

Abstract

Title of Dissertation: THE DEVELOPMENT OF COGNITIVE CONTROL DURING CHILDHOOD: A NEUROCOGNITIVE PERSPECTIVE.

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One of the hallmarks of human cognition is its adaptability and ability to prioritize task demands in order to complete a goal – a concept known as cognitive control. Research has shown that cognitive control develops rapidly over the first decade of life. One of the key control-related developments during childhood is the transition from a heavy reliance on in-the-moment and as-needed control recruitment (known as reactive control) to more planful and sustained control (known as proactive control). This transition has been observed in a small number of studies, but much is still unknown about how this transition takes place, the mechanisms support this change, and whether this change is driven by coincident development of executive functions.

This dissertation examined the development of cognitive control using a cross-sectional design in 79 children – 41 5-year-olds and 38 9-year-olds. To assess cognitive control strategy use, children completed an adapted version of the AX-

Continuous Performance Task (AX-CPT) while we recorded electroencephalography (EEG). Children also completed a standardized executive function battery. Results revealed that 5-year-olds relied on reactive cognitive control strategies, while 9-year-olds relied on proactive cognitive control strategies. These behavioral patterns were associated with differential patterns of neural activation in a component known as the P3b. Executive functions were differentially associated with cognitive control strategy use. Specifically, better working memory and inhibitory control skills were related to proactive strategy use and increased context sensitivity. This study is the first to examine behavioral and neural measures of cognitive control strategy use on an AX-CPT task as well as the unique relations between cognitive control strategy and executive functioning.

THE DEVELOPMENT OF COGNITIVE CONTROL DURING CHILDHOOD: A
NEUROCOGNITIVE PERSPECTIVE.

by

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Dissertation submitted to the Faculty of the Graduate School of the
University of Maryland, College Park, in partial fulfillment
of the requirements for the degree of
Doctorate in Philosophy
2018

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Acknowledgements

First and foremost, I would like to thank my advisor Dr. Nathan Fox. I truly believe that I could not have had a better graduate advisor. Nathan challenged me to be a better scientist and person. He allowed me to stretch my mind, introduced me to the scientific community, gave me endless opportunities, and helped me to become the scientist I am today. Nathan, it has been a great honor being your graduate student. The lessons you have taught me with stay with me and shape who I am the rest of my life. I hope to make you proud.

Second, I would like to thank my husband, Steve Yazicioglu for his love and support during my 6 years of graduate school. He has been there for the late nights, the difficult reviewers, and the 1000s of neuroanatomy flashcards. Steve, thank you for the snack basket, taking the dog for extra walks, and for all of the cups of morning coffee. My life wouldn't be the same without you. I would also like to thank my brother, Drew Troller-Renfree, for being unwaveringly supportive and for inspiring me to work hard for what I want. Drew, I love you and I am so happy that we get to go through this world together as siblings.

I would also like to thank the amazing graduate students in my lab (Tyson Barker, Kathryn Yoo, Sara Haas, Maureen Bowers, and Virginia Salo) for their support and guidance. I cannot count the number of days you all brightened and the number of "stupid" questions you answered for me. A special thank you to Virginia – you are a person and scientist I aspire to do be. It has been amazing sharing an office with you and I will miss seeing you every time I come into work. I would also like to thank my wonderful friend and lab manager Julie Staples-Watson. Julie, thank you for digging me out of at least 100 holes, fixing the printer for me every time I jammed it, making the most delicious peanut butter chocolate pie, and for always calming me down and pointing me north when I needed it.

I would also like to thank the members of my committee -- Professor Nathan Fox, Professor Tracy Riggins, Professor Donald J. Bolger, Professor Luiz Pessoa, and Doctor Daniel Pine – for pushing me to be a better scientist and for supporting me along this journey. I am lucky to have your sage advice guiding me through this process.

Finally, I want to thank all of the amazing post-docs, RAs, lab managers, and undergrads that I have gotten to work with in the Child Development Lab over the last 6 years. Thank you for all of the great science and laughs along the way. I will miss all of you.

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List of Abbreviations

RT – Reaction Time

PFC – Prefrontal Cortex

DLPFC – Dorsolateral Prefrontal Cortex

IFJ – Inferior Frontal Junction

AX-CPT – AX Continuous Performance Task

DMC – Dual Mechanisms of Control

PBSI – Proactive Behavioral Shift Index

ERN – Error-related Negativity

CNV – Contingent Negative Variation

LPP – Late Positive Potential

Chapter 1: Introduction

Childhood is characterized by a period of protracted cognitive and neural development. To date, much of the research detailing the developmental changes associated with cognitive development during childhood has focused more on individual cognitive skills, such as individual executive functions (i.e. inhibition, attentional control, and working memory), and less on the concert and interaction of multiple cognitive domains. However, given that real-world functioning requires rapid management and implementation of a wide array of cognitive skills, understanding how children prioritize cognitive demands in order to complete a goal – a concept known as *cognitive control* – has become of increasing interest. As such, an expanding body of research in the area of developmental cognitive control aims to understand how children prepare and employ cognitive and perceptual resources in order to achieve a goal.

