Received: 7 May 2019 | Revised: 6 February 2020 | Accepted: 7 February 2020

DOI: 10.1111/desc.12959

SHORT REPORT

Developmental Science WILEY

Changes in working memory influence the transition from reactive to proactive cognitive control during childhood

Sonya V. Troller-Renfree | **George A. Buzzell** | **Nathan A. Fox**

Department of Human Development and Quantitative Methodology, University of Maryland, College Park, MD, USA

Correspondence
Sonya V. Troller-Renfree, 525 West 120th St., Russell 21I, New York, NY 10027, USA.
Email: troller-renfree@tc.columbia.edu

Funding information
This study was funded by a National Science Foundation Graduate Research Fellowship awarded to STR, Society for Research in Child Development (SRCD) SECC Dissertation Funding Award awarded to STR, Charles Beaumont Dissertation Award in Human Development awarded to STR, and Support Program for Advancing Research and Collaboration Grant from the University of Maryland awarded to STR. Authors disclose no other conflicts of interest.

Abstract

Cognitive control develops rapidly over the first decade of life, with one of the dominant changes being a transition from reliance on 'as-needed' control (reactive control) to a more planful, sustained form of control (proactive control). Although the emergence of proactive control is important for mature behavior, we know little about how this transition takes place, the neural correlates of this transition, and whether development of executive functions influences the ability to adopt a proactive control strategy. This study addresses these questions, focusing on the transition from reactive to proactive control in a cross-sectional sample of 79 children—forty-one 5-year-olds and thirty-eight 9-year-olds. Children completed an adapted version of the AX-Continuous Performance Task while electroencephalography was recorded and a standardized executive function battery was administered. Results revealed 5-year-olds predominantly employed reactive strategies, whereas 9-year-olds used proactive strategies. Use of proactive control was predicted by working memory ability, above and beyond other executive functions. Moreover, when enacting proactive control, greater increases in neural activity underlying working memory updating were observed; links between working memory ability and proactive control strategy use were mediated by such neural activity. These results provide convergent evidence that the transition from reactive to proactive control may be dependent on age-related changes in neurocognitive indices of working memory and that working memory may influence adopting a proactive control strategy.

KEYWORDS

cognitive control, event-related potential P3b, executive function, working memory

1 | INTRODUCTION

Childhood is characterized by a period of protracted cognitive and neural development (Casey, Tottenham, Liston, & Durston, 2005). Understanding how children develop the ability to prioritize cognitive demands to complete a goal during this period—a concept known as *cognitive control*—has become of increasing interest as perturbations in cognitive control have been linked to a variety of mental health problems in adolescence (e.g., Troller-Renfree, Buzzell, Pine, Henderson, & Fox, 2019). However, much of the research detailing developmental changes associated with cognitive control during childhood has focused on individual cognitive skills, such as *individual* executive functions (i.e., inhibition, attentional control, and working memory) (Miyake et al., 2000) and less on the dynamic interactions *between* cognitive domains. Toward this end, an expanding body of research in the area of cognitive control aims to understand how children prepare and employ a variety of cognitive resources to achieve a goal (Chatham, Frank, & Munakata, 2009).

The Dual Mechanisms of Control theory (DMC; Braver, 2012) postulates two kinds of cognitive control with temporally distinct profiles: proactive control and reactive control. Proactive control is enacted before a control-anticipated event and requires that goal-relevant information is actively maintained to bias attentional and action systems. In contrast, reactive control is recruited on an as-needed basis, typically in response to the detection of conflict. While the DMC has been widely applied to explain adult cognitive control (Braver & Barch, 2002; Braver, Paxton, Locke, & Barch, 2009), only a few studies have examined the development of proactive and reactive control during childhood.

Emerging work suggests that children transition from heavy reliance on reactive control to a more proactive strategy during the first decade of life (Munakata, Snyder, & Chatham, 2012). Empirical evidence suggests this transition begins in early-to-middle childhood (between the ages of 6–8; Chatham et al., 2009; Lorsbach & Reimer, 2008, 2010; Lucenet & Blaye, 2014; Unger, Ackerman, Chatham, Amso, & Badre, 2016). However, it remains unclear what neurocognitive factors support this transition from reactive to proactive control during childhood. One possibility is that young children rely on reactive control because they are unable to remember task-relevant information as a result of the protracted development of working memory during this period (Munakata et al., 2012). Indeed, work in adults implicates the same brain circuitry in both working memory and proactive control paradigms (Aron, 2011; Müller & Knight, 2006). Therefore, sufficient development of working memory capacity may influence the developmental transition from reactive to proactive control. Indeed, some developmental evidence suggests that working memory skills support the emergence of more complex cognitive strategies (Amso, Haas, McShane, & Badre, 2014; Gonthier, Zira, Colé, & Blaye, 2019; Unger et al., 2016). However, other major executive function skills (Miyake et al., 2000), such as inhibitory (Aron, 2011; Chevalier, Chatham, & Munakata, 2014) or attentional control (Miller & Cohen, 2001), may also be central to cognitive control. As such, it remains unclear whether the development of working memory, above other executive functions, underlies the transition from reactive to proactive control.

