JOURNAL OF COGNITION AND DEVELOPMENT, 11(2):185–216

ISSN: 1524-8372 print/1532-7647 online
DOI: 10.1080/15248371003699936

Psychology Press
Taylor & Francis Group

Developmental Differences in Cognitive Control: Goal Representation and Maintenance During a Continuous Performance Task

Thomas C. Lorsbach
University of Nebraska at Omaha

Jason F. Reimer
California State University, San Bernardino

The present study examined whether younger and older children differ in the use of the goal-related information in a continuous performance task (AX-CPT), and if so, whether those age differences are due to the ability to represent and/or maintain goal information. Experiment 1 compared third- and sixth-grade children in their ability to transform the identity of letter cues into goal representations, as well as to sustain those goal representations during a long (5,500 ms) cue-probe delay in the AX-CPT. Experiment 2 used a short cue-probe delay (1,000 ms) and thereby eliminated the demands of maintaining goal representations in working memory. In addition, Experiment 2 varied the level of demand that was placed on the ability to represent context information by varying the features of letter cues. The combined results of these experiments indicated that sixth graders were superior to third graders in cognitive control under conditions that placed demands on either the ability to represent or maintain goal-related information.

Of the many cognitive changes that occur throughout childhood, perhaps the most significant is the child's ability to intentionally control his or her thoughts and behaviors (Bjorklund, 2000). Age-related changes in cognitive

Correspondence should be sent to Thomas C. Lorsbach, Department of Special Education and Communication Disorders, University of Nebraska at Omaha, KH 421C, 6001 Dodge Street, Omaha, NE 68182, USA. E-mail: tlorsbach@mail.unomaha.edu

control are evident in a variety of laboratory tasks. For example, as children grow older, they become more proficient in their ability to control the focus of their attention (e.g., Lane & Pearson, 1982; Ruff & Lawson, 1990), inhibit irrelevant thoughts (e.g., Harnishfeger & Bjorklund, 1993), and resist interference from competing information (Dempster, 1992). Given that cognitive control provides the foundation for virtually all goal-directed behavior and plays a critical role in higher-level thought processes, it has particular significance for theories of child development. A basic challenge for developmental theorists is to identify and explain the function of those mechanisms that are responsible for age-related improvements in cognitive control. Several prominent theories (e.g., Diamond, 2006; Munakata, 2001; Zelazo & Müller, 2002) have attempted to identify those cognitive mechanisms that are responsible for developmental improvements in cognitive control (see reviews by Garon, Bryson, & Smith, 2008; Zelazo, Müller, Frye, & Marcovitch, 2003).

Goal Representation and Maintenance in Cognitive Control

Recently, multiple theorists (e.g., Blair, Zelazo, & Greenberg, 2005; Braver, Gray, Burgess, 2007; Miller & Cohen, 2001; Oberauer, 2005) have emphasized the role of goal representation and maintenance in cognitive control. Indeed, Miller and Cohen (p. 167) describe cognitive control in terms of "the ability to orchestrate thought and action in accordance with internal goals." Oberauer (p. 287) conceptualizes executive function (i.e., cognitive control) in terms of a set of supervisory or control processes that determine whether thoughts and actions are consistent with one's current goals: "This involves maintaining an operative representation of [the] goal — that is, a representation that guides ongoing action, as opposed to one that is merely held in long-term memory or WM [working memory] so that it can be recalled when asked for." Blair et al. (p. 561) note that executive function is a broad term that refers to various psychological processes: the "maintenance of information in working memory, the inhibition of pre-potent responding, and the appropriate shifting and sustaining of attention for the purposes of goal-directed action."

Two recent studies have found that young children may have difficulty representing (Towse, Lewis, & Knowles, 2007) and maintaining (Marcovitch, Boseovski, & Knapp, 2007) task goals. Marcovitch et al. examined goal maintenance in the performance of young children (4- to 5-year-olds) on the Dimensional Change Card Sort (DCCS) task. One version of the task placed demands on the ability to maintain attention to the goal of sorting conflict cards correctly. Specifically, demands were placed on goal maintenance by presenting children with a high proportion (80%) of "redundant" post-switch test cards (a condition where cards may be sorted without regard to specific rules) and a low proportion (20%) of conflict cards (a condition where appropriate card sorting depends on the use of rules). Children frequently sorted conflict cards incorrectly because they had failed to maintain goals and attend to the rules of the task. Failing to maintain task goals led children to exhibit a form of "goal neglect" (Duncan, Emslie, Williams, Johnson, & Freer, 1996), a term that refers to those instances in which participants fail to execute a task appropriately, despite understanding the task and its requirements.

Towse and his colleagues (2007) focused their attention on the goal representations of young children. Based on the observation that self-regulated behavior depends on the strength and completeness of one's goal representations, Towse et al. examined whether goal neglect in young children is affected by the strength of external cues and the ability of those cues to elicit a relevant goal state. Preschoolers were presented with a series of tasks, among which included a goal-neglect task (selective image naming) that used one of two instructional cues: an abstract colored square or a directive arrow. Cues had a differential effect on the initiation of goal-directed behavior, with lapses in behavior occurring more frequently with the colored square. These results suggest that young children experience difficulty with representing less salient external cues and using them to control their behavior.

Braver and his colleagues (Botvinick, Braver, Barch, Carter, & Cohen, 2001; Braver et al., 2001; Braver & Cohen, 2000, 2001; Braver et al., 2007; Braver, Satpute, Rush, Racine, & Barch, 2005; O'Reilly, Braver, & Cohen, 1999; Paxton, Barch, Racine, & Braver, 2008; Paxton, Barch, Storandt, & Braver, 2006) have proposed a theoretical framework in which representing and actively maintaining task goals (plans, instructions) are critical in controlled performance. Specifically, Braver et al. (2001)'s framework is based on the premise that the control of thought and behavior in working memory is dependent on the use of "context" information. 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 et al., 2007, p. 79). Goals and prior stimulus events represent specific examples of context. Because the internal representation of goals (context) guides the allocation of attention and the selection of an appropriate response, it forms the basis of controlled processing in working memory.

According to Braver and his associates, cognitive control is considered to originate in the lateral prefrontal cortex (PFC) where context representations of task-relevant information are maintained (Paxton et al., 2008). This function of the PFC is aided by its interactive connectivity with the dopamine (DA) neurotransmitter system. The DA projection to the PFC serves as a "gating" function and regulates access of information so that only task-relevant context information is actively maintained. Based on the observation that cognitive control depends on the dynamic interaction of the PFC with the DA system, Braver et al. (2001)'s theory predicts that populations who have dysfunctions in the PFC and/or DA systems (e.g., schizophrenia, Parkinson's, attention-deficit hyperactivity disorder, older adults) should have deficits in context processing and cognitive control. Thus, given that healthy older adults exhibit an age-related reduction in the size of the PFC, as well as lower DA transmissions in the PFC, and given that context processing depends upon the interaction of the PFC and DA, healthy older adults might be expected to have difficulty using context to control their behavior. Such a prediction of an age-related decline in context processing has been confirmed in a number of studies by Braver and his colleagues (e.g., Braver et al., 2001; Braver, Satpute, Rush, Racine, & Barch, 2005; Paxton et al., 2006; Paxton et al., 2008).

The AX-CPT Paradigm

A continuous performance task known as the AX-CPT is well suited for examining the ability to represent and maintain goal information in working memory. Indeed, Braver and his colleagues have relied upon the AX-CPT for examining cognitive control deficits associated with typical (Braver et al., 2001; Braver & Barch, 2002; Paxton et al., 2008; Rush, Barch, & Braver, 2006) as well as atypical (Braver et al., 2005) adult aging. In the AX-CPT, sequences of letters are presented on a computer monitor one at a time as cue-probe pairs (see Figure 1 for a schematic overview). The object of the task is to respond with a target response as fast and as accurately as possible to a target probe (X), but only when the probe follows a specific valid cue, "A" (thus, the name AX-CPT). For all other cue-probe pairs, a non-target response is to be given, again with speed and accuracy. Because a correct response to the target probe (X) depends on the nature of the preceding cue/context (A or non-A), the task is considered to rely on the representation of context information. Rather than merely representing the physical attributes of the cue (e.g., phonological or orthographic features), context representations are based on task rules/instructions and carry information regarding the cue's implications for future stimulus evaluation and response (Barch et al., 2001). For example, a context representation of the "A" cue might be in the form of, "Press 'yes' key if next letter is an X." According to Braver et al. (2007), the representations of context cues are "micro-goals," because they are used during brief temporal intervals and serve to bias decisions about forthcoming target events. The AX-CPT presents cue-probe target pairs (AX) with high frequency

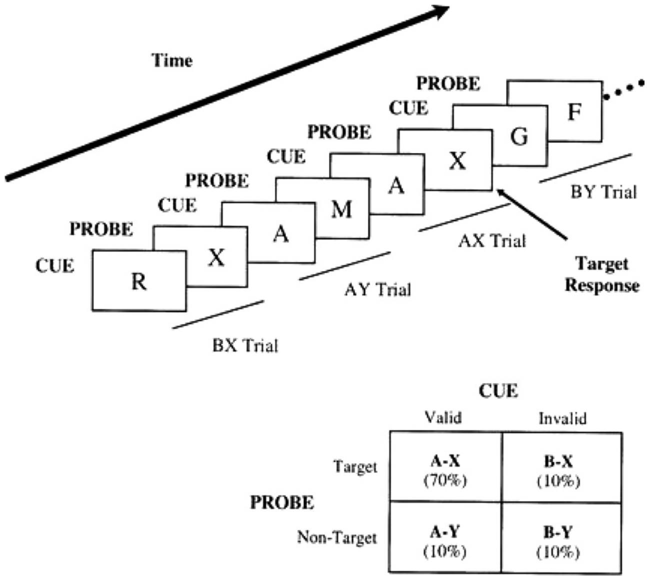

FIGURE 1 Schematic overview of the AX-CPT (adapted, by permission of Oxford University Press, Inc., from Braver, Cohen, & Barch, 2002). Individual letters are presented sequentially as cue-probe pairs. Target trials are defined as cue-probe sequences in which an A cue precedes an X probe. Non-target trials consist of cue-probe sequences in which an invalid cue (i.e., a letter other than A) and/or a non-target probe (i.e., a letter other than X) are presented. Note that B refers to any non-A cue and Y indicates any non-X probe.