While there are a number of theories of cognitive control, one model that has garnered much attention is the Dual Mechanisms of Control (DMC; Braver, 2012). The DMC postulates that there are two kinds of cognitive control with temporally distinct profiles: proactive control and reactive control. Proactive control is enacted prior to a control-anticipated event and requires that goal-relevant information is actively maintained in order to optimally bias attentional and activation systems in order to complete a goal. In contrast, reactive control is commonly recruited on an as-needed basis in response to the detection of conflict. While the DMC has received much attention in adulthood (e.g. Braver & Barch,

2002; Braver, Paxton, Locke, & Barch, 2009), only a few studies have examined the development of proactive and reactive control during childhood.

It has been theorized that children shift from a heavy reliance on reactive control to a more proactive strategy during the first decade of life (Munakata, Snyder, & Chatham, 2012). This shift is characterized by children starting to plan their behaviors in advance of a goal-relevant event instead of reacting to external stimuli in order to enact goal-relevant behaviors. Empirical evidence suggests that this transition begins in early and middle childhood and likely continues into early adulthood (Chatham, Frank, & Munakata, 2009; Lorschach & Reimer, 2010a, 2010b; Lucenet & Blaye, 2014; Unger, Ackerman, Chatham, Amso, & Badre, 2016). However, only a few studies have concurrently measured proactive and reactive control strategies during childhood, which enables one to understand when reactive or proactive strategies are more evident.

Less is known about the developmental phenomena that support the transition from reactive to proactive control during childhood. One hypothesis is that the rapid maturation of neural architecture (e.g. frontal cortex maturation) and networks that support cognitive control (Dosenbach, Fair, Cohen, Schlaggar, & Petersen, 2008; Fair et al., 2007; Hwang, Ghuman, Manoach, Jones, & Luna, 2016; Marek, Hwang, Foran, Hallquist, & Luna, 2015) may allow for more complex reasoning to come “online” during childhood and adolescence (Mahy & Munakata, 2015; Munakata et al., 2012). As such, children may begin to process stimuli and task

goals differently, but there is little empirical evidence detailing the neural processes that facilitate the shift from reactive to proactive control during childhood.

In addition to neural development, cognitive abilities also develop rapidly during early and middle childhood (Mahy & Munakata, 2015; Munakata et al., 2012). Specifically, executive functions such as inhibitory control, attention shifting, and working memory are thought to support cognitive control and have a protracted developmental timeline that spans into adolescence (Davidson, Amso, Anderson, & Diamond, 2006). Two recent studies suggest that increased cognitive control efficiency during childhood and adolescence may be linked to concurrent proficiency in working memory skills (Amso, Haas, McShane, & Badre, 2014; Unger et al., 2016). However, to our knowledge, no studies have simultaneously examined the relations between multiple executive domains and cognitive control strategy use during early and middle childhood.

In the present study, we apply the theoretical framework of the DMC to enhance our understanding of the transition from reactive to proactive control during childhood, identify neural correlates that accompany this cognitive shift, and document the relations between proactive control, reactive control, and executive functioning. This study recruited 79 children across two age ranges: 5-year-olds (N=41) and 9-year-olds (N=38). Participants completed a modified version of a cognitive control task that allows for the discrimination of proactive and reactive control (the AX-Continuous Performance Task [AX-CPT]) while electroencephalography (EEG) was collected. Additionally, participants completed a

standardized cognitive battery that measured multiple domains of executive functioning including attention shifting, working memory, and inhibitory control.

The first aim of the study was to examine whether development is associated with changes in cognitive control strategy use. The second aim of the study was to examine whether developmental shifts in cognitive control strategy use are accompanied by changes in how the brain processes task-related stimuli. The third aim of the study was to examine the relations between executive function development and proactive and reactive strategy use.

This study provides important insight into how children prepare and utilize perceptual, cognitive, and motivational systems in order to complete a goal. Furthermore, the present study is one of the first to document the neural correlates associated with proactive and reactive control in childhood and how executive functioning is related to cognitive control strategy use. This line of research is important not only for furthering our understanding of the development of goal-relevant behaviors, but also may have implications for child mental health, particularly anxious cognition, as perturbations in cognitive control have been implicated in the development of anxiety in children (Henderson, Pine, & Fox, 2014).

Chapter 2: Background

The aim of this chapter is to present theoretical and empirical support for the hypothesis that children utilize two kinds of cognitive control: proactive and reactive control. We postulate that one hallmark of middle childhood is the transition from reactive control to proactive control. Furthermore, we expect this transition to be accompanied by neural changes (as indexed by EEG activity) in how children observe and process goal-relevant information. First, the chapter will introduce the concept of cognitive control and the Dual Mechanisms of Control theory. Next, we will present evidence that cognitive control develops throughout childhood. Following, is a review of behavioral and neural assessments of cognitive control, with a specific focus on two event-related potentials – the N2 and P3b. Finally, we will review the literature relating cognitive control strategy use to executive functioning.

