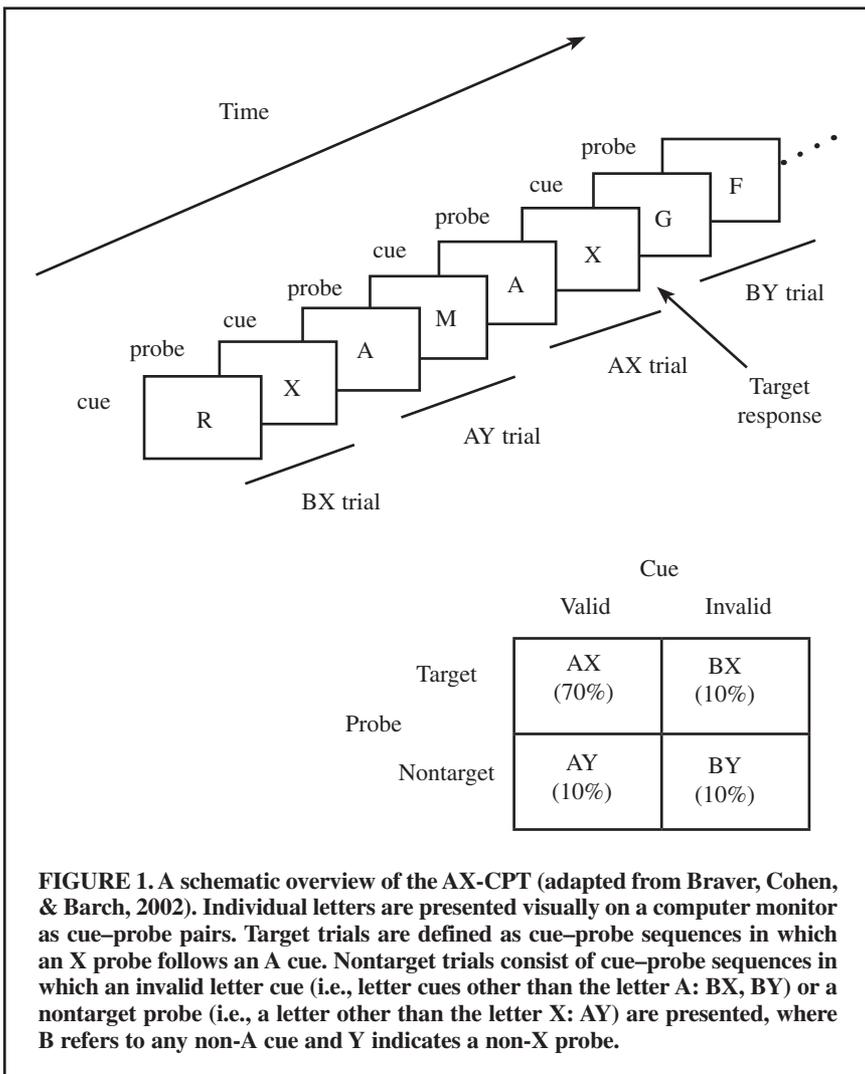
FIGURE 1. A schematic overview of the AX-CPT (adapted from Braver, Cohen, & Barch, 2002). Individual letters are presented visually on a computer monitor as cue–probe pairs. Target trials are defined as cue–probe sequences in which an X probe follows an A cue. Nontarget trials consist of cue–probe sequences in which an invalid letter cue (i.e., letter cues other than the letter A: BX, BY) or a nontarget probe (i.e., a letter other than the letter X: AY) are presented, where B refers to any non-A cue and Y indicates a non-X probe.

of the task is for the participant to respond as quickly and accurately as possible to a target probe (the letter X), but only when the probe follows a specific, valid cue (the letter A). For all other cue–probe pairs, the participant is to give a nontarget response, again with speed and accuracy. The task presents cue–probe target pairs (AX) with high frequency (70% of the trials) and therefore leads participants to develop a high expectation that the letter A will be followed by the letter X. Because a correct response to the target probe (X) depends on the nature of the preceding cue (A or not A), the task relies on the representation of context information.