If the development of more basic executive function skills underlies the transition from proactive to reactive control, then associated neural development during this period (Casey et al., 2005) should also coincide with this transition. That is, rapid maturation of the neural systems supporting cognitive control (Dosenbach, Fair, Cohen, Schlaggar, & Petersen, 2008; Fair et al., 2007; Hwang, Ghuman, Manoach, Jones, & Luna, 2016; Marek, Hwang, Foran, Hallquist, & Luna, 2015) might allow for more complex reasoning to come 'online' during childhood and adolescence (Mahy & Munakata, 2015; Munakata et al., 2012). Specifically, if the development of working memory supports the transition from reactive to proactive control, then such a transition should be observable in a known correlate of working memory: the P3b event-related potential (ERP; Munson, Ruchkin, Ritter, Sutton, & Squires, 1984; Polich, 2003). An increase in magnitude of the P3b has been shown to index the updating of working memory in adults (Polich, 2003) and is also detectable during childhood (Morales, Yudes, Gómez-Ariza, & Bajo, 2015). Critically, the P3b provides a sensitive marker of working memory that has high temporal precision, which is critical for indexing the rapid cascade of processing involved in cognitive control. If the development of working memory influences the reactive to proactive control transition, one would expect such a transition to also coincide with increased activation of the P3b.

Research highlights

- Cognitive control develops rapidly during childhood, with a dominant change being a transition from 'as-needed' control (reactive control) to planful control (proactive control).
- Results show that working memory, above and beyond other executive functions, is critical for the enactment of proactive control during childhood.
- Results also show greater increases in neural activity (P3b) underlying working memory link working memory ability and proactive control strategy use.
- These data suggest that neurocognitive developments in working memory may influence adopting a more mature, and adaptive, proactive control strategy.

To determine whether working memory development supports a transition to proactive control in children, we had 5- and 9-year-olds complete a series of computer-based tasks. Children performed a modified version of a cognitive control task which allows for the discrimination of proactive and reactive control (the AX-Continuous Performance Task [AX-CPT]) while electroencephalography (EEG) was collected. In addition, participants completed a standardized cognitive battery that measured multiple domains of executive functioning. Consistent with prior work, we expected to observe a transition from preferential reliance on reactive control to proactive control across ages 5–9. In line with our hypothesis that working memory supports this transition, we expected that measurement of working memory ability, over and above other executive functions, would predict this transition. Providing converging evidence for this hypothesis, we also expected that working memory-related neural activation (P3b) during the AX-CPT would predict the transition from reactive to proactive control and would *mediate* the relations between working memory skill and cognitive control strategy use.

2 | METHODS

2.1 | Participants

Seventy-nine children—forty-one 5-year-olds and thirty-eight 9-year-olds—were recruited for participation in this study. Sample size was determined prior to data collection to achieve 80% power on the basis of the observed effect sizes (d = 0.77–1.18) in previous studies (Chatham et al., 2009; Lorsbach & Reimer, 2010; Lucenet &

Blaye, 2014). Following IRB approval, participants were recruited from the greater metropolitan area of a large city on the eastern coast of the United States.

Participants were excluded from participation if parents reported any psychiatric disorders, previous brain injury, significant birth defects, uncorrected visual impairments, any physical disability that would prohibit task completion, or any prescribed medication for neurological or mental health issues. As a result, one child (age 5) was excluded. As such, our final sample consisted of forty 5-year-olds (M_{age} = 5.35 years; SD = 0.37) and thirty-eight 9-year-olds (M_{age} = 9.05 years; SD = 0.43). Age groups were matched on gender (age 5:46% male; age 9:50% male).

2.2 | Procedure

Upon arrival at the laboratory, parents were informed of all procedures, and informed consent was obtained. Children also gave written or verbal assent. Following consent, parents completed questionnaires. Children went to a physiology collection room and were fitted with an EEG net and asked to perform the AX-CPT task. Following the AX-CPT, the child completed the NIH toolbox assessment. Finally, families were compensated $20 and children selected a small prize. The experimental visit lasted approximately 2 hr.

2.3 | Demographics questionnaire

Parents completed one standard demographics questionnaire. Information collected included age of participant, race, and other relevant information.

2.4 | Child AX-CPT laboratory task

An adapted child-friendly version of the AX-CPT (Braver, 2012; Cohen, Barch, Carter, & Servan-Schreiber, 1999) was administered using E-prime stimulus presentation software (Psychology Software Tools, Inc.). The AX-CPT was comprised of four trial types—AX, AY, BX, and BY (Figure 1 for task schematic). AX trials were the target trial for this task and had a different response (either 1 or 4 on a button box) than the other three trial types. Consistent with past EEG and ERP studies using the AX-CPT, AX trials were presented 55% of the time while each other trial type (AY, BX, BY) was presented 15% of the time (Lamm, Pine, & Fox, 2013). Trials were presented in a random order.

Consistent with past studies in children (Chatham et al., 2009), the traditional letter-based AX-CPT stimuli were replaced with cartoon figures and participants only responded once to the probe stimuli. Each trial began with a central fixation cross followed by a cue stimulus (A or B), which was presented for 500 ms. The cue stimulus was followed by a randomized interstimulus interval of 1,400–1,600 ms. Finally, one of two probe stimuli (X or Y) was presented until the participant responded or until the conclusion of the response window. Consistent with past research (Chatham et al., 2009), the initial response window was set to 6,000 ms, but was adjusted to be a maximum of 150% of the previous eight correct responses. Eight versions of the task were programmed to ensure cue and probe pairings were counterbalanced across participants.