(70% of the trials). A valid cue (A) precedes a non-target probe (Y) on 10% of the remaining trials, where "Y" refers to any non-X probe. An invalid cue (B) precedes the target probe (X) on 10% of the remaining trials, where "B" refers to any invalid cue (i.e., any letter other than "A"). The remaining 10% of the trials present invalid cues (B) prior to non-targets (Y). The ability to actively maintain the goal representation of the cue in working memory may also be assessed by using a long temporal interval (e.g., 5,000 ms) between the cue and the probe in the AX-CPT paradigm.

In the AX-CPT, updating, representing, and actively maintaining the goal information of the cue are required to prepare a response to the forthcoming probe. The high frequency (70%) of target trials (AX) leads the cue to drive expectations about the upcoming probe. Attention to a valid cue (A) facilitates or primes a rapid and accurate response to a target probe (X) on AX trials. Unfortunately, representing and maintaining the valid cue (A) comes with a cost on those trials where it precedes a non-target probe (Y) on AY trials. Because the cue (A) primes the target probe (X), presenting the letter "A" makes it more difficult for someone to reject non-target letters when they appear on AY trials and consequently produces slower responses and/or more errors. Thus, representing and maintaining the context information of a valid cue leads to benefits (i.e., greater speed and/or accuracy on "AX" trials), as well as costs (i.e., slower and/or less accurate responses on "AY" trials) for participants. Presenting AX pairs with high frequency also creates a bias to provide a target response whenever an "X" probe appears. Thus, one must inhibit the dominant tendency to make a target response to the "X" on BX trials. Participants must represent and actively maintain invalid cues (B) to inhibit the tendency to provide a target response to the letter "X." Therefore, the representation of context information (invalid cue, "B") improves performance on BX trials by aiding in the inhibition of a strong response tendency. Overall, forming context representations during the AX-CPT enhances performance on AX and BX trials but impairs performance on AY trials (Paxton et al., 2008).

Importantly, Paxton et al. (2008) have observed that a different set of predictions would be offered by theories of cognitive control that merely focus on the ability to inhibit dominant response tendencies (e.g., Bjorklund & Harnishfeger, 1995; Diamond & Kirkham, 2005; Harnishfeger & Bjorklund, 1993; Hasher & Zacks, 1988). Inhibitory theories of cognitive control would predict that a deficit in inhibitory processes should lead to poor performance on *both* BX and AY trials, because both trial types require the ability to inhibit strong biases. Recall that the high frequency with which AX trials are presented develops a dominant tendency to provide a target response whenever the "X" appears. Thus, on BX trials, there is a bias to provide a target response when the "X" probe is presented. Deficits in the ability to inhibit this dominant response tendency would be evident in greater errors and/or slower responses on BX trials. On AY trials, there is a strong expectation that a valid cue "A" will be followed by an "X" probe. Deficits in the ability to inhibit this expectancy bias would be manifested in greater errors and/or slower responses on AY trials.

The Present Study

Lorsbach and Reimer (2008) recently reported the results of an experiment that suggest children may have difficulty representing and/or maintaining goal information in the AX-CPT. Lorsbach and Reimer compared the performance of sixth-grade children (*M* age = 12 years) and young adults (*M* age = 22 years) on the AX-CPT using a 4,900-ms cue-probe delay. On BX trials, children committed more false alarms than young adults. Thus, children were less skilled in representing and maintaining the goal-related implications of invalid cues (B) and in using that information to inhibit the dominant tendency to make a target response to the "X" on BX trials. However, children were *faster* than young adults in the AY condition. The faster responses of children on AY trials suggest that they possess a deficit in the ability to represent and/or maintain goal information of the cue. Because of a deficit in the representation and/or maintenance of the cue's goal information, children did not have to overcome a strong bias that the letter "A" would be followed by the letter "X." In contrast, the slower responses of young adults suggest that they possessed greater ability to represent and maintain the goal information of the cue. Unfortunately, this ability came with a cost in that they needed more time to overcome the strong bias when presented with non-target probe "Y."

Although Lorsbach and Reimer (2008) found that, relative to young adults, sixth-grade children experienced greater difficulty representing and/or maintaining the cue's goal information during the AX-CPT, additional research is needed to compare the performance of sixth graders with that of younger children. Unfortunately, much of the previous developmental research on executive function has focused on early childhood, as opposed to middle childhood. Comparing third graders and sixth graders is important given that changes in executive functions, particularly inhibitory processes, have been found to be especially active during early and middle childhood (Anderson, 2002; Brocki & Bohlin, 2004; Levin et al., 1991; Williams, Ponesse, Schachar, Logan, & Tannock, 1999). Comparing younger and older children is also appropriate given that Braver et al. (2001)'s framework predicts that populations with dysfunctions in either the PFC or the DA system should be impaired in the representation and maintenance of goal information. The PFC is one of the last neuroanatomic structures to develop, reaching maturity during late adolescence (e.g., V. Anderson, 2001; Bunge, Dudukovic, Thomason, Vaidya, & Gabrieli, 2002; Casey, Giedd, & Thomas, 2000; Diamond, 2001; Zelazo & Müller, 2002). Similarly, the development of the DA system has been described as "protracted" (Diamond, 2001). Anderson (2002) observes that there are different periods of rapid growth in the frontal lobes, with one occurring between ages 7 and 9 years and another between ages 11 and 13 years, and that these growth spurts correspond to developmental changes in various executive functions. Given the importance of the PFC and DA systems in the representation and maintenance of goal-related context information, and based on the fact that the PFC and the DA systems do not reach maturity until late adolescence or early adulthood, it is reasonable to expect age-related improvements in the use of goal-related context information between the ages of 9 and 12 years.

Thus, the general purpose of the present study was to extend the recent investigation of Lorsbach and Reimer (2008) to a younger age group by examining whether third- and sixth-grade children differ in their ability to represent and/or maintain the goal-related information of context cues in the AX-CPT. Furthermore, the present study attempted to determine specifically whether age-related changes in performance on the AX-CPT are due to developmental differences in the ability to represent or differences in the ability to maintain the cue's goal information in the AX-CPT. The performance of third- and sixth-grade children is compared in two experiments that use different versions of the AX-CPT. Experiment 1 presents a standard version of the AX-CPT using a long (5,500 ms) cue-probe delay. Given the nature of the design used in Experiment 1, any observed age differences in performance would be based on the ability to represent and/or maintain the goal information of context cues. To determine whether developmental differences in Experiment 1 are related to processes that are specific to the representation or the maintenance of goal information, Experiment 2 shortens the cue-probe delay (1,000 ms) and also varies the identity (A or non-A) and color (red or green) of cues in the AX-CPT. Using a 1,000-ms cue-probe delay minimizes the amount of time a context representation must be held in working memory. In addition, systematically varying the features of letter cues is designed to vary the level of demand placed on the ability to represent context cues.

EXPERIMENT 1

Experiment 1 compares third- and sixth-grade children on the AX-CPT to determine whether there are developmental differences in the use of the goal-related information of context cues. If the ability to represent and/ or maintain goal information (context cues) improves with age, the performance of older children should reflect a greater expectation that valid cues (A) will be followed by targets (X). However, such an expectation should lead to costs (i.e., slower responses and/or more errors) on AY trials. In addition, if older children are more adept in the use of goal information, the representation and/or maintenance of context cues should result in the inhibition of the dominant tendency to make a target response to the X probe on BX trials. Thus, relative to younger children, older children should exhibit superior speed and/or accuracy of performance on BX trials but inferior performance (i.e., slower and/or less accurate) on AY trials. Such a pattern of results would provide evidence for the existence of developmental differences in the use of goal information in working memory.

Method

Participants. Participants were 30 third-graders ($M = 9.06$ years, $SD = .28$ years) and 24 sixth-graders ($M = 11.96$ years, $SD = .37$ years) who were recruited from an elementary school. None of the participants were receiving special education services.

Design. Age group (third grade vs. sixth grade) and trial type (AX, AY, BX, and BY) were manipulated in a mixed design, with trial type varied within participants. The dependent measures consisted of error rates and response times (RTs).