Cognitive control on the AX-CPT requires the participant's use of attention and inhibition, with each process dependent on the ability to represent context information (i.e., cue–probe relations). The high frequency of target trials (AX) leads the cue to drive expectations about the forthcoming probe. Attention to the context representation of a valid cue (A) facilitates or primes a rapid and accurate response to a target probe (X) on AX trials. Unfortunately, attention to the valid cue (A) comes with a cost on those trials in which A precedes a nontarget probe (Y), where *Y* refers to any non-X probe. Because the cue (A) primes the target probe (X), presenting the letter A makes it more difficult for participants to reject nontarget letters when they appear on AY trials and consequently they produce slower responses and more errors. Thus, attention to the context representation of a valid cue leads to benefits (i.e., greater speed and accuracy on AX trials) and costs (i.e., slower speed and less accuracy on AY trials).

Inhibitory processes are required on BX trials, in which *B* refers to trials containing an invalid (non-A) cue. Because AX pairs occur with high frequency (e.g., 70% of the trials), they create a bias to provide a target response whenever an X probe appears. In the BX condition, the participant must use context to inhibit the dominant tendency to make a target response to the X. The participant must use a context representation of the invalid cue (B) to inhibit the tendency to provide a target response to the letter X. Thus, the use of context information (invalid cue, B) improves performance on BX trials by aiding in the inhibition of a strong response tendency.

In addition to attention and inhibition functions, the maintenance of context information within working memory may be assessed by manipulating the temporal interval between the cue and the probe in the AX-CPT paradigm. By incorporating a delay between the presentation of the cue and the probe (e.g., 5 s), the AX-CPT task requires that context representations of the cue be actively maintained within working memory during the delay.

Braver and colleagues have argued that attention, inhibition, and working memory functions on the AX-CPT yield important information about the integrity of cognitive control and, ultimately, provide information about the ability to represent and maintain context information within the PFC (Braver & Barch, 2002; Braver et al., 2002). Measuring the integrity of cognitive control focuses on the relation of AY performance relative to BX performance. If the internal

representation of context is intact, performance on AY trials should be worse than performance on BX trials (i.e., on AY trials, participants should evidence more false alarms and slower reaction times). Intact performance is based on attention to the context information that is provided by the cue. If attention is given to the context representation of a valid cue (A), it comes with an expectancy bias that the letter A will be followed by the letter X. This expectation comes with a cost that is manifested by an increased tendency to false alarm on AY trials. Also, if attention is given to the context representation of an invalid cue (B), this context information may be used to inhibit the dominant tendency to provide a target response to the X. If the maintenance of context representations in working memory is intact, performance on the AY and BX trials should not vary between short and long delays.

Braver, Barch, and Cohen (1999) tested more than 200 healthy young adults in a series of studies and found that the attention, inhibition, and working memory functions on the AX-CPT were consistent with the predictions of their model. When compared with the BY (baseline) condition, participants had more errors and slower reaction times on both AY and BX trials. Greater errors and longer reaction times on the AY trials reflect the costs of paying attention to a valid context cue (A) on nontarget trials, whereas errors and longer reaction times on the BX trials reflect the difficulty associated with inhibiting the prepotent tendency to respond to the letter X. Most important, the fact that young adults were slower and less accurate on AY trials relative to BX trials indicates that they were using context. Also noteworthy is that the pattern of the error data indicates that the difference between AY and BX performances interacted with delay. More specifically, when comparing changes in error data between short and long cue–probe delays, Braver, Barch, and Cohen found that BX errors decreased, AY errors increased, and BY errors remained the same at long delays. This finding suggests that context information not only was maintained but also became stronger at long cue–probe delays.

The model of Braver and colleagues indicates that the contextual information provided by the cue in the AX-CPT is represented and maintained in the PFC during the delay between the cue and the probe (Braver & Barch, 2002; Braver et al., 2002. To test this component of their theory, Braver et al. (2002) performed a series of studies that used functional magnetic resonance imaging (fMRI) to examine brain activity during short- and long-delay conditions in the AX-CPT. A series of studies have shown that activity within an area of the dorsolateral PFC known as *Brodmann's area 46/9* was greater in a long delay between the cue and the probe relative to a short delay (Barch et al., 1997; Braver & Cohen, 2001). These neuroimaging studies provide compelling evidence for the importance of the PFC in context processing and cognitive control.

To further examine the validity of their model of cognitive control, Braver and colleagues have generated hypotheses about the locus of cognitive control difficulties of populations that are known to possess disrupted DA systems.