Before the task, participants completed 12 practice trials, which had to be completed at least 70% accuracy to move forward. Stimuli were presented in blocks of 40 trials. Participants were encouraged to complete as many blocks as possible, with a maximum of eight blocks. On average, participants only completed approximately six blocks (M_{trials} = 236.13; SD = 52.07; Supporting Information S1 for block-level analyses). To ensure participants understood task instructions, participants with <60% accuracy on BY trials (trials without a target cue or probe) were excluded from all analyses (N = 1; Supporting Information S2 for more information on data cleaning). A behavioral composite indexing proactivity—known as d' context—was computed (information on d' calculation can be found in Supporting Information S2; see Supporting Information S3 for investigations using accuracy and reaction time; see Supporting Information S4 for investigations using the Proactive Shift Index; see Supporting Information S5 for investigations of A-cue bias). The d' context metric reflects how sensitive a participant is to the identity of the cue (A or B) and increases with more proactive strategy use.

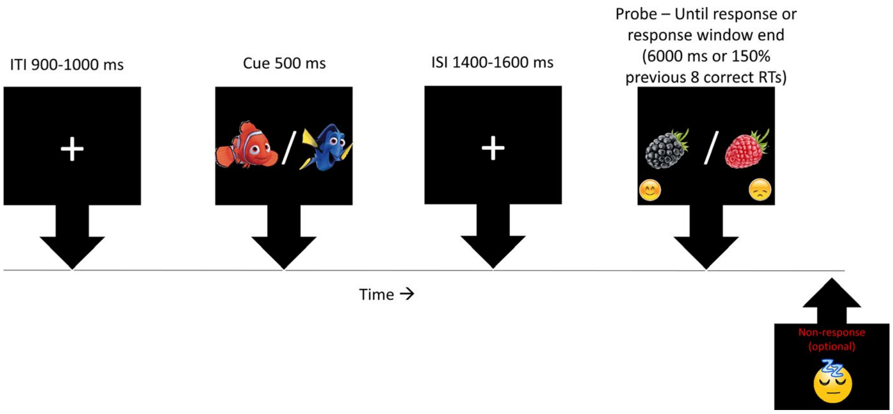

FIGURE 1 Child AX-Continuous Performance Task schematic. ISI, interstimulus interval; ITI, intertrial interval; RT, reaction time

2.5 | EEG recording and processing

Continuous EEG was recorded using a 128-channel Geodesic Sensor Net and sampled at 500 Hz (Electrical Geodesic, Inc.). Before data collection, electrode impedances were reduced to below 50 kΩ. During collection, electrodes were referenced to electrode Cz. Following data collection, data were re-referenced to an average reference. EEG/ERP processing was completed using EEGLAB (Delorme & Makeig, 2004) and ERP PCA Toolkit (Dien, 2010).

Data were filtered offline using a digital band-pass FIR filter from 0.3–50 Hz. Data were segmented separately for 'A' cue and 'B' cue trials from 200 ms before the presentation of the cue to 1,000 ms following cue presentation. Only trials that resulted in a correct behavioral response were analyzed. Channels were marked bad if the electrode amplitude exceeded 150 μV or if a channel differed by more than 40 μV from any neighboring channel. Channels were marked globally bad if the correlation between neighboring channels was <0.30 or if the channel was bad on >20% of trials (A trials: 4.9%, B trials: 4.9%). Trials were marked bad if more than 20% of channels were determined to be bad (A trials: 27.7%, B trials: 27.2%). Bad channels on remaining good trials were interpolated. Participants needed at least 10 artifact-free trials in each condition to be included in the analysis. Consistent with other developmental work, the P3b was evaluated as the mean amplitude between 350 and 650 ms (Morales et al., 2015) at a grouping of parietal electrodes surrounding electrode Pz (electrodes 54, 61, 62, 67, 72, 77, 78, and 79; see Supporting Information S6 and Figure S3 for heat maps).

2.6 | NIH toolbox childhood cognition battery

The NIH toolbox cognition battery (Weintraub et al., 2013) is a validated cognitive assessment tool constructed by a team of scientists in collaboration with the National Institutes of Health (NIH). The NIH Early childhood cognitive assessment battery includes five short tasks aimed at assessing cognitive functioning in children (Zelazo et al., 2013). Three tasks are specifically aimed at assessing executive functions in young children: Dimensional Change Card Sort (DCCS; attention shifting), the Flanker (inhibitory control), and List Sorting Working Memory (LSWM; working memory). Task data were scored and age normed using the NIH Toolbox iPad app.

2.7 | Data analysis plan

Before exploring the main study aims, multiple Pearson's correlations were conducted to explore the intercorrelations among age, performance on the AX-CPT, the P3b, and executive functioning (see Table 1 for descriptive and correlations).

2.7.1 | Analyses of control strategy

Consistent with past studies utilizing the AX-CPT to assess cognitive control strategy use, a signal detection theoretic measures—known as d' context—was computed (Cohen et al., 1999; Swets & Sewall, 1963). Higher scores for the d' context measure reflect a greater reliance on proactive control; group differences in d' context were tested using an independent samples *t*-tests.