Apparatus and procedure. The apparatus and procedure were similar to that used by Lorsbach and Reimer (2008). Letters were presented sequentially in a continuous manner on a Dell laptop computer. Figure 1 presents a schematic overview of the events that occurred within each trial. E-Prime software (Schneider, Eschman, & Zuccolotto, 2002) was programmed to present the sequence of events within each trial and to record the accuracy and latency of each participant's response. Red letters were presented on a black background in the center of the monitor using 24-point uppercase Helvetica font. Each trial began with a cue (500 ms), followed by a blank screen (5,500 ms) representing the cue-probe delay, and ended with a letter probe (500 ms). A 2,000 ms-interval was used between trials and was filled with a blank computer screen. Target trials (AX) were defined as cue-probe sequences in which a valid letter cue (A) appeared and was followed immediately by the target probe letter (X). Non-target trials consisted of cue-probe sequences in which an invalid letter cue (i.e., letter cues other than the letter A) and/or a non-target probe (i.e., a letter other than the letter X) were presented. Because of their similarity to the target probe letter X, the letters K and Y were not used as non-target probes. There were three types of non-target 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 that is any letter other than A followed by a probe that is any letter other than X). The letter sequences were presented randomly, with target trials appearing 70% of the time and non-targets trials (AY, BX, and BY) appearing 30% of the time. Each of the non-target trial types occurred with equal frequency (10% each). Participants were instructed to respond to each letter by pressing one of two keys labeled "YES" (target) and "NO" (non-target) on the keyboard as quickly, but as accurately, as possible. Given that children were tested, the labels "YES" and "NO" were used rather than "target" and "non-target." Responses were made using two fingers of the same hand. Right-handed participants were instructed to respond with their right hand using their index finger for target trials (J key) and their middle finger for non-target 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 non-target trials (G key). The probe was presented for 500 ms and participants were given an additional 2,000 ms in which to respond. Responses that exceeded the 2,500-ms time limit were accompanied by a message appearing on the monitor reminding the participant to respond quickly and were excluded from analyses. Practice and test trials were presented 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, while the remaining four blocks were experimental trials. Practice trials were excluded from all analyses. Participants were given the opportunity to rest briefly between trial blocks.

Results and Discussion

Table 1 presents the mean error rates, RTs, and *z*-scores of third graders and sixth graders in the target (AX) and non-target (AY, BX, and BY) conditions. Trials in which correct RTs were <200 ms or >1,500 ms above or below the overall mean were excluded from the analyses (2.0% and 0.8% of trials for the third- and sixth-grade groups, respectively). Furthermore, data were excluded from the analyses for participants who failed to provide

TABLE 1
Mean Error Rates (%E), Correct Response Times (RT; in ms), and *z*-scores by Age Group and Trial Type in Experiment 1

	Trial type			
Age group	*AX*	*AY*	*BX*	*BY*
Third Grade				
%E	25.4 (22.0)	38.3 (28.5)	12.2 (14.7)	4.0 (4.7)
RT	556 (174)	648 (148)	621 (259)	556 (180)
z-score	−0.25 (0.17)	+0.67 (0.70)	−0.06 (0.60)	−0.18 (0.31)
Sixth Grade				
%E	12.7 (9.2)	43.0 (24.8)	8.2 (17.1)	4.2 (6.6)
RT	431 (111)	545 (79)	418 (129)	412 (110)
z-score	+0.31 (0.11)	+1.11 (0.82)	−0.36 (0.38)	−0.35 (0.30)

Note. Standard deviations are in parentheses.

at least one correct response in one or more of the critical conditions (AX, BX, AY). As a result, 3 third graders and 4 sixth graders were excluded from the analyses. Target and non-target responses were analyzed separately due to different response requirements (target button vs. non-target button press) and different numbers of trials (i.e., 84 AX target trials and 12 trials each for AY, BX, and BY non-target trials). As with previous studies that have used the AX-CPT paradigm (e.g., Braver et al., 2001, 2005; Lorsbach & Reimer, 2008), planned comparisons were used to test for age differences in the target and non-target conditions. An alpha level of .05 was used for all statistical tests in this and the subsequent experiment.

Following the convention of recent studies that have examined age differences on the AX-CPT (Braver et al., 2005; Paxton et al., 2006; Paxton et al., 2008), analysis of the speed of correct responses on target and non-target trials was based upon *z*-score transformations of RTs to correct for individual differences (including age-related changes) in the speed of processing on the AX-CPT. The computation of *z*-score transformations on each trial for a given participant began by calculating a mean RT and a standard deviation that were based on all of the correct trials for that participant. The RT for each trial was then standardized by subtracting the participant's mean RT and dividing by the participant's corresponding standard deviation. For each participant, median *z*-scores were then calculated in each condition and were used in the subsequent analyses. The median *z*-scores for each condition thus represent standardized deviations from the participant's global RT, with negative *z*-scores reflecting faster RTs and positive values reflecting slower RTs. The use of *z*-score transformations equates the global RTs of all participants with respect to their mean (0.0) and standard deviation (1.0).

The first set of analyses examined the accuracy and speed of performance of third- and sixth-grade children on target trials (AX). Third graders committed significantly more errors ($M = 25.4\%$) than sixth graders ($M = 12.7\%$), $t(52) = 2.637$, and the two groups did not differ in their *z*-transformed RTs. Consistent with previous research using the AX-CPT (e.g., Braver et al., 2001; Braver et al., 2005; Cohen, Barch, Carter, & Servan-Schreiber, 1999; Lorsbach & Reimer, 2008; Paxton et al., 2008), the analysis of performance accuracy also examined d′ context, 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). Because d′ context is computed using only BX false alarms, and not all types of false alarms (i.e., AY, BX, and BY), it is considered to provide a specific estimate of sensitivity to context (Cohen et al.). That is to say, d′ context provides a measure of one's ability to use prior context (A or non-A) to differentiate target and non-target responses to the letter X. Before calculating d′ scores, the hit and false alarm rates were corrected by adding .5 to each frequency and dividing by $N+1$, where N equals the number of AX or BX trials (Snodgrass & Corwin, 1988). Sixth-grade children produced significantly larger d′ context scores than third-grade children, Ms $= 2.564$ and 1.996 respectively, $t(52) = -2.801$. The larger d′ scores of sixth graders indicate that they were, relative to third graders, more proficient at using prior context information in their attempt to distinguish targets and non-targets. That is to say, the age differences in d′ context scores indicate that when presented with an X probe, sixth graders were more sensitive to the preceding context (i.e., A or non-A) than third graders.

Error rates on the non-target trials were submitted to a 2 (age group: third grade vs. sixth grade) × 3 (non-target trial type: AY, BX, BY) mixed design analysis of variance (ANOVA). Only the main effect of non-target trial type was significant, $F(2, 104) = 57.384$, $MSE = 357.847$. Post-hoc comparisons indicated that error rates in the AY ($M = 40.4\%$) condition were greater than those in the BX ($M = 10.4\%$) condition, which were in turn greater than those in the BY ($M = 4.1\%$) condition. Planned comparisons of errors rates did not reveal differences between third graders and sixth graders in the AY, BX, or BY non-target trial types, all ts $< |1|$.

The speed of correct responses on non-target trials were analyzed by submitting z-transformed RTs to a 2 (age group: third grade vs. sixth grade) × 3 (non-target trial type: AY, BX, BY) mixed-design ANOVA. The effect of non-target trial type was significant, $F(2, 104) = 68.085$, $MSE = .334$, and interacted with age group, $F(2, 104) = 6.297$, $MSE = .334$. Most importantly, planned comparisons of z-scores indicated that third and sixth graders differed significantly on each of the three types of non-target trials. The z-scores of sixth graders were significantly *lower* than that of third graders in the BX condition, $t(52) = 2.07$, ($M = -0.36$ and -0.06, respectively). In contrast, the z-scores of sixth graders were significantly *higher* than that of third graders in the AY condition, $t(52) = -2.158$ ($M = 1.11$ and 0.67, respectively). Finally, sixth graders produced significantly lower z-scores ($M = -0.35$) than third graders ($M = -0.18$) in the BY condition, $t(52) = 2.045$.

The pattern of z-scores on AY non-target trials is consistent with the hypothesis that developmental differences exist in the use of context processing. Although third and sixth graders exhibited comparable error rates on AY trials, the analysis of z-scores revealed age differences in the time needed to render correct rejections of non-targets (Y). Compared with sixth graders, the z-scores of third graders were significantly lower on AY trials, suggesting that the identity of the letter cue (A) did not bias their expectation about the probe as strongly as older children. The larger *z*-scores of sixth graders in the AY condition reflect the cost of overcoming the invalid expectation that a target letter (X) would follow the letter A. This cost reflects a stronger representation and/or maintenance of the goal information within the cue.

Similarly, performance on BX trials also suggests that sixth graders were able to represent and/or maintain cue information more effectively than third graders. Although third and sixth graders had comparable error rates on BX trials, the analysis of *z*-scores revealed age differences in the time needed to render correct rejections of non-targets (X). Compared with sixth graders, third graders' *z*-scores were significantly higher in the BX condition, suggesting that they experienced greater difficulty than sixth graders using the preceding context cue (B) to overcome the dominant tendency to make a target response to the letter X. Sixth graders, on the other hand, used the cue information and prepared themselves to make fast, non-target responses.