2.1 Theories and Development of Cognitive Control

2.1.1 What is Cognitive Control?

The world would be a terrifying place if you could only think about one thing at a time. For instance, consider all of the different cognitive systems you use to simply drive a car down the street – you have complex visual input including traffic patterns and road signs, differential motor demands for your hands (steering) and feet (acceleration), cognitive demands including determining your route and recalling traffic laws, and internal motivational systems. If you could only

concentrate on one of these systems at a time, you would never leave your driveway! Luckily, you are able to automate many cognitive processes so they do not have to be actively managed, and many processes can operate in parallel until something happens where processing needs to change. For example, if a deer runs in front of your car, you have to hit the brakes and swerve to miss it. One of the hallmarks of human cognition is its adaptability and ability to prioritize task demands in order to complete a goal – a concept known as *cognitive control* (Botvinick, Braver, Barch, Carter, & Cohen, 2001). Broadly, cognitive control is defined as the ability to optimally prime perception and activation systems in order to achieve a goal (Botvinick et al. , 2001; Munakata et al., 2012). Cognitive control is thought to be employed for non-automatic processes, given that they are sensitive to distraction and interference (Shenhav et al., 2013). Given the importance of cognitive control to daily life and the multi-faceted nature of cognitive control, many theories detailing how cognitive control is enacted have emerged.

2.1.2 Theories of Cognitive Control

One of the complexities facing cognitive control research is the many bodies of research that contribute to our understanding of cognitive control – not only across subject areas (e.g. perception, motivation, cognition) – but also within domains. For instance, research on attention, conflict detection, planfulness, and memory, among others, all contribute to our understanding of cognitive control. While it may be prudent to review all of the major theories concerning cognitive

control, it is not practical. For the purposes of the current study, we will focus on one prominent theory of cognitive control - the Dual Mechanisms of Control (DMC; Braver, 2012; Braver, Gray, & Burgess, 2007), but for reviews of other prominent theories see (Botvinick & Braver, 2015; Botvinick et al., 2001; Fischer, 1980; Nigg, 2017; Shenhav et al., 2013).

The DMC postulates two temporally distinct profiles of cognitive control: reactive control and proactive control (Braver, 2012; Braver et al., 2007). Proactive control is characterized by the early selection and maintenance of goal-relevant information in anticipation of an upcoming stimulus or event. Due to the prolonged time course of proactive control, it is possible for one to optimally bias attention and activation systems in a goal-driven manner. However, the prolonged time course also makes proactive processes more vulnerable to distraction and interruption. Conversely, reactive control is recruited on an as-needed or just-in-time manner, often in response to a high-conflict event. An illustrative example of proactive and reactive control can be found in how one transitions from the far left lane to the right lane in order to exit a multi-lane highway. Someone using a proactive strategy is likely to plan for their impending exit by signaling and slowly transitioning from the far left lane to the far right lane in advance of their exit, while someone using reactive control is likely to see an external reminder (e.g. an exit sign or landmark) and then rapidly cut across lanes in order to make their exit. In sum, the primary difference between proactive and reactive control is their temporal profiles, with proactive control being enacted prior to and sustained until the occurrence of a

goal-relevant event and reactive control being implemented after a goal-relevant event has occurred.

Given the distinct temporal profiles of proactive and reactive control, it follows that they would be supported by differential neural dynamics and chronometry. One cortical region that has been heavily implicated in cognitive control functioning is the prefrontal cortex (PFC) – particularly the dorsolateral prefrontal cortex (DLPFC) and inferior frontal junction (IFJ; Braver et al., 2009). DLPFC activation has been implicated in the active maintenance of goal-relevant information. Anticipatory or sustained activation of the DLPFC prior to task-relevant information has been hypothesized to be reflective of a top-down, planful bias for upcoming cognitive demands, whereas more transient activation of the DLPFC (along with other brain regions) is thought to reflect reflexive, bottom-up activation of task goals (Braver, 2012; Braver et al., 2009). These divergent patterns of activation in the PFC map nicely onto proactive control (sustained activation) and reactive control (transient activation) profiles. Beyond theory, there is empirical evidence for the mapping between proactive and reactive control and activation dynamics within PFC regions (Braver et al., 2009; neural correlates of proactive and reactive control are discussed more extensively later in this chapter).

While proactive and reactive control appear to be distinct constructs, individuals likely use both control mechanisms during daily life (Braver, 2012; Braver et al., 2007). In adulthood, the preferential utilization of a proactive or reactive strategy in any given situation is largely based on the context in which the task is

being completed, the perception of optimal strategy, and the individual's ability to enact the selected strategy (Burgess & Braver, 2010; Speer, Jacoby, & Braver, 2003). Variations in the availability of cognitive resources and the influence of environmental contexts are thought to influence the selection and implementation of control strategies. For instance, it may be optimal to use a more reactive strategy when the environment is complex or there is a high cognitive load since reactive strategies require less sustained attention and are less cognitively demanding. Similarly, there is variation in the appropriateness of the cognitive control strategy employed based on task demands. For example, a participant may elect to use a reactive strategy on a task best suited for proactive control and vice versa. Employing non-optimal strategies may be attributable to a wide variety of factors such as individual differences in cognitive ability, internal states (e.g. stress, anxiety, etc.), motivation, and reward.