A number of populations who have difficulties with cognitive control (e.g., those diagnosed with schizophrenia, Parkinson's, or ADHD; older adults) also have impaired PFC or DA systems. Because context processing depends on the dynamic interaction of the PFC with the DA system, the theory of Braver and colleagues predicts that these populations should exhibit a selective deficit in the use of cognitive control on the AX-CPT. For example, because healthy older adults exhibit an age-related reduction in the size of the PFC as well as lower DA transmissions in the PFC, and because context processing depends on the interaction of the PFC and DA, Braver and colleagues (Braver et al., 2001; Braver et al., 2005) have hypothesized that the cognitive control difficulties of healthy older adults are due to a deficit in the processing of context. Braver et al. (2001) tested this hypothesis by comparing the performance of younger and older adults on the AX-CPT. Older adults made more BX errors but fewer AY errors. In addition, there was significant age-related slowing on the BX trials but not on the AY trials. These results were offered as evidence for an age-related deficit in context processing. Braver and Barch (2002) subsequently provided additional support of this context-processing deficit. They obtained fMRI measures of younger and older adults during the AX-CPT and found that older adults exhibited less activity in the DL-PFC, the region that was identified in previous studies as responsible for the maintenance of context representations, than did younger adults.

The Present Study

Because cognitive control difficulties of healthy older adults have been linked to a decline in the ability to process context information (Braver & Barch, 2002; Braver et al., 2001), in the present study we examined whether context-processing ability may play a role in developmental changes in cognitive control. We compared the performance of children and young adults on the AX-CPT. We expected children to show a pattern of performance that is similar to that which has been previously exhibited by older adults (Braver et al., 2001). We based this expectation on multiple observations. First, researchers have found developmental differences in various functions of cognitive control, including inhibition in working memory (Harnishfeger & Bjorklund, 1993), resistance to interference (Dempster, 1992), and executive processes (Zelazo, Carter, Reznick, & Frye, 1997). Second, although the available evidence is limited, research find-dings suggest that there are developmental improvements in the deliberate use of context information. For example, Simpson and colleagues (Simpson & Foster, 1986; Simpson & Lorsbach, 1983) have found that the conscious use of context during letter and word processing improves as children grow older. Third, the PFC, which is thought to play a key role in representing and maintaining context information in Braver et al.'s theory, is one of the last neuroanatomic structures to develop, reaching maturation during late adolescence (e.g., Anderson, 2001; Casey, Giedd, & Thomas, 2000; Diamond, 2001). The dorsolateral region of

the PFC is particularly slow to develop and is not fully mature until adulthood (Diamond, 1996). Last, the DA system, which, according to Braver et al.'s theory, regulates the flow of information into the PFC, exhibits a protracted development that is similar to that of the PFC (Diamond, 2001).

In the present experiment, we compared the performance of sixth-grade children and college students. In previous research with young adults (Braver & Cohen, 2000; Braver et al., 2002), researchers have found that two biases are created in the AX-CPT as a result of presenting target trials (AX) 70% of the time. First, because target probes (X) appear most of the time, there is a strong tendency for participants to provide a target response whenever the X probe appears. This dominant tendency to make a target response to the letter X may be inhibited on BX trials only if one forms a representation of the preceding context cue (B). If developmental differences exist in the representation of context cues, children should be less able to inhibit the tendency to make a target response to the letter X on BX trials. Such difficulty with inhibition would be manifested by children exhibiting more errors or longer response latencies to X probes on BX trials than young adults.[1] A second type of bias is observed in the AY condition. Because the letter A precedes the letter X most of the time, attention to the letter A provides leads to the strong expectation that one is about to make a target response to the next letter. Unfortunately, performance suffers (more errors or longer reaction times [RTs]) on those trials in which the letter A is followed by a nontarget letter (Y). If developmental differences exist in context processing, this attentional function of context processing should be less evident in children. Paradoxically, children should show fewer errors or faster RTs in the AY condition than should young adults.

Method

Participants

Participants were 25 children ($M = 11.9$ years, $SD = 0.32$ years) and 27 young adults ($M = 21.7$ years, $SD = 3.61$ years). We recruited young adults from introductory psychology classes and recruited children from two elementary parochial schools. None of the child participants were receiving special education services.