The results of the present experiment are consistent with the recent findings of Lorsbach and Reimer (2008) and provide further evidence of developmental differences in the use of goal information within context cues. Age-related improvements in the use of context were evident in each of these experiments when an older, more mature age group demonstrated that they were more skillful in representing and/or maintaining letter cues to prepare a response to a forthcoming probe in the AX-CPT. Due to the differential use of context information, the older comparison group in each experiment exhibited superior performance on AX and BX trials yet paradoxically "inferior" performance on AY trials. The pattern of these developmental differences is fully compatible, and indeed predictable, within the context-processing framework of Braver and his colleagues (Braver et al., 2007). In contrast to the developmental improvements in the use of context cues that we have observed on the AX-CPT, studies of adult aging have found that older adults experience an age-related decline in their ability to use context cues (A or non-A) to distinguish target (AX) and non-target (BX) responses to the X probe in the AX-CPT. In addition, relative to younger adults, older adults have greater difficulty inhibiting the strong tendency to respond "yes" to the X probe during BX trials. Finally, younger adults demonstrate the paradoxical result of being *slower* than older adults on AY trials.

Finally, it is important to note that although the pattern of results may be explained according to a theory that emphasizes the representation and/or maintenance of goal information (Braver et al., 2007), the results are difficult to explain in terms of a theory that focuses solely on inhibition (e.g., Diamond & Kirkham, 2005). That is to say, Braver et al.'s (2007) theory may account for the inferior performance of younger children on BX trials and their *superior* performance on AY trials, by attributing this pattern to developmental differences in the ability to represent and/or maintain the goal-related information. In contrast, the pattern of age differences that emerged on BX and AY trials poses a challenge for theories that focus on developmental differences in inhibitory processes (e.g., Diamond & Kirkham). Inhibitory theories would anticipate younger children performing more poorly on both BX and AY trials.

EXPERIMENT 2

Although the results of Experiment 1 provide evidence for the existence of developmental differences in context processing, the exact nature of those differences remains unclear. One possibility is that the results reflect age-related improvements in the ability to actively maintain context information during a relatively long (5 seconds) cue-probe delay. Another possibility is that the results of Experiment 1 may have been due to developmental differences in the ability to initially represent goal information. The AX-CPT was modified in Experiment 2 to examine these possible explanations.

One modification involved the length of time between the cue and the probe in the AX-CPT. Instead of using a 5,500 ms cue-probe delay, Experiment 2 used a relatively short (1,000 ms) delay to minimize the amount of time context representations must be maintained in working memory. If age differences in the AX-CPT are absent with a 1,000-ms cue-probe delay, it would suggest that the results of Experiment 1 were due to age-related improvements in the ability to actively maintain context representations during the longer (5 seconds) cue-probe delay.

A second modification in Experiment 2 involved varying two features of the cue: identity (A or non-A) and color (red or green). Four cue types were generated by systematically varying the identity and color of cues: A_{red}, A_{green}, B_{red}, and B_{green}[1] (where "B" represents any letter other than "A"). The red "A" (A_{red}) was the valid cue, whereas the three remaining cue types (A_{green}, B_{red}, B_{green}) were invalid.[2] Thus, a cue must contain both a valid identity (A) and a valid color (red) to be considered valid. Invalid cues, on the other hand, contained any one of the following combinations of

[1]Letter cues were presented in red or green font. The use of subscripts designates the color of the letter cues. For example, A_{red} indicates that a red letter A was presented.

[2]This was the case for half of the participants in each group. For the remaining participants, a green "A" (A_{green}) was the valid cue, whereas the three remaining cue-types (A_{red}, B_{green}, B_{red}) were invalid.

TABLE 2
Examples of Trial Types Used in Experiment 2

	Cue types			
Probe types	*Valid identity/ valid color*	*Valid identity/ invalid color*	*Invalid identity/ valid color*	*Invalid identity/ invalid color*
Target	$A_{red}X$	$A_{green}X$	$B_{red}X$	$B_{green}X$
Non-target	$A_{red}Y$	$A_{green}Y$	$B_{red}Y$	$B_{green}Y$

Note. Target trials presented a cue containing a valid identity and a valid color followed by a target probe (X). Non-target trials consisted of an invalid cue and/or a non-target probe (Y). Invalid cues contained an invalid identity and/or an invalid color. A valid cue was designated by a red letter "A" (A_{red}) for half of the participants in each age group. For the remaining participants, a valid cue was designated by a green letter "A" (A_{green}). This table presents only those cue-probe pairs that were used when a red letter "A" (A_{red}) was used as a valid cue.

identity and color: an invalid identity (B) and an invalid color (green), a valid identity (A) and an invalid color (green), or an invalid identity (B) and a valid color (red). By crossing the four cue types with the two probe types (X or Y), eight trial types were formed: $A_{red}X$, $A_{green}X$, $B_{red}X$, $B_{green}X$, $A_{red}Y$, $A_{green}Y$, $B_{red}Y$, and $B_{green}Y$. Examples of trial types used in Experiment 2 may be found in Table 2. Participants were instructed to press the "Yes" button only if an "X" followed a valid cue (A_{red}). Unless the cue contained *both* of the valid features, the cue was invalid and participants were instructed to press the non-target button regardless of the type of probe (X or Y). In summary, target trials consisted of valid cues (A_{red}) followed by an "X." The remaining seven trial types (see Table 2) were non-target trials because they contained an invalid cue and/or a non-target probe (Y).

Recall that the use of cue information in the AX-CPT depends, in part, upon the ability to transform the cue into a goal representation. Given that this transformation requires cognitive resources, systematically varying cue features allows context processing to be examined under conditions that place either low or high demands on the ability to represent context information. Low representational demands may be observed in four ($A_{red}X$, $A_{red}Y$, $B_{green}X$, $B_{green}Y$) of the eight trial types listed in Table 2. The $A_{red}X$ and $A_{red}Y$ trial types possess cues in which both their identity and color are valid, whereas $B_{green}X$ and $B_{green}Y$ trial types contain cues in which both their identity and color are each invalid. Each of these four trial types provides congruent information in that the identity and color information within a given cue are both valid or are both invalid. A correct response to the probe in these four trial types does not depend on forming a representation that includes both the cue's identity and color, because responding solely on the basis of a partial representation of the cue will suffice. That is to say, context representations that include only one of the cue's features would still produce a correct response to the following probe. For example, participants may respond correctly to the probe on A_{red} X trials even when they form a representation based only on the cue's identity or only its color. This is the case, because both the identity and color of these cues provide valid information in a somewhat redundant manner. Given the congruent nature of the cues in these four trial types (i.e., $A_{red}X$, $A_{red}Y$, $B_{green}X$, $B_{green}Y$), the representational demands on context processing are relatively low. At this point, it is important to note that these congruent trial types are comparable to the trial types presented in Experiment 1 in that in each case, successful context processing may be achieved by merely representing a single feature of the cue.

In contrast, controlled performance on the remaining four trial types listed in Table 2 ($A_{green}X$, $A_{green}Y$, B_{red} X, $B_{red}Y$) place high demands on representing context information. This is the case because controlled performance depends on one's ability to form a context representation that integrates or binds the identity and color features of the cue. In this case, the two cue types provide incongruent information in that the identity and color information within a cue are not consistent with each other (i.e., one feature is valid and the other is invalid). If a representation of the cue in one of these trial types is based on only a single feature, cognitive control will be impaired. For example, if a participant only forms a representation of the cue's identity, but not its color, a response to the probe would be based on partial information. As a result of this incomplete representation of the cue, the participant may use the cue's valid identity (A) but fail to use the cue's invalid color (green) on $A_{green}X$ trials and thereby fail to reject "X" probes. Conversely, if a participant represents the cue's color but not its identity, responses to the subsequent probe would likewise be based on incomplete information. As a result of representing the cue's valid color (red), but not its invalid identity (B) on B_{red} X trials, the participant may again fail to reject "X" probes. Therefore, failing to meet the relatively high representational demands of these incongruent trial types will compromise cognitive control on the AX-CPT.

As in Experiment 1, participants in Experiment 2 were third- and sixth-grade children. Participants were presented with a modified AX-CPT in which the color and the identity of cues were manipulated, and a short (1,000 ms) cue-probe delay was used. If the results of Experiment 1 were due solely to developmental differences in the ability to maintain context representations across a long (5,500 ms) cue-probe delay, those age differences should be absent when a short cue-probe delay is used in Experiment 2, regardless of whether cues contain congruent or incongruent features.

On the other hand, if the results of Experiment 1 were due only to age differences in the ability to represent, as opposed to maintain, context information, the performance of third- and sixth-grade children should differ on trials containing both congruent or incongruent cues. Furthermore, these age differences should be larger with trials containing incongruent cues where greater demands are placed on the ability to represent context information.

One additional possibility exists. It may be that age differences in context processing emerge only under more demanding conditions that impact either the representation or the maintenance of cues. If this explanation is accurate, the cognitive demands of requiring participants to actively maintain context representations during a long delay could have been responsible for the developmental differences observed in Experiment 1. Although using a 1,000-ms cue-probe delay in Experiment 2 will reduce the cognitive demands associated with holding a cue's representation in working memory, using cues with incongruous information alternatively places demands on the ability to represent context information. Relative to congruent cues, incongruent cues place greater demands on the ability to represent context information. Therefore, age differences should be found with trials containing incongruent, but not congruent, information. That is to say, the performance of third- and sixth-grade children should not differ on non-target trials requiring the representation of cues containing congruent information, either in the form of valid identity and valid color or invalid identity and invalid color: $A_{red}Y$, $B_{green}X$, and $B_{green}Y$. However, developmental differences should be found only with incongruent trials which require a context representation that includes both identity and color. Specifically, sixth graders should be faster and/or more accurate than third graders on non-target trials with incongruent cues, either in the form of valid identity and invalid color ($A_{green}X$, $A_{green}Y$) or invalid identity and valid color (B_{red} X, $B_{red}Y$).