In addition to context, it has been hypothesized that the propensity to employ one control strategy over another may be linked to meaningful individual differences – particularly individual differences in value and cost/benefit tradeoffs, which are theorized to be integral to control functions (Braver, 2012; Shenhav et al., 2013). Studies also link individual differences in cognitive control strategy use to a wide array of other cognitive functions, including working memory (Amso, Haas, McShane, & Badre, 2014; Kane & Engle, 2002; Unger et al., 2016), fluid intelligence (Burgess & Braver, 2010; Duncan, Emslie, Williams, Johnson, & Freer, 1996; Kane & Engle, 2002), reward sensitivity (Jimura, Locke, & Braver, 2010; Locke & Braver,

2008; Savine, Beck, Edwards, Chiew, & Braver, 2010), threat sensitivity (Savine et al., 2010), and anxiety (Eysenck, Derakshan, Santos, & Calvo, 2007; Fales et al., 2008; Krug & Carter, 2012). There are data suggesting that cognitive control strategy use may be altered in a number of special populations including individuals with ADHD (Burgess et al., 2010), individuals with schizophrenia (Barch et al., 2001; Braver, Barch, & Cohen, 1999; Cohen, Braver, & O'Reilly, 1996; Sheffield et al., 2014), individuals with negative affect (As measure by the Beck Depression Inventory II; West, Choi, & Travers, 2010), and individuals at risk for anxiety (Henderson et al., 2014). Finally, there is mounting evidence that cognitive control strategy use changes throughout the lifespan, including a transition from reactive control to proactive control in childhood (Chatham et al., 2009; Lorschach & Reimer, 2008, 2010; Lucenet & Blaye, 2014; Munakata et al., 2012), increasing proactive efficiency in adolescence (Andrews-Hanna et al., 2011; Iselin & DeCoster, 2009), and a decline in proactive efficiency in old age (Braver et al., 2001; Czernochowski, Nessler, & Friedman, 2010). In the following section, we will outline more specifically the theories and existing evidence for such developmental shifts.

2.1.4 The Development of Cognitive Control in Childhood

It has been hypothesized that children go through many developmental transitions related to cognitive control throughout the first decade of life (Fischer, 1980; Munakata et al., 2012) and there are many empirical data to support these

claims. However, the precise timing of these transitions and the neural and cognitive mechanisms that support these changes are unclear.

Munakata and colleagues (2012) have hypothesized that children go through three key cognitive transitions. The first transition is the development of the ability to utilize cognitive control in response to environmental stimuli, which enables children to overcome habitual actions. An example of this first transition may be children overcoming the A-not-B error (Piaget, 1954)– a perseverative error in infancy where infants are more likely to search in a place they previously found a toy rather than where they last saw a toy hidden. The second transition that Munakata and colleagues (2015) posit is that children change the temporal dynamics of their cognitive strategies from in-the-moment and as-needed control recruitment (reactive control) to more planful and sustained recruitment (proactive control). However, during this transition, children still rely on external cues to enact control. An example of the second transition may be found in a child being told that they may go out to play after they clean their room. A child enacting reactive control would likely clean their room, but as they cleaned they would forget that they got to go outside until they finished cleaning and were reminded that they could now go outside to play. A child using proactive control may race to clean their room while thinking of their goal (going outside) for the entirety of the time they cleaned. Finally, the third hypothesized control-related transition is from externally-driven control (i.e. motivated by explicit exogenous cues) to more internally generated control (i.e. implementation of actions generated by internally maintained goals). An

example of this third transition may be the change from a child doing their homework after they are told to in order to get something they want (e.g. permission to watch TV) versus a child doing their homework on their own accord in order to get something they want. While all of these transitions are important for cognitive control development in children, the second transition – the transition from reactive to proactive control – is of primary interest for the current study.

To date, there have not been any longitudinal studies tracking the development of proactive control throughout the lifespan. However, if the existing papers are considered together, it is possible to glean a developmental trajectory of proactive control development (the transition from reactive to proactive control will be discussed in detail later in this section). The paper that examines proactive control in the youngest age group is by Chatham and colleagues (2009), and observed that 3.5-year-olds use less proactive control, when compared to 8-year-olds. Similarly, a study of 5- and 6-year-olds found that even across this narrow age range, children exhibit increasing proactive control efficiency with age (Lucenet & Blaye, 2014). Additional studies suggest that proactive control efficiency continues to develop throughout adolescence. For example, 11-year-olds are less adept at detecting and maintaining contextual cues than young adults (Lorsbach & Reimer, 2008). Similarly, children and adolescents (aged 9-15) show less preparatory, or proactive, neural activity as indexed by fMRI when compared to young adults (Church, Bunge, Petersen, & Schlaggar, 2016). Interestingly, in old age there is evidence of a decrease in the efficiency of proactive control (particularly in context

maintenance and representation; Braver et al., 2001; Braver, Satpute, Rush, Racine, & Barch, 2005; Braver & Barch, 2002).