Apparatus and Procedure

We based our procedure on Braver et al.'s (2001) study. Figure 1 presents a schematic overview of the events that occurred within each trial. Letters were presented sequentially in a continuous manner on a Dell laptop computer. We programmed E-Prime software (Schneider, Eschman, & Zuccolotto, 2002) to present the sequence of events within each trial and to record the accuracy and latency of each participant's
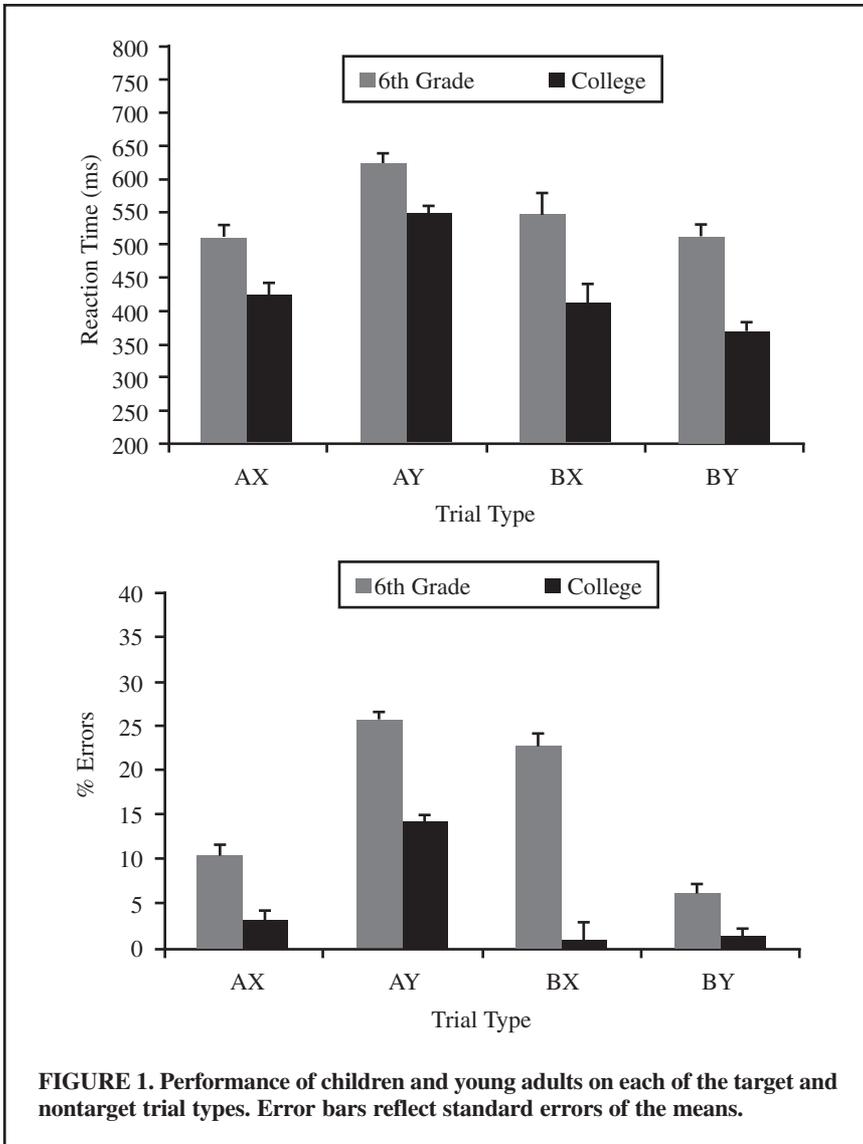
response. Letters were presented using 24-point uppercase Helvetica font in the center of the monitor (red letters on a black background) for 500 ms. We defined target trials (AX) as cue–probe sequences in which a valid letter cue (A) appeared and was followed immediately by the target probe letter (X). Nontarget trials consisted of cue–probe sequences in which an invalid letter cue (i.e., letter cues other than the letter A) or a nontarget probe (i.e., a letter other than the letter X) appeared. Because of their similarity to the target probe letter X, we did not use the letters K and Y as nontarget probes. There were three types of nontarget trials: BX (a cue other than the letter A followed by an X probe), AY (an A cue followed by any letter other than X), and BY (a cue other than the letter A followed by a probe that was any letter other than X). The letter sequences were presented in a pseudorandom manner, with target trials appearing 70% of the time and nontargets trials (AY, BX, and BY) appearing 30% of the time. Each of the nontarget trial types occurred with equal frequency (10% each). A 4,900 ms delay occurred between the onset of the cue and the onset of the probe. The intertrial interval was 1,000 ms.