Method

Participants. Participants were 30 third graders ($M = 8.75$ years, $SD = .46$ years) and 30 sixth graders ($M = 11.94$ years, $SD = .38$ years) who were recruited from an elementary parochial school. None of the participants were receiving special education services. Participants were screened for color vision deficiencies (Waggoner, 2002), and none were found to have difficulty with color discrimination.

Design. Age group (third grade vs. sixth grade) and trial type ($A_{red}X$, $A_{red}Y$, $B_{red}X$, $B_{red}Y$, $A_{green}X$, $A_{green}Y$, $B_{green}X$, and $B_{green}Y$) were manipulated in a mixed design, with trial type being varied within participants. The dependent measures consisted of error rates and correct RTs.

Apparatus and procedure. E-Prime software (Schneider et al., 2002) was used to present stimuli and record response accuracy and latency on a Dell laptop computer. The sequence depicted in Figure 1 was again used within each trial. Each trial began with a cue (500 ms), followed by a blank screen (1,000 ms) representing the cue-probe delay, and ended with a letter probe (500 ms). A 2,000-ms interval was used between trials and was filled with a blank computer screen.

Stimuli were presented in 28-point uppercase Arial font in the center of a computer monitor containing a black background. Cues were presented in either red or green lettering. However, only one of these two colors was considered valid for a given participant. Thus, for half of the participants, a valid cue was a red "A" (A_{red}), whereas for the remaining participants a valid cue was a green "A" (A_{green}). To control for unforeseen individual or group differences in the use of color, the color (red or green) of valid cues was used equally often across participants within each age group. Probes were always presented in white lettering.

Testing occurred in a single session that consisted of 250 trials that were divided into five blocks of 50 trials each. The first block represented practice trials, while the remaining four blocks served as experimental trials. Practice trials were excluded from all analyses. Practice and test trials were presented only after participants demonstrated their understanding of the procedure during an initial instructional activity that consisted of 13 "trials" exemplifying the target and non-target cue-probe combinations listed in Table 2. Each of the 50-trial blocks included 36 target trials (e.g., $A_{red}X$). The high frequency of target trials in each block (72% of all trials) was designed to create a bias to provide a target response whenever the "X" probe appeared. The 14 non-target trials comprised 28% of the trials. Thus, the 14 non-target trials in each block systematically varied the color and identity of cues: 2 $A_{red}Y$ trials, 2 $B_{red}X$ trials, 2 $B_{red}Y$ trials, 2 $A_{green}Y$ trials, 2 $B_{green}X$ trials, 2 $B_{green}Y$ trials, and 2 $A_{green}X$ trials. Other than the use of a short cue-probe delay, the procedure was the same as that used in Experiment 1.

Results and Discussion

Table 3 presents the mean error rates, RTs, and *z*-scores of third graders and sixth graders in both the target and non-target conditions. Trials in which RTs were <100 ms or $>1{,}000$ ms were removed from the analyses (2.1% and 0.6% of trials for the third- and sixth-grade groups, respectively). As with Experiment 1, data were excluded from the analyses for participants

TABLE 3

Mean Error Rates (%E), Correct Response Times (RT; in ms), and *z*-scores by Age Group and Trial Type in Experiment 2

	Trial type							
Age group	$A_{red}X$	$A_{red}Y$	$B_{red}X$	$B_{red}Y$	$A_{green}X$	$A_{green}Y$	$B_{green}X$	$B_{green}Y$
Third Grade								
%E	5.4 (3.3)	71.4 (24.0)	18.9 (20.6)	12.5 (13.4)	14.0 (17.2)	13.7 (14.2)	12.9 (16.1)	8.1 (13.5)
RT	362 (125)	637 (164)	390 (153)	394 (152)	384 (165)	377 (128)	401 (166)	398 (159)
z-score	−0.30 (0.12)	+1.89 (1.16)	−0.01 (0.52)	+0.18 (0.65)	−0.08 (0.63)	+0.05 (0.48)	+0.00 (0.54)	−0.02 (0.53)
Sixth Grade								
%E	3.8 (3.3)	61.8 (26.4)	11.9 (16.6)	6.7 (10.2)	7.9 (10.6)	4.0 (5.8)	8.2 (10.5)	6.1 (9.6)
RT	335 (105)	583 (138)	334 (134)	350 (132)	326 (132)	332 (129)	345 (145)	345 (127)
z-score	−0.26 (.14)	2.07 (.77)	−0.23 (.48)	−0.10 (.50)	−0.40 (.56)	−0.34 (.34)	−0.17 (.51)	−0.15 (.49)

Note. Standard deviations are in parentheses.

who failed to provide at least one correct response in one or more of the critical conditions (AX, BX, AY). Consequently, 3 third graders and 1 sixth grader were excluded from the analyses. As with Experiment 1, target and non-target trials were analyzed separately. Analysis of the speed of correct responses on target and non-target trials was again based on *z*-score transformations of RTs. Any differential effect of the two colors (i.e., red or green) used in presenting valid cues was not of interest. Therefore, type of valid cue (A_{red} or A_{green}) was collapsed across trial type and age group. Furthermore, because we were not interested in whether there are developmental differences in the ability to independently represent color or identity, the four non-target trials containing incongruent cues were collapsed for analysis into two non-target trial types. Specifically, data obtained from A_{green}X and B_{red} X trials were collapsed to form a single trial type: A_{green}/B_{red} X. Similarly, data obtained from A_{green}Y and B_{red}Y trials were collapsed to form a single trial type: A_{green}/B_{red}Y.

Error rates and RTs were analyzed for target and non-target trials and were analyzed separately for trials containing congruent and incongruent cues. The first set of analyses examined error rates and RTs on target trials (A_{red}X). In addition, the analysis of target error rates examined d′ context scores, an index of sensitivity to the preceding context. Because of the nature of the present design, d′ context scores were computed separately for BX trials containing congruent cue information (A_{red}X vs. B_{green}X), as well as for BX trials containing incongruent cue information (A_{red}X vs. A_{green}/B_{red} X). The second set of analyses examined performance on the non-target trials with congruent cues (A_{red}Y, B_{green}X, and B_{green}Y), followed by an analysis of non-target trials with incongruent cues (A_{green}/B_{red}X and A_{green}/B_{red}Y).

Target trials. Third graders committed more errors ($M = 5.4\%$) than sixth graders ($M = 3.8\%$) on target trials (A_{red}X), and this difference was marginally significant, $t(58) = -1.935$, $p = .058$. A comparison of *z*-transformed RTs (A_{red} X) indicated that third graders and sixth graders did not differ significantly in the speed with which they responded on target trials, $t(58) = -1.012$, $M = -0.30$ and -0.26, respectively. Thus, similar to Experiment 1, third- and sixth-grade children were again comparable in the speed with which they responded on target trials (AX). However, unlike Experiment 1 where third-grade children committed significantly more errors than sixth-grade children with target trials, age differences in error rates were only marginally significant in Experiment 2. This minor difference in the pattern of error rates between the two experiments was perhaps due to the use of different cue-probe delays, with Experiment 1 using a longer (5,500 ms) and Experiment 2 using a shorter (1,000 ms) cue-probe delay. The effect of the short cue-probe delay in Experiment 2 greatly reduced the cue maintenance demands of the task and therefore may have resulted in a marginally significant effect of age group on the error rate data.

A measure of d′ context was calculated that compared the proportion of trials in which a participant used valid cues (A_{red}) to correctly identify a target probe (X), relative to the proportion of trials in which the participant failed to use invalid cues with *congruent* features (B_{green}) and consequently falsely identified the probe as a target. The difference between third- and sixth-grade d′ context scores only approached significance, $t(58) = -1.922$, $p = .059$, $M = 2.74$ and 3.08, respectively. Context sensitivity was also analyzed on trials containing *incongruent* cue information by comparing the proportion of trials in which a participant used a valid cue (A_{red}) to correctly identify a target probe (X), relative to the proportion of trials in which the participant failed to use a cue possessing incongruent information (A_{green}/B_{red}) to reject the probe (X). Sixth graders produced significantly larger d′ scores than third graders, $t(58) = -2.257$, $M = 3.34$ and 3.00, respectively.

Although developmental differences were evident in d′ scores with cues containing both congruent and incongruent information, it is important to note that the effect of age group was statistically significant only when invalid cues with incongruent information were used in the calculation of d′. Furthermore, the size of the age group effect on trials with invalid cues containing incongruent information ($\eta^2 = .081$) was slightly larger than that found on trials with congruent information ($\eta^2 = .06$). While only suggestive, these results are consistent with the claim that representational demands are increased with invalid cues possessing incongruent information.

Non-target trials: Congruent cues. Error rates on non-target trials containing congruent cues were computed for each participant and submitted to a 2 (age group: third grade vs. sixth grade) × 3 (trial type: $A_{red}Y$, $B_{green}X$, and $B_{green}Y$) mixed-design ANOVA. Only the main effect of trial type was significant, $F(2,116) = 251.08$, MSE = .027. Post-hoc comparisons indicated that the error rates in $A_{red}Y$ trials ($M = 66.6\%$) were higher than either $B_{green}X$ ($M = 10.5\%$) and $B_{green}Y$ ($M = 7.1\%$) trials, but the latter two trial types did not differ from each other. There was no effect of age group, $F(2,58) = 3.101$, MSE = .042, $p = .084$, nor did it interact with trial type ($F < 1$). More importantly, planned comparisons confirmed that there were no age differences on $A_{red}Y$, $t(58) = -1.469$, $p = .147$, $B_{green}X$, $t(58) = -1.319$, $p = .192$, and $B_{green}Y$, $t < |1|$, trial types.