In addition to increases in proactive control across early development, there is an emerging body of literature documenting an important transition from the preferential employment of reactive control to preferential employment of proactive control in typically-developing children (Chatham et al., 2009; Chevalier, Martis, Curran, & Munakata, 2015; Lorscheid & Reimer, 2010; Lucenet & Blaye, 2014; Van Gerven et al., 2016). One study detailing this transition, conducted by Chatham and colleagues (2009), used behavioral and pupillometry data to show that 3.5-year-olds used more reactive control than 8-year-olds, who relied more heavily on proactive control strategies. This finding has been supported by a number of other developmental studies using similar tasks (Lorscheid & Reimer, 2008, 2010; Lucenet & Blaye, 2014), as well as one study using event-related potentials (by examining the Late Positive Potential) and pupillometry which found that 5-year-olds engaged less preparation than 10-year-olds on a task where preparation is advantageous (for more information, see section 2.2.2; Chevalier et al., 2015).

In sum, both theoretical and empirical evidence support that cognitive control develops rapidly during childhood. Although there are no longitudinal studies examining within-child development, the smattering of cross-sectional studies reviewed in this section show not only increasing proficiency in cognitive control functions, but also a shift from the preferential selection of reactive control to proactive control. However, weaknesses in the literature include wide variations

in ages tested, lack of replication in tasks and parameters used, and the sparsity of studies examining the neural activity associated with the transition from reactive control to proactive control.

2.2 Cognitive and Neural Assessments of Proactive and Reactive Control

2.2.1 Tasks used to assess proactive and reactive control

Only a handful of tasks have been used to investigate the development of proactive and reactive control in childhood. Regardless of the task employed, an important aspect of cognitive control assessment is that the tasks allow for different cognitive control strategies to be employed with measurable costs and benefits for using one control strategy (e.g. proactive control) over another (e.g. reactive control). One of the most commonly used tasks to assess proactive and reactive control is the AX Continuous Performance Task (AX-CPT; Braver et al., 2001; Cohen et al., 1999). In an AX-CPT paradigm (see Figure 1 for task schematic), the participant is presented with a series of cue ('A' or 'B') and probe ('X' or 'Y') pairs that require differential responses depending on the cue and probe relationship. Cues that are any letter other than 'A' are called 'B' cues and probes that are any letter other than 'X' are called 'Y' probes. Participants are instructed to make a response to both the cue and the probe for each letter pair. When the 'A' cue is followed by the 'X' probe (70% of trials) the rule is to press a '2' button for the cue and a '1' button for the probe. For all other cue and probe sequences (AY: 10% of trials; BX: 10% of trials; BY:

10% of trials), the participant must press a '2' button for both the cue and probe. The idea behind these differential responses is that proactive control will be employed after the presentation of the cue ('A' or 'B') whereas reactive control will be employed following the presentation of the probe ('X' or 'Y'). Two trial types, or stimuli pair sequences, are used to index the amount a participant favors a proactive strategy over a reactive strategy: AY and BX. AY trials are difficult for participants who are employing proactive strategies because following the presentation of an 'A' cue, it is optimal for participants to prime their response for an 'X' probe since AX trials are much more common than AY trials (70% vs 10%). BX trials, in contrast, are more difficult for participants who are employing reactive strategies since participants must recall what cue ('A' or 'B') preceded the presentation of the 'X' probe. Given the opposing nature of proactive and reactive strategy use, two composites can be computed to reflect the degree of control engaged by a participant. The first composite, known as the Proactive Behavioral Shift Index (PBSI; Braver et al., 2009), compares performance on AY trials relative to BX trials, with higher scores indicating increased used of proactive control. The second composite is the d' context (Cohen et al., 1999; Swets & Sewall, 1963), which compares the sensitivity to the X probe in the presence (AX trials) and absence (BX trials) of an informative contextual cue, and thus provides a measure of sensitivity to context (for more information of the computation for both PBSI and d' context refer to methods section). Higher d' context scores (lower numbers of BX false alarms relative to AX hits) reflect more sensitivity to context (i.e. attributing meaning to the

cue), while lower values (higher numbers of BX false alarms relative to AX hits) reflect less context sensitivity.