2.7.2 | Analysis of associations between executive functions and control strategy

A linear regression was conducted to examine the relations among age, executive functions, and cognitive control strategy. The regression had age group (dichotomously coded) as well as age-corrected scores from all three of the NIH toolbox executive tasks (DCCS,

TABLE 1 Zero-order correlations, means, and standard deviations of measures of interest

	1.	2.	3.	4.	5.	6.
1. Age	1					
2. d' context	0.613**	1				
3.ΔP3b	0.279*	0.294*	1			
4. Flanker—(inhibitory control; uncorrected score)	0.769**	0.516**	0.296*	1		
5. DCCS—(attention shifting; uncorrected score)	0.730**	0.415**	0.281*	0.695**	1	
6. LSWM—(working memory; uncorrected score)	0.792**	0.553**	0.436*	0.737**	0.615**	1
M	7.1872	2.5257	1.9219	75.3421	78.2368	83.0139
SD	1.8934	0.96255	3.8250	21.3076	21.2112	18.3744

Abbreviations: DCCS, Dimensional Change Card Sort; LSWM, List Sorting Working Memory.

*$p < .05$.

**$p < .01$.

Flanker, and LSWM) entered into the model as predictors with *d′* serving as the outcome. In addition, interaction terms for age group by each executive task were entered into the model to examine how executive skills associated with proactive and reactive strategy use in each age group.

2.7.3 | Testing relations between neurocognition and control strategy

Analyses of the relations between cognitive functioning and cognitive control strategy use took place in two steps.

First, the cue-locked P3b was assessed using a 2 Group (5-year-old, 9-year-old) by 2 Condition (A cue, B cue) repeated-measures ANOVA. Significant main and interaction effects were explored using paired sample *t*-tests for within-subjects effects and independent samples *t*-test for between-subject effects. Bonferroni corrections for multiple comparisons were applied when necessary. Relations between the P3b component and cognitive control strategy were examined by correlating component mean amplitude with *d′* context.

Second, to investigate whether the relation between executive functioning and cognitive control was mediated by neural activation, a mediation model was conducted for significant predictors in the previous analysis step (testing relations between executive function skills and cognitive control strategy) were conducted using the PROCESS macro for SPSS (version 3; Hayes, 2013). Indirect effects were tested using a percentile bootstrap estimation approach with 10,000 samples.

2.8 | Participant inclusion

For all behavioral and ERP analyses, one 5-year-old was excluded due to <60% accuracy on BY trials. In addition, for the P3b analyses, one 9-year-old was excluded due to refusing the EEG cap and a total of five 5-year-olds were excluded: three for refusing the EEG cap and two due to an insufficient number of correct and artifact-free B trials.

Participants were excluded on a task-by-task basis for analyses examining associations between cognitive control strategy use and executive functioning. For the Flanker and DCCS, one child was excluded due to toolbox refusal (Table 2). For the LSWM task, a total of five 5-year-olds were excluded—one due to time constraints and four who did complete enough items to yield a score.

3 | RESULTS

3.1 | Development and behavioral indices of cognitive control strategy use

The *t*-tests for the *d′* context measure of proactive control (context sensitivity) revealed 9-year-olds (M = 3.08, SD = 0.72) exhibited a greater reliance on proactive control than 5-year-olds (M = 1.99, SD = 0.87), $t(75) = -6.00$, $p < .001$, d = 1.365. This pattern suggests 9-year-olds used the cue identity to inform their responding more than 5-year-olds, thus using more proactive strategies. This pattern held even after controlling for the number of trials completed by each child ($p < .001$).

3.2 | Relations between executive functions and cognitive control strategy use

A linear regression was conducted to investigate how executive functions and age group relate to cognitive control strategy. The model reached significance ($F(7, 64) = 6.409$, $p < .001$, $R^2 = .412$). Examination of individual predictors revealed age group significantly predicted *d′* context scores ($t(69) = 5.509$, $p < .001$), which was qualified by an age group by working memory interaction ($t(69) = 2.049$, $p = .045$). Follow-up analyses revealed that for the 9-year-old group, working memory skill, above and beyond other executive functions, was positively predictive of the implementation of a more proactive strategy. This pattern was not evident in 5-year-olds.

3.3 | Development in cognitive control strategy and neural activation

To examine differences in the P3b amplitude, a 2 Group (5-year-old, 9-year-old) by 2 Condition (A cue, B cue) repeated-measures ANOVA was conducted (Figure 2 for waveforms). The model revealed a main effect for Condition $F(1, 69) = 18.306$, $p < .001$, $\eta^2 = 0.210$, which was qualified by a significant Group by Condition interaction $F(1, 69) = 6.171$, $p = .015$, $\eta^2 = 0.082$. Bonferroni-corrected follow-up tests revealed 9-year-olds had a larger P3b for B cues (M = 7.9416, SD = 4.60614) relative to A cues (M = 4.9765, SD = 3.67452; $F(1, 69) = 23.875$, $p < .001$, $\eta^2 = 0.257$), whereas 5-year-olds P3b did not differ by trial type (A cues: M = 7.485, SD = 4.586; B cues: M = 8.271, SD = 5.377; $F(1, 69) = 1.545$, $p = .218$, $\eta^2 = 0.022$). In addition, on A cues, 9-year-olds had a significantly

TABLE 2 Participant inclusion by age for each measure of interest

Enrolled		Behavioral		P3b ERP		Flanker		DCCS		LSWM	
5	9	5	9	5	9	5	9	5	9	5	9
41	38	39	38	34	37	38	38	38	38	34	38

Abbreviations: DCCS, Dimensional Change Card Sort; ERP, event-related potential; LSWM, List Sorting Working Memory.

smaller P3b than 5-year-olds, $F(1, 69) = 6.158$, $p = .013$, $\eta^2 = 0.086$. P3b amplitude on B trials did not differ between groups, $F(1, 69) = 0.077$, $p = .782$, $\eta^2 = 0.001$.