We instructed participants to respond to each letter by pressing one of two keys labeled *Yes* and *No* on the keyboard as quickly but as accurately as possible. Participants made responses using two fingers of the same hand. Right-handed participants responded with their right hand using their index finger for target trials (J key) and their middle finger for nontarget trials (L key). Left-handed participants responded with their left hand using their index finger for target trials (J key) and their middle finger for nontarget trials (G key). Beginning with the onset of the stimulus, participants had 1,500 ms in which to respond. Responses to probes that exceeded this time limit were accompanied by a message on the monitor that reminded the participant to respond quickly and were excluded from analyses. We presented practice and test trials only after participants demonstrated their understanding of the procedure during an initial instructional activity.

Testing occurred in a single session containing 150 trials divided into five blocks of 30 trials each. The first block represented practice trials and the remaining four blocks were experimental trials. Participants had the opportunity to rest briefly between trial blocks.

Results

Figure 2 presents the means for the error rates and reaction times in the target and nontarget conditions for each age group. We analyzed responses on target and nontarget trials separately because each has different response requirements (target button press vs. nontarget button press) and different frequencies of occurrence (i.e., 70% for target trials and 10% each for nontarget trials). We assessed accuracy of performance using a measure of d' for target trials and using false alarm rates for nontarget trials. We calculated the speed of correct responses on target and nontarget trials using mean RTs. We used an alpha level of .05 for all statistical tests.

FIGURE 1. Performance of children and young adults on each of the target and nontarget trial types. Error bars reflect standard errors of the means.

Our analysis of performance accuracy on target trials focused on *d′* context (Cohen, Barch, Carter, & Servan-Schreiber, 1999), a signal detection measure that is based on the proportion of trials in which a subject responds correctly in AX trials by pressing the *Yes* key (Hits), relative to the proportion of trials in which the subject responds incorrectly in the BX condition by pressing the *Yes* key (False Alarms). Before calculating *d′* scores, we corrected the hit and false

alarm rates by adding .5 to each frequency and dividing by $N + 1$, where N equaled the number of old or new trials (Snodgrass & Corwin, 1988). Children produced significantly lower d' context scores than did young adults, Ms = 2.25 and 3.65, respectively, $t(50) = -6.369$. The lower d' scores of children indicated that they were, relative to young adults, less proficient at using prior context information when attempting to distinguish between targets and nontargets. That is, when given the probe letter X, children were less sensitive to whether the preceding context was an A or a non-A. Analysis of mean latencies of correct responses in the target condition indicated that the children ($M = 511$ ms) responded significantly more slowly than did young adults ($M = 424$ ms), $t(50) = 3.149$. These age differences in response latency are consistent with developmental differences in processing rate (Kail, 1991).

Of greater interest was the performance on nontarget trials (AY, BX, BY). Nontarget error rates and RTs were submitted separately to a 2 (age group: children vs. young adults) × 3 (nontarget trial type: AY, BX, BY) mixed design analysis of variance (ANOVA), with nontarget trial type as the within-subject factor. For the nontarget errors, the effects of age group, $F(1, 50) = 27.987$, $MSE = .023$, and nontarget trial type, $F(2, 100) = 25.155$, $MSE = .014$, were each significant, as was their interaction, $F(2, 100) = 6.943$, $MSE = .014$. Similarly, for the nontarget RTs, the effect of age group, $F(1, 50) = 16.972$, $MSE = 31,476.542$, and nontarget trial type, $F(2, 100) = 60.069$, $MSE = 4,829.693$, were each significant, as was their interaction, $F(2, 100) = 3.828$, $MSE = 4,829.693$.

Planned contrasts indicated that, relative to the BY condition, age differences were not found in the AY error rates, $t(50) = 1.645$, $p > .10$. However, in comparison with the BY condition, we found age differences in the AY RTs. Specifically, the performance of children revealed a smaller difference between the AY and BY RTs than did that of young adults (children: $M = 109$ ms; young adults: $M = 179$ ms), $t(50) = -3.754$. These age differences in response latency suggest that young adults experienced more interference from the preceding A context when comparing conditions that hold the Y constant (AY and BY) than did children.