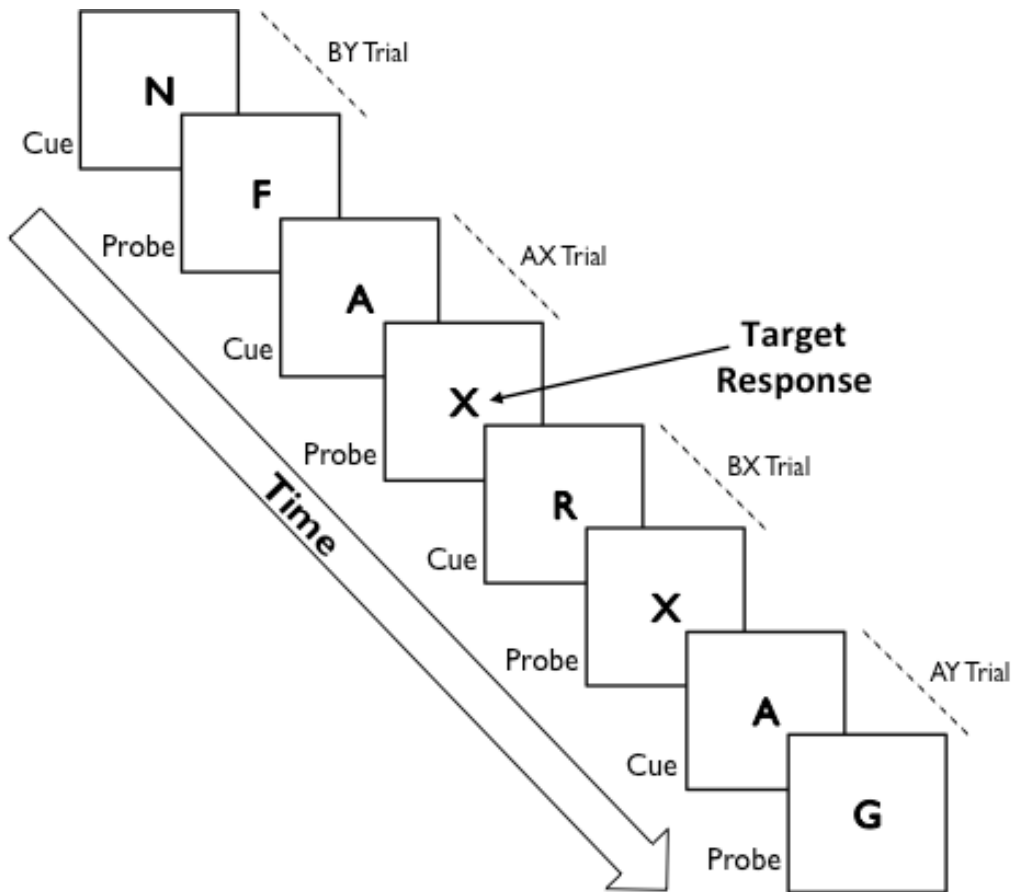


Figure 1. AX-CPT Task.

Another paradigm used to assess the employment of proactive and reactive control during childhood is the cued task-switching paradigm (e.g. Chevalier et al., 2015). In cued task-switching paradigms (also sometimes referred to as cueing paradigm and task-cueing paradigm for review see Monsell, 2003), a participant switches between a number of simple tasks to be performed based on a cue that appears either with or before the stimulus of interest. Behavioral metrics from cued task-switching paradigms commonly include trial accuracy (employing a correct

response) and reaction time (RTs). It is important to note that there are many variants of cued task-switching paradigms, with variable levels of complexity, delays, and degrees of hierarchy (Amso et al., 2014; Chevalier et al., 2015; Unger et al., 2016). One weakness of cued-task switching paradigms is that, while they do effectively index proactive control, they do not directly assess reactive control (Chevalier et al., 2015). More specifically, unlike the AX-CPT, cued task-switching paradigms are unable to parse reactive control from non-controlled processes since it is not possible to directly assess how task conflict influences performance (Chevalier et al., 2015).

It is worth noting that a number of other tasks have been used to assess cognitive control use in children. Many of these tasks are unable to parse proactive and reactive control given that they do not provide enough meaningful information for the participant to optimally prime their cognitive and motor resources. Tasks that fall into this category include standard versions of the Stroop task (Stroop, 1935), Go/NoGo, Flanker (Eriksen & Eriksen, 1974), Dimensional Change Card Sort (Zelazo, 2006), and traditional continuous performance tasks (e.g. Conners; Conners, Staff, Connelly, Campbell, MacLean, & Barnes, 2000).

2.2.2 Neural correlates of proactive and reactive control

A preponderance of the studies examining the neural activation associated with proactive and reactive control in adulthood have utilized functional magnetic resonance imaging (fMRI). These studies examine changes in blood oxygen levels

(BOLD activation) during trials that rely more on proactive versus reactive control. Many fMRI studies in healthy adults found that on DLPFC activation (particularly the left-lateralized activation) is critical for the representation and maintenance of contextual information (Barch et al., 1997; Braver et al., 2009). However, while fMRI provides good spatial specificity detailing regions that are active during trials that utilize either proactive or reactive control, the poor temporal specificity of fMRI makes it difficult to understand the neural chronometry associated with different cognitive control styles. Additionally, there are many difficulties facing task-related fMRI collection in young children including increased movement artifact, difficulty acclimating to the imaging environment, and cognitive fatigue due to increased task lengths (Kotsoni, Byrd, & Casey, 2006), which make the collection of fMRI AX-CPT data in young children very difficult.