Relations between the P3b and cognitive control strategy were examined using a Pearson's correlation. To do this, first a P3b difference score was created by subtracting the amplitude of the 'A' cue from the 'B' cue. The P3b difference score was significantly and positively correlated with the d' context score ($r(69) = .294$, $p = .013$) suggesting the larger the amplitude difference between the 'A' and 'B' cues, the more a proactive strategy was implemented. However, this relation was no longer significant after controlling for age ($r(68) = .147$, $p = .147$), suggesting that age-related differences may be driving this effect.

3.4 | Relations among executive skills, neural activation, and cognitive control strategy use

The findings described above demonstrate that both a behavioral metric of working memory ability (LSWM) and a neural index of working memory updating (P3b) both predict a greater reliance on proactive control in children. Therefore, a mediation model was conducted to investigate whether differences in P3b amplitude serve as a *neurobehavioral marker* explaining relations between working memory ability and proactive strategy use. To investigate this question, a single mediation model was conducted (Figure 3). The indirect effect for this model reached significance ($B = 0.006$, $SE = 0.003$, 95% CI [0.001, 0.014]), suggesting that children with better working memory ability are more likely to exhibit a neural correlate of working memory updating when performing the AX-CPT and, in turn, the more likely to demonstrate use of a primarily proactive control strategy.

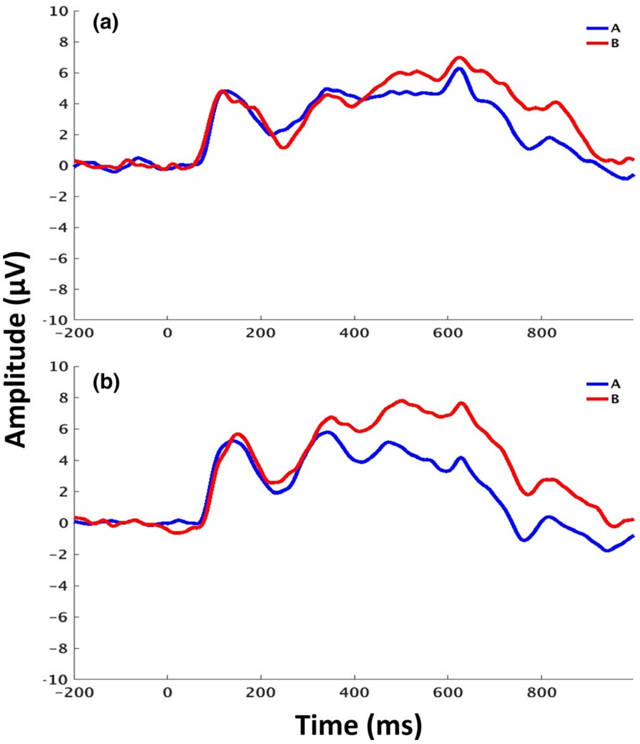

FIGURE 2 (a) ERP waveforms for the P3b (top) for 5-year-olds. (b) ERP waveforms for the P3b (bottom) for 9-year-olds. ERP, event-related potential

4 | DISCUSSION

The goal of this study was to examine age-related transitions in cognitive control strategy use and identify underlying neurocognitive factors associated with that transition. Consistent with prior work (Chatham et al., 2009; Chevalier, Martis, Curran, & Munakata, 2015; Munakata et al., 2012) and the DMC (Braver, 2012) theory, data from this study showed that children transition between a reliance on reactive cognitive control strategies in early childhood (age 5) to proactive cognitive control strategies use in later childhood (age 9). Critically, data suggest that working memory, above and beyond other executive functions (attention shifting and inhibitory control), is integral to the implementation of a proactive strategy in older children. Finally, a neural index of working memory updating (P3b) was increased for older children who employed a more proactive control strategy and the P3b-mediated relations between behavioral assessments of working memory ability and cognitive control strategy. Together, these data are the first to show converging evidence that neurocognitive indices of working memory may be an important influence for adopting a more mature, and adaptive, proactive control strategy for many children during childhood. These findings are also of interest as perturbations in cognitive control have been linked to a variety of mental health problems (Braver, Barch, & Cohen, 1999; Troller-Renfree et al., 2019) affording an understanding of the etiology and possible factors for intervention.

In this study, we assessed independent measures of three executive functions—inhibitory control, working memory, and attentional control—and found that age-related increases in d' context (proactive control) were specifically mediated by working memory ability. That is, while 9-year-olds as a whole exhibited increased reliance on proactive control strategies, this transition was most prominent for those children also exhibiting greater working memory ability.