The z-transformed RTs on non-target trials containing congruent cues were computed for each participant and submitted to a 2 (age group: third grade vs. sixth grade) $\times$ 3 (trial type: $A_{red}Y$, $B_{green}X$, and $B_{green}Y$) mixed-design ANOVA. There was a significant effect of trial type, $F(2,116) = 152.735$, $MSE = .558$. Post-hoc comparisons indicated that z-scores on $A_{red}Y$ trials ($M = 1.98$) were significantly higher than z-scores on $B_{green}X$ ($M = -0.09$) and $B_{green}Y$ ($M = -0.09$), but the latter two trial types did not differ from each other. The effect of age group was not significant, nor did it interact with trial type (both Fs < 1). Similarly, the z-transformed RTs of third and sixth graders were not statistically different on the $A_{red}Y$, $t < |1|$, $B_{green}X$, $t(58) = -1.213$, $p = .23$, and $B_{green}Y$, $t < |1|$, non-target conditions.

The results of the analysis of non-target trials containing congruent features indicates that third- and sixth-grade children do not differ significantly on either accuracy or speed of performance. The absence of age differences on non-target trials containing congruent features indicates that the cognitive control of younger and older children is comparable when the demands on context processing are low, both in terms of representation (i.e., congruent cues) and maintenance (i.e., 1,000-ms cue-probe delay).

When these results are considered along with those of Experiment 1, it suggests that the age effects on non-target trials in Experiment 1 were due to developmental differences in the ability to maintain, as opposed to represent, context representations. This conclusion is based on the previous observation that the trial types used in Experiment 1 and the congruent trial types in this experiment are comparable in that successful context processing in each case may be achieved by representing a single feature of the cue. What differentiates these two experiments is the length of the cue-probe delay. The longer cue-probe delay in Experiment 1 placed demands on context maintenance, whereas the short cue-probe delay in this experiment greatly reduced or eliminated those demands. Therefore, the fact that age differences were absent with congruent non-target trials in the current experiment suggests that the age differences found with non-target trials in Experiment 1 were due to developmental differences in the ability to maintain context representations.

It is important to note, however, that although successful performance may be based on the processing of a single feature in congruent trial types, children were instructed to process both color and identity. To the extent that participants processed both color and identity, the representational demands of congruent trial types of Experiment 2 were actually greater than those of Experiment 1. However, differences in representational demands between the two experiments cannot account for the observed pattern of results. If representational demands were responsible for the developmental differences in Experiment 1, age differences should have been yet greater in Experiment 2 where representational demands were increased. The fact that developmental differences were observed in Experiment 1 under conditions that had fewer representational demands than Experiment 2 actually provides additional support to the conclusion that the results of Experiment 1 were due to age-related differences in the maintenance of context representations.

Non-target trials: Incongruent cues. Error rates on non-target trials containing incongruent cues were computed for each participant and submitted to a 2 (age group: third grade vs. sixth grade) × 2 (trial type: $A_{green}/B_{red}X$ vs. $A_{green}/B_{red}Y$) mixed-design ANOVA. The main effect of age group was significant, $F(1, 58) = 8.477$, MSE = .018, with third graders committing more errors ($M = 14.6\%$) than sixth graders ($M = 7.5\%$). There was also a significant effect of trial type, $F(1, 58) = 6.979$, MSE = .006, with more errors being observed with $A_{green}/B_{red}X$ ($M = 13.0\%$) than with $A_{green}/B_{red}Y$ ($M = 9.1\%$) trial types. Most importantly, planned comparisons of the two age groups were performed on error rates separately for both $A_{green}/B_{red}X$ and $A_{green}/B_{red}Y$ trial types. Differences in error rates between third and sixth graders in the $A_{green}/B_{red}X$ condition were marginally significant, $t(58) = -1.932$, $p = .058$, $M = 16.5$ and 9.9, respectively. However, the comparison of the two age groups in the $A_{green}/B_{red}Y$ condition indicated that third graders made significantly more errors than sixth graders, $t(58) = -3.485$, $M = 13.1\%$ and 5.3%, respectively.

The z-transformed RTs on non-target trials containing incongruent cues were computed for each participant and submitted to a 2 (age group: third grade vs. sixth grade) × 2 (trial type: $A_{green}/B_{red}X$ vs. $A_{green}/B_{red}Y$) mixed-design ANOVA. The effects of age group, $F(1,58) = 9.429$, MSE = .298, and trial type, $F(1,58) = 7.496$, MSE = .064, .064, were each significant, with third graders producing higher z-scores ($M = 0.04$) than sixth graders ($M = -0.27$), and $A_{green}/B_{red}X$ trial types yielding lower z-scores than $A_{green}/B_{red}Y$ trial types, $M = -0.18$ and $M = -0.05$, respectively. Most importantly, planned comparisons of the two age groups were also performed on z-transformed RTs, separately for both $A_{green}/B_{red}X$ and $A_{green}/B_{red}Y$ trial types. Significant age differences were present in z-transformed RTs on $A_{green}/B_{red}X$ trials, $t(58) = 2.436$, with third graders exhibiting higher z-scores ($M = -0.05$) than sixth graders ($M = -0.32$). Third graders also produced significantly higher z-scores than sixth graders in the $A_{green}/B_{red}Y$ condition, $t(58) = 3.158$, $M = 0.13$ and -0.22, respectively.

Difficulties with the representational demands of incongruent cues were apparent in the performance of third graders in the $A_{green}/B_{red}Y$ condition.

Higher false alarm rates indicated that when compared with sixth graders, third graders more frequently represented invalid cues (A_{green}/B_{red}) as valid (A_{red}). The use of invalid cue information as valid by third graders was likely the result of only forming a partial representation of the cue. In contrast, the lower false alarm rates of sixth graders in the $A_{green}/B_{red}Y$ condition reflect an age-related increase in the ability to form a complete representation of the cue that included both valid and invalid information. As a result of forming a bound representation of both valid *and* invalid cue information, sixth graders used the invalid cue and consequently avoided generating strong expectations that a target letter (X) would follow. The lower expectations of sixth graders in the $A_{green}/B_{red}Y$ condition are reflected in reduced false alarm rates.

Developmental differences in the ability to represent context cues under more demanding conditions were also apparent in the analysis of z-scores in the $A_{green}/B_{red}Y$ condition. Again, assuming that third graders accepted invalid cues (A_{green}/B_{red}) as valid (A_{red}), they would have used invalid cues (A_{green}/B_{red}) to generate the expectation that a target letter (X) would follow. When they were able to correctly reject non-target probes in the $A_{green}/B_{red}Y$ condition, the higher z- scores of third graders indicate that they needed more time to overcome the invalid expectation that a target (X) would appear. On the other hand, assuming that sixth graders did not represent A_{green}/B_{red} cues as valid (A_{red}), they did not anticipate the appearance of a target letter (X) and the need to make a target response. Thus, lower z-scores of sixth graders were the result of correctly representing A_{green}/B_{red} cues as invalid and the expectation of a non-target letter.

With respect to the $A_{green}/B_{red}X$ trials, third graders committed more errors than sixth graders. Although these differences were only marginally significant, it suggests that third graders experienced greater difficulty using cues containing incongruent features to inhibit the dominant tendency to respond "Yes" to the letter X. This interpretation is confirmed in the analysis of the z-scores in the $A_{green}/B_{red}X$ condition where third graders produced significantly higher z-scores than sixth graders. The higher z- scores of third graders indicate that they experienced greater difficulty using the invalid information contained in incongruent cues to correctly reject the dominant tendency to respond "Yes" to the X probe. In contrast, the lower z-scores of sixth graders reflect faster responses, indicating they were better able to use the invalid component of incongruent cue information to correctly inhibit a pre-potent response to the letter X. When considered along with the absence of age differences on non-target trials containing congruent features, the presence of age differences of non-target trials with incongruent features indicates that developmental differences in cognitive control are most evident when the representational demands on context processing are high.[3]

GENERAL DISCUSSION

The present study examined whether younger and older children differ in their ability to represent and/or maintain the goal-related information of context cues within a continuous processing task. Recall that performance on the AX-CPT requires representing and maintaining the cue's information so that a fast and accurate response may be made to the subsequent probe. Attending to the goal representation of a valid cue leads to benefits (i.e., greater speed and/or accuracy) on AX trials as well as costs (i.e., slower and/or less accurate) on AY trials. In addition, the use of invalid cues (B) allows one to inhibit the dominant tendency to provide a target response to the letter X. Experiment 1 compared third- and sixth-grade children in their ability to transform the identity of letter cues (A or non-A) into goal representations, as well as to sustain those goal representations during a long (5,500 ms) cue-probe delay. Relative to younger children, older children were better able to represent and maintain goal-related information within the letter cues. Consequently, older children displayed a greater expectation that a valid cue (A) would be followed by a target (X). Although this expectancy bias led older children to experience greater benefits on AX trials, this bias was accompanied by costs on AY trials. In addition, older children were found to be more proficient in using invalid cues (B) to inhibit the dominant tendency to make a target response to the X probe on BX trials. The results of Experiment 1 indicate that older children were superior to younger children in their ability to represent and/or maintain the goal information of context cues in the AX-CPT.