Planned contrasts also showed that, relative to the BY condition, there were age differences in BX error rates, $t(50) = 4.815$. Children exhibited a larger difference between the BX and BY error rates than did the young adults (children: $M = 16.6\%$; young adults: $M = -0.3\%$). These age differences suggest that when the context cue was held constant, children experienced greater difficulty in using a context cue (B) to inhibit a dominant yet contextually inappropriate response to the letter X. Planned comparisons did not reveal any age differences between children and young adults in the BX RTs, $t < |1|$.

Discussion

The results of the present study are consistent with the hypothesis that children and young adults differ in their ability to use context information to control

their behavior. When attempting to identify target probes, children were less sensitive to prior context information than were young adults. Specifically, the lower d' context scores indicate that children frequently failed to use context cues (A or non-A) when making decisions about X probes. In contrast, the higher d' context scores of young adults show that they were more proficient than children in using valid and invalid context information (A or non-A) when making decisions about X probes.

In addition, the results of nontarget trials suggest that developmental differences in context processing may be responsible for age differences in two separate functions of cognitive control. First, participants' performance on AY trials indicates that developmental differences in context processing affect the attention function of cognitive control. If one attends to letter cues, the presentation of a high proportion of AX trials creates a strong expectation that a valid cue (A) will be followed by a target stimulus (X). Because of the expectation that A will be followed by X, the presentation of the letter A makes it difficult to reject nontarget probes on AY trials. Consequently, performance on AY trials is characterized by errors or slower decisions for correct responses. Although the two age groups were not differentiated by error rates, young adults were slower than children to respond in the AY condition relative to the BY condition. The longer response times of younger adults reflect a cost that came from our using representations of A cues to generate a strong expectation that the X probe would appear next. The counterintuitive finding that young adults were slower than children in the AY condition is particularly noteworthy, because young adults are known to process information more rapidly than do children (Kail, 1991).

Second, the comparison of children and young adults in the BX condition indicates that developmental differences in context processing were also responsible for age differences in the cognitive control function of inhibition. Given that target trials (AX) appear frequently in the AX-CPT, participants develop a strong tendency to make a target response whenever the X probe appears. The fact that children made significantly more false alarms than did young adults in the BX condition, relative to the BY condition, indicates that they experienced greater difficulty in using prior context information to override a dominant response tendency.

In addition to providing attention and inhibition functions, the context-processing mechanism also plays a role in the working memory domain of cognitive control (Braver et al., 2001). In the present experiment, we used a 5-s cue–probe delay and, therefore, required that context representations be actively maintained in working memory. Although the present results suggest developmental differences in the maintenance of context information, we were limited in our ability to test the role of context processing in the working memory function of cognitive control in children and young adults. The present results may have been due to developmental differences in the ability to form a representation of context or the ability to maintain a context representation during the 5-s cue–probe delay. To determine whether developmental differences in context processing are due to the representation

or the maintenance of context (or both), future researchers should compare the performance of children and adults with both brief (1 s) and long (5 s) cue–probe delays. A brief cue–probe delay would minimize the need to maintain a representation in memory and, therefore, would primarily assess participants' ability to form a context representation. A long delay, however, would require both the representation and the maintenance of context information during the cue–probe delay. Braver et al. (2001) noted that if there are problems associated with the working memory function of context processing, context-processing difficulties should become more pronounced at a long (5–10 s), relative to a brief (1 s), cue–probe delay.

Munakata and colleagues (Morton & Munakata, 2002; Munakata, 2001; Munakata & McClelland, 2003) have also generated a connectionist model of cognitive control and one that attempts to identify those mechanisms that are responsible for developmental changes in executive function. Munakata and colleagues have distinguished between active and latent memory representations. Active memory representations are formed in the PFC and actively represent and maintain task-relevant information, such as rules. Latent memory traces, however, are thought to be formed in posterior cortical areas. Although latent traces are inaccessible to other regions of the brain, they influence processing through changes in activation to subsequent stimuli (Morton & Munakata). Strong, active representations of task relevant information are needed when conflict is present. When the ability to maintain active traces is relatively weak, as researchers presume it to be in younger children, the system falls back on latent representations and tends to perseverate (Munakata & McClelland). As the PFC develops throughout childhood, there is a corresponding improvement in the ability to actively maintain representations of task-relevant information in the presence of competing information. Although different neural mechanisms are invoked, Munakata and colleagues' model is somewhat similar to the context-processing framework of Braver and colleagues (Braver at al., 2002). Munakata and colleagues' model would suggest that the performance of children in the present study may have resulted from a failure to maintain strong, active representations of cue information. As a result of their failure to actively represent and maintain cue information, children presumably relied on latent representations and consequently experienced difficulty in the identification of both target and nontarget probes. Thus, presumably because of their relatively weak ability to maintain active representations of cue information, children made more errors in the AX condition and perseverated with prepotent responses to invalid letter cues in the BX condition. Unfortunately, the model of Munakata and colleagues has difficulty accounting for the developmental differences that were observed in the AY condition. Specifically, it is difficult to explain how a failure to maintain a strong representation of the letter cue in the AY condition would lead children to produce responses to probes that were faster than those of young adults.