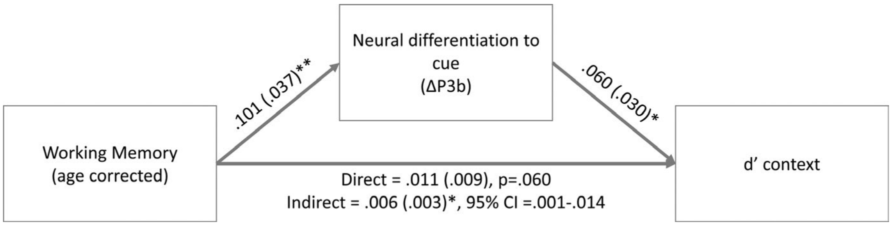

FIGURE 3 Mediation model. Unstandardized effects reported with standard errors in parentheses

Moreover, while children who utilized proactive strategies also had better working memory, this pattern was not evident in younger children who did not enact such strategies, suggesting a lack of specificity among executive functions for reactive strategy use in young children. This pattern of findings fits nicely with a growing body of research that suggests executive functions measured in early childhood reflect a single cognitive factor and become increasingly distinct skills with age (Hughes, Ensor, Wilson, & Graham, 2009; Wiebe, Espy, & Charak, 2008; Wiebe et al., 2011). It is important to note that while we assessed executive functions in line with a three-factor theory of executive function (Miyake et al., 2000), other related cognitive functions (e.g., sustained attention) were not assessed and should be examined in future research as contributors to cognitive control strategy use. Finally, these data suggest a link between working memory and proactive strategy, likely driven by involvement of a dorsolateral prefrontal cortex circuitry (Aron, 2011; Braver et al., 2009; Bunge, Ochsner, Desmond, Glover, & Gabrieli, 2001; Müller & Knight, 2006).

Our target candidate for identifying the neural correlates reflecting the transition from reactive to proactive control was the cue-locked P3b, which is thought to be reflective of cue-related updating of working memory for task-relevant information (van Wouwe, Band, & Ridderinkhof, 2011). We demonstrated that the more a child demonstrated increased P3b differentiation between the different types of task-relevant information given in advance of a response event (e.g., 'A' vs. 'B' cue), the more likely a child was to use a proactive strategy (i.e., the P3b magnitude predicted d' context). However, the relations between neurocognitive markers of working memory and subsequent task behavior did not survive correction for age. As such, effect should be interpreted with caution and replicated in a larger sample where age is more continuously distributed. In addition, our data suggest that 9-year-olds (vs. 5-year-olds) were more likely to display enhanced neural discrimination for different kinds of task-relevant information given in advance (i.e., larger P3b amplitude for 'B' relative to 'A' cues). This pattern is pattern consistent with existing literature suggesting an increased P3b magnitude is related to increased working memory updating (Polich, 2003, 2007). Moreover, we found that P3b amplitude reflecting working memory updating (Munson et al., 1984; Polich, 2003) mediated relations between age-corrected behavioral assessments of working memory ability and proactive strategy implementation, suggesting that activation of preparatory stimulus-locked classification and memory functions are critical for a proactive strategy.

This study created a version of the AX-CPT for very young children that could be used with acquisition of EEG. Data from this study were consistent with other studies suggesting older children (e.g., 9-year-olds) observe and use environmental cues to in order to complete a goal, whereas younger children (e.g., 5-year-olds) use instantaneous stimulus-related information to drive their responding (Chatham et al., 2009; Chevalier, Dauvier, & Blaye, 2018; Chevalier et al., 2014; Lorsbach & Reimer, 2010; Lucenet & Blaye, 2014). The consistency of findings was an important validation of the new task, given that slight alterations in task timings and trial proportions were necessary for the calculation of ERPs. However, this study does have limitations. Of note, the sample size was modest and future studies should replicate the findings reported here in a larger—potentially longitudinal—sample. Furthermore, this study did not examine probe-related activity, which would be a valuable direction for future research detailing the neurocognitive signatures of cognitive control strategy use and their relations to executive functioning.

In conclusion, evidence from this study suggests the transition from a preferential reliance on in-the-moment to more planful strategies in children is contingent on working memory. Critically, this transition is related to neural activity linked to stimulus categorization and the updating working memory.

ACKNOWLEDGEMENTS

The authors would like to thank Lauren Steel and Elizabeth Salisbury for their help with data collection. Also special thanks to Drs. Daniel Pine, Tracy Riggins, and Luiz Pessoa for comments in a previous version of this manuscript.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available on request from Sonya Troller-Renfree. The data are not publicly available due to privacy or ethical restrictions.

ORCID

Sonya V. Troller-Renfree https://orcid.org/0000-0001-9979-4696

REFERENCES

Amso, D., Haas, S., McShane, L., & Badre, D. (2014). Working memory updating and the development of rule-guided behavior. *Cognition*, *133*(1), 201–210. https://doi.org/10.1016/j.cognition.2014.06.012

Aron, A. R. (2011). From reactive to proactive and selective control: Developing a richer model for stopping inappropriate responses. *Biological Psychiatry*, *69*(12), e55–e68. https://doi.org/10.1016/j.biopsych.2010.07.024

Braver, T. S. (2012). The variable nature of cognitive control: A dual mechanisms framework. *Trends in Cognitive Sciences*, *16*(2), 106–113. https://doi.org/10.1016/j.tics.2011.12.010

Braver, T. S., & Barch, D. M. (2002). A theory of cognitive control, aging cognition, and neuromodulation. *Neuroscience & Biobehavioral Reviews*, *26*(7), 809–817. https://doi.org/10.1016/S0149-7634(02)00067-2

Braver, T. S., Barch, D. M., & Cohen, J. D. (1999). Cognition and control in schizophrenia: A computational model of dopamine and prefrontal function. *Biological Psychiatry*, *46*(3), 312–328. https://doi.org/10.1016/S0006-3223(99)00116-X