In contrast to the long cue-probe delay (5,500 ms) in Experiment 1, Experiment 2 used a short cue-probe delay (1,000 ms) and thereby greatly reduced the demands of maintaining goal representations in working

[3]Although the shorter cue-probe delay (1,000 ms) used in Experiment 2 reduced the cognitive demands associated with maintaining a cue's representation, it may also have shortened the amount of time available for processing cue information. Given that younger children are slower to process information than older children, a shorter cue-probe delay may have had an adverse effect on the ability of third graders to represent cues. Thus, it is not entirely clear whether third graders' difficulty in representing incongruent, as opposed to congruent, cues was the result of a deficit in forming a bound representation or a deficit in the speed of executing the required operations in forming a bound representation. In either case, the present results support the claim that younger children have greater difficulty representing the goal information of context cues.

memory. In addition, Experiment 2 varied the level of demand that was placed on the ability to represent context information by systematically varying cue features in terms of their identity and color. Developmental differences were observed in context processing only under conditions that placed high demands on the ability to represent the goal-related information of context cues. More specifically, sixth graders were superior to third graders on non-target trials containing incongruent, but not congruent, cues. Together, the results of these experiments lead to the conclusion that differences in cognitive control between third- and sixth-grade children emerge only under more demanding conditions that affect the representation or the maintenance of goal-related information.

The present results are compatible with those of two recent studies that examined the representation (Towse et al., 2007) and maintenance (Marcovitch et al., 2007) of goal information in younger children. Recall that Towse and his associates varied the salience of instructional cues (color patch vs. directive arrow) that were presented in a goal-neglect task and found that the less salient cues led to greater goal neglect in younger children. Similarly, the configuration of cues in the present study had an effect on the goal-directed behavior of third- and sixth-grade children. In this case, cue configuration had a differential effect on the cognitive control of younger and older children, with sixth graders demonstrating greater control than third graders when presented with incongruent but not congruent cues. Using a version of the DCCS in which there was a high proportion (80%) of "redundant" post-switch test cards, Marcovitch et al. found that goal neglect in preschoolers may be attributed to a failure to maintain goals and attend to the rules of a task. Likewise, the current study found that the ability to hold cue information in working memory differentiates the controlled performance of third- and sixth-grade children. Thus, the development of cognitive control depends on growth of the ability to represent and maintain goal-related information in working memory. That is to say, whether a given task reveals developmental differences in cognitive control appears to depend on the salience of informational cues, as well as the amount of time those cues must be actively maintained in working memory.

The results of Marcovitch et al. (2007) and Towse et al. (2007) have demonstrated that goal representation and maintenance are each important in the development of cognitive control in children. Unfortunately, as observed by Marcovitch et al., there are currently no theories that address the importance of goal maintenance (and representation) in the development of cognitive control in children. Although originally intended to explain age-related declines in the cognitive control of healthy older adults (Braver et al., 2001), Braver et al.'s (2007) theory can account for the age differences that were observed in the ability to represent and maintain goal-related information of context cues in the current study. Braver et al. (2007)'s theory indicates that cognitive control depends upon the ability to represent and maintain the goal-related information of context cues in a form that allows one to respond appropriately to a forthcoming event. The ability to represent and maintain the goal-related information of context cues is presumably tied to underlying neurobiological mechanisms, such as the lateral PFC and the DA neurotransmitter system (Braver et al., 2007). Manipulating the demands placed on the ability to represent the context cue revealed that, relative to sixth graders, third graders are immature in their ability to transform the goal-related information of a context cue into a representation that allows them to control their response to a forthcoming stimulus. Similarly, the manipulation of the cue-probe delay indicates that younger children are not as proficient as older children in their ability to maintain goal-related information of context cues in working memory for longer periods of time. The application of Braver et al. (2007)'s theory is further supported by the fact that those neurobiological mechanisms (lateral PFC and DA system) that underlie the decline of cognitive control in older adults also develop as children grow older (Diamond, 2001).

Given the appropriateness of Braver et al. (2007)'s theory for explaining developmental differences in the representation and maintenance of task goals in middle childhood, an important extension of the present study would be to use the context processing framework to examine cognitive control in preschoolers. One possibility would be to adapt the AX-CPT so that it is appropriate for use with preschoolers. The AX-CPT would not only have to be shortened but perhaps would also have to include non-alphabetic stimuli. Finding that preschoolers differ from older children in their ability to represent and/or maintain the goal-related information of context cues may provide an interesting alternative to existing theories (e.g., Diamond, 2006; Munakata, 2001; Zelazo & Frye, 1997, 1998) that have attempted to identify those cognitive mechanisms responsible for developmental improvements in cognitive control.

Strategy Use in the AX-CPT

Recently, Braver and his colleagues (Braver et al., 2007; Paxton et al., 2008) have argued that two different strategies may be used by participants during the AX-CPT. One strategy, referred to as *proactive* control, is a form of top-down cognitive control that represents and actively maintains context information to prepare the system to respond appropriately to forthcoming events. This proactive strategy captures how goal-directed attention has been portrayed thus far in the present study. As previously indicated, representing and actively maintaining the goal-related information of cues during the AX-CPT leads to benefits (i.e., greater speed and accuracy on "AX" trials), as well as costs[4] (i.e., slower and less accurate on "AY" trials). In addition, proactively attending to invalid cues (B) enhances performance on BX trials by inhibiting the dominant tendency to make a target response to "X" on BX trials.

The second strategy identified by Braver et al. (2007) is referred to as *reactive* control. Participants using a reactive approach to the AX-CPT give only minimal attention to the cue when it is presented. Because the context information of the cue is represented in only a transient manner, it decays rapidly over time during the cue-probe delay. Participants using a reactive strategy presumably wait for the probe to appear, reactivate the goal information contained within the cue, and then use that information as they attempt to respond appropriately to the probe. Given that cues are not used to prepare a response to the upcoming probe, participants using a reactive strategy have fewer expectations about the upcoming probe and consequently display fewer costs on AY trials. However, costs associated with using a reactive approach appear in the BX condition. If participants are unable to access the cue's representation, they fail to inhibit the dominant tendency to make a target response. In those instances where they are able to reactivate the cue, correctly inhibiting the tendency to make a target response occurs slowly because of the additional time needed to reactivate the cue.

The distinction between proactive and reactive control strategies on the AX-CPT leads to an alternate explanation for the current results. Specifically, although the ability to represent and maintain context information may have been comparable in third and sixth graders, each age group may have used different strategies. For example, third graders may have used a reactive strategy, whereas sixth graders may have used a proactive strategy. This alternate account contrasts with our position that, although both younger and older children were attempting to be proactive, younger children were less efficient because of deficits in the ability to represent and maintain context information. Unfortunately, the results of Experiment 1 alone cannot distinguish between these two accounts. However, when the results of Experiment 1 are considered along with those of Experiment 2, we do not believe they are consistent with the explanation that younger and older children were engaged in different strategies. In particular, the performance of third and sixth graders in Experiment 2 were comparable when congruent cues were used but not when incongruent cues were presented. If

[4]The notion that proactive control has associated costs is somewhat similar to the idea that preparatory attentional processes consume limited conscious resources in Smith et al.'s theory of prospective memory (Smith, 2003; Smith, Hunt, McVay, & McConnell, 2007).

the developmental differences found with the incongruent cues of Experiment 2 were due to the differential use of proactive and reactive cognitive control strategies, it is unclear why those differences were not also found with congruent cues.

Conclusions

The results of the present study advance our understanding of those variables that may produce developmental differences in cognitive control. More specifically, the current study demonstrates that children improve in their ability to represent and maintain the goal-related information of context cues under more demanding conditions during middle childhood. These findings are compatible with recent studies that have attempted to identify variables that may lead children to neglect to perform a task's goal, despite their knowledge and understanding of the goal (Marcovitch et al., 2007; Towse et al., 2007).

ACKNOWLEDGEMENTS

The research reported in this article was supported by Grant 1 R15 HD052541 from the National Institute of Child Health and Human Development.

Portions of this research were presented at the fifth biennial meeting of the Cognitive Development Society in Santa Fe, NM, October, 2007, and the annual meeting of the Psychonomic Society, Chicago, IL, 2008.

The authors thank Kayla Koeber and Tiffany Ackerman for their help with data collection.

REFERENCES

Anderson, P. (2002). Assessment and development of executive function (EF) during childhood. *Child Neuropsychology*, *8*, 71–82.

Anderson, V. (2001). Assessing executive functions in children: Biological, psychological, and developmental considerations. *Pediatric Rehabilitation*, *4*, 119–136.

Barch, D. M., Carter, C. S., Braver, T. S., Sabb, F. W., MacDonald, A., III, Noll, D. C., et al. (2001). Selective deficits in prefrontal cortex function in medication-naïve patients with schizophrenia. *Archives of General Psychiatry*, *58*, 280–288.

Bjorklund, D. F. (2000). *Children's thinking: Developmental function and individual differences*. Belmont, CA: Wadsworth.

Bjorklund, D. F., & Harnishfeger, K. K. (1995). The evolution of inhibition mechanisms and their role in human cognition. In F. N. Dempster & C. J. Brainerd (Eds.), *Interference and inhibition in cognition* (pp. 142–175). New York: Academic Press.