Several studies have examined the temporal dynamics of proactive and reactive control in the brain using electroencephalography (EEG), which is easier to employ with young children. However, to date, EEG methods and neural components used to index proactive and reactive control have varied widely. Analysis methods have ranged from time-frequency analyses, event-related desynchronization, and event-related potentials (ERPs). Even within ERP studies, many components of interest have been identified including P1 (Dias, Bickel, Epstein, Sehatpour, & Javitt, 2013; Dias, Butler, Hoptman, & Javitt, 2011), N1 (Dias et al., 2013, 2011; Umbricht et al., 2003), P2 (Umbricht et al., 2003), N2 (Dias et al., 2013, 2011; van Wouwe, Band, & Ridderinkhof, 2011), P3b (Dias et al., 2013; Tekok-

Kilic, Shucard, & Shucard, 2001; van Wouwe et al., 2011), error-related negativity (ERN; Suchan, Zoppelt, & Daum, 2003; van Wouwe et al., 2011), contingent negative variation (CNV; Bickel, Dias, Epstein, & Javitt, 2012; Dias et al., 2013, 2011; van Wouwe et al., 2011), and late positive potential (LPP; Chevalier et al., 2015), among others (Manzi, Nessler, Czernochowski, & Friedman, 2011). Given the large number of methods and measures available, theoretically-driven data analysis is essential. To that end, we will review the literature surrounding components that are both developmentally robust and we believe may be modulated by cognitive control strategy use.

To our knowledge, only one study has utilized EEG to examine proactive and reactive strategy use in early childhood. In a study by Chevalier and colleagues (2015), 5-year-olds and 10-year-olds completed a cued task-switching paradigm while behavioral responses, EEG, and pupillometry were recorded. Following data collection, ERPs were computed for the late posterior positive slow-wave (LPP). Findings from this study suggest that ten-year-olds engaged more proactive strategies when possible, as evidenced by faster RTs, more pronounced cue-locked posterior positivity, and greater cue-related pupil dilation in conditions where proactive control was possible. In contrast, 5-year-olds displayed a bias towards reactive control even when proactive control was possible. Critically, this study also demonstrated that 5-year-olds could engage proactive control when the advantage of proactive control over reactive control was increased, suggesting that 5-year-olds have the ability to enact proactive control but elect not to. The examination of the

late posterior positive slow-wave following the cue presentation provides evidence that older children who used more proactive preparation had a more pronounced LPP activation related to cue processing, though little is known about whether there are developmental changes in how children process target stimuli and identify conflict. While there is evidence for a behavioral shift from reactive to proactive control during childhood, to date, no study has examined the changes in the neural correlates of proactive and reactive control during AX-CPT task performance in typically-developing children under the age of 9.

There is much to be gained from examining developmental changes in how children process task-relevant stimuli and task-related conflict. A number of adult studies have examined such processes using cue-locked and probe-locked ERP components. As previously stated, a large number of components have been examined. However, two components, in particular, have been of great interest – the cue-locked P3b and probe-locked N2.

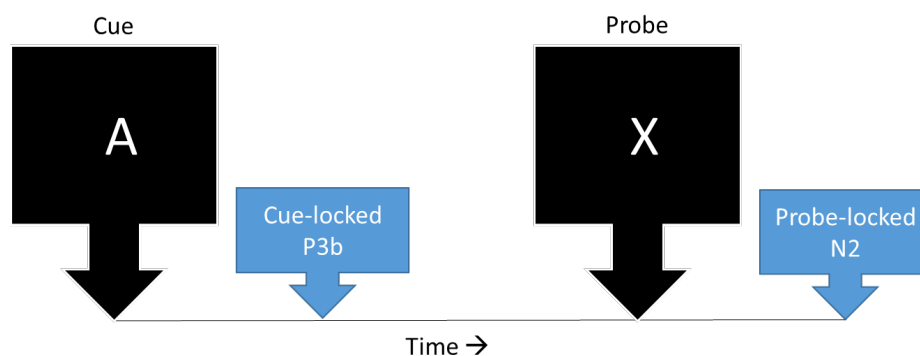


Figure 2. Cue-locked P3b and Probe-locked N2 in an AX-CPT Task.

The cue-locked P3b is a parietal positivity (maximal at electrode Pz; Polich, 2003) that peaks between 350-450 ms following cue presentation (Dias, Foxe, &

Javitt, 2003; Javitt, Shelley, Silipo, & Lieberman, 2000; Tekok-Kilic et al., 2001), is detectable in early and middle childhood (Davis, Bruce, Snyder, & Nelson, 2003; Ridderinkhof & van der Molen, 1995; Rueda, Posner, Rothbart, & Davis-Stober, 2004), and is thought to reflect the detection of infrequent and task-relevant stimuli (Dias et al., 2003; Knight & Scabini, 1998). More specifically, the AX-CPT cue-locked P3b has been thought to reflect target categorization, context-updating, and memory activation of task-relevant information with larger P3b amplitudes to 'B' cues reflecting increased proactive control strategy use (Morales, Yudes, Gómez-Ariza, & Bajo, 2015; van Wouwe et al., 2011). Given the evidence that children transition from more reactive strategies to more proactive strategies over the first decade of life (Chatham et al., 2009; Chevalier et al., 2015; Munakata et al., 2012), it follows that amplitude of the P3b to 'A' and 'B' cues may also change, although no study has examined this transition.