Braver, T. S., Paxton, J. L., Locke, H. S., & Barch, D. M. (2009). Flexible neural mechanisms of cognitive control within human prefrontal cortex. *Proceedings of the National Academy of Sciences of the United States of America*, *106*(18), 7351–7356. https://doi.org/10.1073/pnas.0808187106

Bunge, S. A., Ochsner, K. N., Desmond, J. E., Glover, G. H., & Gabrieli, J. D. (2001). Prefrontal regions involved in keeping information in and out of mind. *Brain : A Journal of Neurology*, *124*(Pt 10), 2074–2086. Retrieved from http://www.ncbi.nlm.nih.gov/pubmed/11571223

Casey, B. J., Tottenham, N., Liston, C., & Durston, S. (2005). Imaging the developing brain: What have we learned about cognitive development? *Trends in Cognitive Sciences*, *9*(3), 104–110. https://doi.org/10.1016/J.TICS.2005.01.011

Chatham, C. H., Frank, M. J., & Munakata, Y. (2009). Pupillometric and behavioral markers of a developmental shift in the temporal dynamics of cognitive control. *Proceedings of the National Academy of Sciences of the United States of America*, *106*(14), 5529–5533. https://doi.org/10.1073/pnas.0810002106

Chevalier, N., Chatham, C. H., & Munakata, Y. (2014). The practice of going helps children to stop: The importance of context monitoring in inhibitory control. *Journal of Experimental Psychology: General*, *143*(3), 959–965. https://doi.org/10.1037/a0035868

Chevalier, N., Dauvier, B., & Blaye, A. (2018). From prioritizing objects to prioritizing cues: A developmental shift for cognitive control. *Developmental Science*, *21*(2), e12534. https://doi.org/10.1111/desc.12534

Chevalier, N., Martis, S. B., Curran, T., & Munakata, Y. (2015). Metacognitive processes in executive control development: The case of reactive and proactive control. *Journal of Cognitive Neuroscience*, *27*(6), 1125–1136. https://doi.org/10.1162/jocn_a_00782

Cohen, J. D., Barch, D. M., Carter, C. S., & Servan-Schreiber, D. (1999). Context-processing deficits in schizophrenia: Converging evidence from three theoretically motivated cognitive tasks. *Journal of Abnormal Psychology*, *108*(1), 120–133.

Delorme, A., & Makeig, S. (2004). EEGLAB: An open source toolbox for analysis of single-trial EEG dynamics including independent component analysis. *Journal of Neuroscience Methods*, *134*(1), 9–21. https://doi.org/10.1016/j.jneumeth.2003.10.009

Dien, J. (2010). The ERP PCA Toolkit: An open source program for advanced statistical analysis of event-related potential data. *Journal of Neuroscience Methods*, *187*(1), 138–145. https://doi.org/10.1016/j.jneumeth.2009.12.009

Dosenbach, N. U. F., Fair, D. A., Cohen, A. L., Schlaggar, B. L., & Petersen, S. E. (2008). A dual-networks architecture of top-down control. *Trends in Cognitive Sciences*, *12*(3), 99–105. https://doi.org/10.1016/j.tics.2008.01.001

Fair, D. A., Dosenbach, N. U. F., Church, J. A., Cohen, A. L., Brahmbhatt, S., Miezin, F. M., … Schlaggar, B. L. (2007). Development of distinct control networks through segregation and integration. *Proceedings of the National Academy of Sciences of the United States of America*, *104*(33), 13507–13512. https://doi.org/10.1073/pnas.0705843104

Gonthier, C., Zira, M., Colé, P., & Blaye, A. (2019). Evidencing the developmental shift from reactive to proactive control in early childhood and its relationship to working memory. *Journal of Experimental Child Psychology*, *177*, 1–16. https://doi.org/10.1016/j.jecp.2018.07.001

Hayes, A. F. (2013). *Introduction to mediation, moderation, and conditional process analysis: A regression-based approach*. New York, NY: Guilford Press.

Hughes, C., Ensor, R., Wilson, A., & Graham, A. (2009). Tracking executive function across the transition to school: A latent variable approach. *Developmental Neuropsychology*, *35*(1), 20–36. https://doi.org/10.1080/87565640903325691

Hwang, K., Ghuman, A. S., Manoach, D. S., Jones, S. R., & Luna, B. (2016). Frontal preparatory neural oscillations associated with cognitive control: A developmental study comparing young adults and adolescents. *NeuroImage*, *136*, 139–148. https://doi.org/10.1016/j.neuroimage.2016.05.017

Lamm, C., Pine, D. S., & Fox, N. A. (2013). Impact of negative affectively charged stimuli and response style on cognitive-control-related neural activation: An ERP study. *Brain and Cognition*, *83*(2), 234–243. https://doi.org/10.1016/j.bandc.2013.07.012

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. https://doi.org/10.3200/GNTP.169.1.34-50

Lorsbach, T. C., & Reimer, J. F. (2010). Developmental differences in cognitive control: Goal representation and maintenance during a continuous performance task. *Journal of Cognition and Development*, *11*(2), 185–216. https://doi.org/10.1080/15248371003699936

Lucenet, J., & Blaye, A. (2014). Age-related changes in the temporal dynamics of executive control: A study in 5- and 6-year-old children. *Frontiers in Psychology*, *5*, 831. https://doi.org/10.3389/fpsyg.2014.00831