It is important to note that context-processing theory also can explain developmental differences on the Dimensional Change Card Sort (DCCS) task (Zelazo,

Muller, Frye, & Marcovitch. 2003), a more commonly used measure of executive function in children. According to Zelazo and Frye (e.g., 1997, 1998), performance on the DCCS requires the ability to represent a hierarchical, embedded rule structure. There are two higher order categories in the DCCS task (e.g., shape and color). Two rules are embedded within each of the categories. If one follows the rule in the color sort task ("The blue things go here and the red things go there"), blue rabbits are placed with blue boats. However, if one follows the rule for the shape sort task, blue rabbits go with red rabbits. Younger children presumably have difficulty representing this complex rule structure and, consequently, experience difficulty on the DCCS. Context-processing theory refers to context as "information that must be actively held in mind in such a form that it can be used to mediate task appropriate behavior" (Cohen et al., 1999, p. 120). The representation and maintenance of task-relevant instructions and rules provide the critical context information that enables the participant to orchestrate thought and action appropriately on the DCCS task. The DCCS task that is used commonly with younger children (ages 3–5 years) incorporates a blocked-presentation format, with rules changing between the pre- and postswitch conditions. Younger children typically perseverate during the second phase of the task by continuing to apply rules that were learned during the first phase of the task. Context-processing theory would attribute the greater error rates of younger children on the DCCS to a failure to update context information when the rule changes on the postswitch task. Failing to update context information results in younger children being unable to inhibit response tendencies (prepotent responses) acquired during the preswitch phase of the task.

   Although researchers must be cautious when interpreting results of a single experimental task, the present findings provide important groundwork for the hypothesis that developmental differences in the cognitive control functions of attention, inhibition, and working memory are each based on age-related changes in a single, underlying context-processing mechanism. If future research confirms the results of the present study, the identification of a single mechanism that explains multiple functions of cognitive control would be valuable in at least two respects. First, although developmental theorists have previously identified individual mechanisms that explain separate functions of cognitive control (e.g., Dempster, 1992; Harnishfeger & Bjorklund, 1993), a single underlying context-processing mechanism that simultaneously explains multiple cognitive functions represents a more integrative and parsimonious approach for explaining age-related improvements in cognitive control. Second, proposing that there are developmental differences in context processing has particular significance in light of the context-processing deficits that researchers have observed at the opposite end of the life span with healthy older adults. Braver and colleagues recently presented a theory of aging in which older adults are considered to have difficulties in processing context, which lead to problems of cognitive control (Braver & Barch, 2002; Braver et al., 2001). Several studies using the AX-CPT paradigm have provided support for an age-related deficit in context processing (e.g., Braver et al., 2001; Braver et

al., 2005). In each case, older adults performed in a manner that was indicative of a context-processing deficit: (a) more errors or increased slowing on BX trials and (b) fewer errors or decreased slowing on AY trials. Because healthy older adults exhibit an age-related reduction in the size of the PFC and lower DA transmissions in the PFC, Braver and colleagues have argued that the cognitive control difficulties of healthy older adults are due to a deficit in the processing of context (Braver et al., 2001). When considered with Braver and colleagues' research on adult age differences, the present results may reflect changes in life-span cognitive development: The neuroanatomic structures and information-processing systems that may be responsible for cognitive control are the last to develop in children and appear to be the first to decline during the natural aging process.

NOTE

1. Although a strict interpretation of the context-processing model would predict comparable changes in both error rates and RTs, Braver et al. (2005) recently indicated that their model is "agnostic as to which behavioral measure would be most impacted by context-processing disruption" (p. 41).

AUTHOR NOTES

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