Blair, C., Zelazo, P. D., & Greenberg, M. (2005). The assessment of executive function in early childhood: Prospects and progress. *Developmental Neuropsychology*, *28*, 561–571.

Botvinick, M. M., Braver, T. S., Barch, D. M., Carter, C. S., & Cohen, J. D. (2001). Conflict monitoring and cognitive control. *Psychological Review*, *108*, 624–652.

Braver, T. S., & Barch, D. M. (2002). A theory of cognitive control, aging cognition, and neuromodulation. *Neuroscience and Biobehavioral Reviews*, *26*, 809–817.

Braver, T. S., Barch, D. M., Keys, B. A., Carter, C. S., Cohen, J. D., Kaye, J. A., et al. (2001). Context processing in older adults: Evidence for a theory relating cognitive control to neurobiology in healthy aging. *Journal of Experimental Psychology: General*, *130*, 746–763.

Braver, T. S., & Cohen, J. D. (2000). On the control of control: The role of dopamine in regulating prefrontal function and working memory. In S. Monsell & J. Driver (Eds.), *Attention and performance XVIII* (pp. 713–738). Cambridge, MA: MIT Press.

Braver, T. S., & Cohen, J. D. (2001). Working memory, cognitive control, and the prefrontal cortex: Computational and empirical studies. *Cognitive Processing*, *2*, 25–55.

Braver, T. S., Cohen, J. D., & Barch, D. M. (2002). The role of the prefrontal cortex in normal and disordered cognitive control: A cognitive neuroscience perspective. In D. T. Stuss & R. T. Knight (Eds.), *Principles of frontal lobe function* (pp. 428–448). Oxford, England: Oxford University Press.

Braver, T. S., Gray, J. R., & Burgess, G. C. (2007). Explaining the many varieties of working memory: Dual mechanisms of cognitive control. In A. Conway, C. Jarrold, M. Kane, A. Miyake, & J. N. Towse (Eds.), *Variation in working memory* (pp. 76–106). New York: Oxford University Press.

Braver, T. S., Satpute, A. B., Rush, B. K., Racine, C. A., & Barch, D. M. (2005). Context processing and context maintenance in healthy aging and early-stage dementia of the Alzheimer's Type. *Psychology and Aging*, *20*, 33–46.

Brocki, K. C., & Bohlin, G. (2004). Executive functions in children aged 6 to 13: A dimensional and developmental study. *Developmental Neuropsychology*, *26*, 571–593.

Bunge, S. A., Dudukovic, N. M., Thomason, M. E., Vaidya, C. J., & Gabrieli, J. D. E. (2002). Immature frontal lobe contributions to cognitive control in children: Evidence from fMRI. *Neuron*, *33*, 301–311.

Casey, B. J., Giedd, J. N., & Thomas, K. M. (2000). Structural and functional brain development and its relation to cognitive development. *Biological Psychology*, *54*, 241–257.

Cohen, J. D., Barch, D. M., Carter, C., & Servan-Schreiber, D. (1999). Context-processing deficits in schizophrenia: Converging evidence from three theoretically motivated cognitive tasks. *Journal of Abnormal Psychology*, *108*, 120–133.

Dempster, F. N. (1992). The rise and fall of the inhibitory mechanism: Toward a unified theory of cognitive development and aging. *Developmental Review*, *12*, 45–75.

Diamond, A. (2001). A model system for studying the role of dopamine in prefrontal cortex during early development in humans. In C. Nelson & M. Luciana (Eds.), *Handbook of developmental cognitive neuroscience* (pp. 433–472). Cambridge, MA: MIT Press.

Diamond, A. (2006). The early development of executive functions. In E. Bialystok & F. I. M. Craik (Eds.), *Lifespan cognition: Mechanisms of change* (pp. 70–95). New York: Oxford University Press.

Diamond, A., & Kirkham, N. (2005). Not quite as grown-up as we like to think: Parallels between cognition in childhood and adulthood. *Psychological Science*, *16*, 291–297.

Duncan, J., Emslie, H., Williams, P., Johnson, R., & Freer, C. (1996). Intelligence and the frontal lobe: The organization of goal-directed behavior. *Cognitive Psychology*, *30*, 257–303.

Garon, N., Bryson, S. E., & Smith, I. M. (2008). Executive function in preschoolers: A review using an integrative framework. *Psychological Bulletin*, *134*, 31–60.

Harnishfeger, K. K., & Bjorklund, D. F. (1993). The ontogeny of inhibition mechanisms: A renewed approach to cognitive development. In M. L. Howe & R. P. Pasnak (Eds.), *Emerging themes in cognitive development: Vol. 1. Foundations* (pp. 28–49). New York: Springer-Verlag.

Hasher, L., & Zacks, R. T. (1988). Working memory, comprehension, and aging: A review and a new view. In G. H. Bower (Ed.), *The psychology of learning and motivation: Advances in research and theory* (Vol. 22, pp. 193–225). San Diego, CA: Academic Press.

Lane, D. M., & Pearson, D. A. (1982). The development of selective attention. *Merrill-Palmer Quarterly*, *28*, 317–337.

Levin, H. S., Culhane, K. A., Hartmann, J., Evankovich, K., Mattson, A. J., Harward, H., et al. (1991). Developmental changes in performance on tests of purported frontal lobe functioning. *Developmental Neuropsychology*, *7*, 377–395.

Lorsbach, T. C., & Reimer, J. F. (2008). Context processing and cognitive control in children and young adults. *The Journal of Genetic Psychology*, *169*(1), 34–50.

Marcovitch, S., Boseovski, J. J., & Knapp, R. (2007). Use it or lose it: Examining preschoolers' difficulty in maintaining and executing a goal. *Developmental Science*, *10*, 559–564.

Miller, E. K., & Cohen, J. D. (2001). An integrative theory of prefrontal cortex function. *Annual Review of Neuroscience*, *21*, 167–202.

Munakata, Y. (2001). Graded representations in behavioral dissociations. *TRENDS in Cognitive Sciences*, *5*, 309–315.

Oberauer, K. (2005). Executive functions, working memory, verbal ability, and theory of mind — Does it all come together? In W. Schneider, R. Schumann-Hengsteler, & B. Sodian (Eds.), *Young children's cognitive development: Interrelationships among executive functioning, working memory, verbal ability, and theory of mind* (pp. 285–299). Mahwah, NJ: Lawrence Erlbaum Associates.

O'Reilly, R. C., Braver, T. S., & Cohen, J. D. (1999). A biologically based computational model of working memory. In A. Miyake & P. Shah (Eds.), *Models of working memory: Mechanisms of active maintenance and executive control* (pp. 102–134). New York: Cambridge University Press.

Paxton, J. L., Barch, D. M., Racine, C. A., & Braver, T. S. (2008). Cognitive control, goal maintenance, and prefrontal function in healthy aging. *Cerebral Cortex*, *18*, 1010–1028.

Paxton, J. L., Barch, D. M., Storandt, M., & Braver, T. S. (2006). Effects of environmental support and strategy training on older adults' use of context. *Psychology and Aging*, *21*, 499–509.

Ruff, H. A., & Lawson, K. R. (1990). Development of sustained, focused attention in young children's free play. *Developmental Psychology*, *26*, 85–93.

Rush, B. K., Barch, D. M., & Braver, T. S. (2006). Accounting for cognitive aging: Context processing, inhibition, or processing speed? *Aging, Neuropsychology, and Cognition*, *13*, 588–610.

Schneider, W., Eschman, A., & Zuccolotto, A. (2002). *E-Prime user's guide*. Pittsburgh, PA: Psychology Software Tools.

Smith, R. E. (2003). The cost of remembering to remember in event-based prospective memory: Investigating the capacity demands of delayed intention performance. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *29*, 347–361.

Smith, R. E., Hunt, R. R., McVay, J. C., & McConnell, M. D. (2007). The cost of event-based prospective memory: Salient target events. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *33*, 734–746.

Snodgrass, J. G., & Corwin, J. (1988). Pragmatics of measuring recognition memory: Applications to dementia and amnesia. *Journal of Experimental Psychology: General*, *117*, 34–50.

Towse, J. N., Lewis, C., & Knowles, M. (2007). When knowledge is not enough: The phenomenon of goal neglect in preschool children. *Journal of Experimental Child Psychology*, *96*, 320–332.

Waggoner, T. L. (2002). *Color vision made easy*. Elgin, IL: Goodlite Company.
Williams, B. R., Ponesse, J. S., Schachar, R. J., Logan, G. D., & Tannock, R. (1999). Development of inhibitory control across the life span. *Developmental Psychology*, *35*, 205–213.
Zelazo, P. D., & Frye, D. (1997). Cognitive complexity and control: A theory of the development of deliberate reasoning and intentional action. In M. Stamenov (Ed.), *Language structure, discourse, and the access to consciousness* (pp. 113–153). Amsterdam: John Benjamins.
Zelazo, P. D., & Frye, D. (1998). Cognitive complexity and control: The development of executive function. *Current Directions in Psychological Science*, *7*, 121–126.
Zelazo, P. D., & Müller, U. (2002). Executive function in typical and atypical development. In U. Goswami (Ed.), *Blackwell handbook of childhood cognitive development* (pp. 445–469). Malden, MA: Blackwell Publishers, Inc.
Zelazo, P. D., Müller, U., Frye, D., & Marcovitch, S. (2003). The development of executive function in early childhood. *Monographs of the Society for Research in Child Development*, *68*(3, Serial No. 274).