Mahy, C. E. V., & Munakata, Y. (2015). Transitions in executive function: Insights from developmental parallels between prospective memory and cognitive flexibility. *Child Development Perspectives*, *9*(2), 128–132. https://doi.org/10.1111/cdep.12121

Marek, S., Hwang, K., Foran, W., Hallquist, M. N., & Luna, B. (2015). The contribution of network organization and integration to the development of cognitive control. *PLoS Biology*, *13*(12), e1002328. https://doi.org/10.1371/journal.pbio.1002328

Miller, E. K., & Cohen, J. D. (2001). An integrative theory of prefrontal cortex function. *Annual Review of Neuroscience*, *24*(1), 167–202. https://doi.org/10.1146/annurev.neuro.24.1.167

Miyake, A., Friedman, N. P., Emerson, M. J., Witzki, A. H., Howerter, A., & Wager, T. D. (2000). The unity and diversity of executive functions and their contributions to complex 'frontal lobe' tasks: A latent variable analysis. *Cognitive Psychology*, *41*(1), 49–100. https://doi.org/10.1006/cogp.1999.0734

Morales, J., Yudes, C., Gómez-Ariza, C. J., & Bajo, M. T. (2015). Bilingualism modulates dual mechanisms of cognitive control: Evidence from ERPs. *Neuropsychologia*, *66*, 157–169. https://doi.org/10.1016/j.neuropsychologia.2014.11.014

Müller, N. G., & Knight, R. T. (2006). The functional neuroanatomy of working memory: Contributions of human brain lesion studies. *Neuroscience*, *139*(1), 51–58. https://doi.org/10.1016/j.neuroscience.2005.09.018

Munakata, Y., Snyder, H. R., & Chatham, C. H. (2012). Developing cognitive control three key transitions. *Current Directions in Psychological Science*, *21*(2), 71–77. https://doi.org/10.1177/0963721412436807

Munson, R., Ruchkin, D. S., Ritter, W., Sutton, S., & Squires, N. K. (1984). The relation of P3b to prior events and future behavior. *Biological Psychology*, *19*(1), 1–29. https://doi.org/10.1016/0301-0511(84)90007-3

Polich, J. (2003). Theoretical overview of P3a and P3b. In J. Polich (Ed.), *Detection of change* (pp. 83–98). Boston, MA: Springer. https://doi.org/10.1007/978-1-4615-0294-4_5

Polich, J. (2007). Updating P300: An integrative theory of P3a and P3b. *Clinical Neurophysiology*, *118*(10), 2128–2148. https://doi.org/10.1016/j.clinph.2007.04.019

Swets, J. A., & Sewall, S. T. (1963). Invariance of signal detectability over stages of practice and levels of motivation. *Journal of Experimental Psychology*, *66*(2), 120–126. https://doi.org/10.1037/h0049098

Troller-Renfree, S. V., Buzzell, G. A., Pine, D. S., Henderson, H. A., & Fox, N. A. (2019). Consequences of not planning ahead: Reduced proactive control moderates longitudinal relations between behavioral inhibition and anxiety. *Journal of the American Academy of Child and Adolescent Psychiatry*, *58*(8), 768–775.e1. https://doi.org/10.1016/j.jaac.2018.06.040

Unger, K., Ackerman, L., Chatham, C. H., Amso, D., & Badre, D. (2016). Working memory gating mechanisms explain developmental change in rule-guided behavior. *Cognition*, *155*, 8–22. https://doi.org/10.1016/j.cognition.2016.05.020

van Wouwe, N. C., Band, G. P. H., & Ridderinkhof, K. R. (2011). Positive affect modulates flexibility and evaluative control. *Journal of Cognitive Neuroscience*, *23*(3), 524–539. https://doi.org/10.1162/jocn.2009.21380

Weintraub, S., Dikmen, S. S., Heaton, R. K., Tulsky, D. S., Zelazo, P. D., Bauer, P. J., … Gershon, R. C. (2013). Cognition assessment using the NIH Toolbox. *Neurology*, *80*(11 Suppl 3), S54–S64. https://doi.org/10.1212/WNL.0b013e3182872ded

Wiebe, S. A., Espy, K. A., & Charak, D. (2008). Using confirmatory factor analysis to understand executive control in preschool children: I. Latent structure. *Developmental Psychology*, *44*(2), 575–587. https://doi.org/10.1037/0012-1649.44.2.575

Wiebe, S. A., Sheffield, T., Nelson, J. M., Clark, C. A. C., Chevalier, N., & Espy, K. A. (2011). The structure of executive function in 3-year-olds. *Journal of Experimental Child Psychology*, *108*(3), 436–452. https://doi.org/10.1016/J.JECP.2010.08.008

Zelazo, P. D., Anderson, J. E., Richler, J., Wallner-Allen, K., Beaumont, J. L., & Weintraub, S. (2013). NIH toolbox cognition battery (CB): Measuring executive function and attention. *Monographs of the Society for Research in Child Development*, *78*(4), 16–33. https://doi.org/10.1111/mono.12032

SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section.

How to cite this article: Troller-Renfree SV, Buzzell GA, Fox NA. Changes in working memory influence the transition from reactive to proactive cognitive control during childhood. *Dev Sci*. 2020;23:e12959. https://doi.org/10.1111/desc.12959