The probe-locked N2 is a fronto-central negativity that peaks between 150-300 ms following probe presentation (Van Veen & Carter, 2002b) and is detectable in early and middle childhood (Davis et al., 2003; Rueda et al., 2004). The N2 is thought to index conflict detection with larger amplitudes for less frequent responses, inhibiting prepotent responses, and reconciling response conflict. Source localization data suggesting that the N2 is generated in the anterior cingulate cortex (ACC; Lamm, Zelazo, & Lewis, 2006; Van Veen & Carter, 2002a, 2002b; Yeung, Botvinick, & Cohen, 2004). Given that proactive control relies on the optimal priming of resources following cue presentation, the probe of BX trials should be low conflict

for participants utilizing proactive strategies since the 'B' cue is always followed by the same probe response. In contrast, the probe presentation of AY trials should be high conflict and evoke a larger N2 since an 'A' cue is most commonly followed by an 'X' probe. Thus, the preparatory response for an 'A' cue should be an 'X' response, which would make the presentation of a 'Y' stimuli a high conflict event. It follows that the aforementioned pattern would be reversed in participants using reactive strategies since BX trials should be high conflict (larger N2) due to the 'X' probe being presented and AY trials should evoke low conflict (smaller N2) since the probe is not an 'X'. Given the differential patterns of conflict elicited by the probe stimulus in proactive and reactive control, children should show alterations in N2 amplitude as they transition from reactive to proactive control, although this has yet to be examined.

2.3 Executive Functioning and Cognitive Control

While theory and data both suggest that children transition from more reactive cognitive control strategies to more proactive strategies during the first decade of life (Chatham et al., 2009; Chevalier et al., 2015; Munakata et al., 2012), the cognitive mechanisms that support this change are largely unknown. Executive functions, or a grouping of cognitive skills thought to be necessary for guiding goal-relevant behaviors, also develop rapidly over the first decade of life (Davidson et al., 2006; De Luca et al., 2003; Zelazo, Carter, Reznick, & Frye, 1997; Zelazo, Muller, Frye, & Marcovitch, 2003) and are thought to be intimately related, yet separable (both

behaviorally and neurally), from cognitive control (Davidson et al., 2006; Miyake et al., 2000; Niendam et al., 2012). While the transition from reactive control to proactive control occurs during a time of rapid executive development, few studies have examined the relations between executive skills and proactive and reactive control use during childhood. The prevailing theory of executive functioning contends that three separable cognitive skills comprise executive functions – attention shifting, working memory, and inhibitory control (Miyake et al., 2000), each of which may uniquely contribute to reactive and proactive control.

A number of studies have shown that working memory skills are related to rule-guided behaviors in childhood and adulthood. It has been theorized that young children may rely on reactive control simply because they are unable to remember and maintain task-relevant information (Munakata et al., 2012). Indeed, there are data that suggest working memory supports proactive strategy use in children. A series of two studies conducted by Amso, Badre, and colleagues (Amso et al., 2014; Unger et al., 2016), demonstrated that the development of rule-guided behaviors and cognitive control are linked to memory gating efficiency. More specifically, their results indicated that children engage more reactive-style control and the less efficient selective input gating strategies (working memory) when compared to adolescents (Unger et al., 2016). Furthermore, their results show that children who used more adolescent-like memory strategies also had better task performance, suggesting that working memory may be intimately related to more planful control strategies. Furthermore, there is neural evidence in adulthood for a link between

working memory and proactive control. Functional neuroimaging data has implicated the dorsolateral prefrontal cortex (DLPFC) in both working memory and proactive control paradigms (Aron, 2011; Braver et al., 1997, 2009; Bunge, Ochsner, Desmond, Glover, & Gabrieli, 2001; Müller & Knight, 2006). Additionally, pharmacologically reducing the functionality of the DLPFC in monkeys causes impairment in both preparatory inhibition and working memory (Li, Mao, Wang, & Mei, 1999; Ma, Qi, Peng, & Li, 2003). Together, while these studies suggest a relation between cognitive control and working memory, it is unclear whether working memory, over and above other executive functions, is responsible for the transition from reactive to proactive control. To date, we are not aware of any studies in children or adults that concurrently measure all three domains of executive functions as well as proactive and reactive control in order to understand whether working memory supports proactive functioning.

Inhibitory control, or the ability to stop a prepotent response, has been related to both proactive and reactive control strategies. A review by Aron (2011) postulates two separable kinds of inhibition: proactive inhibition and reactive inhibition. Similar to proactive and reactive cognitive control, proactive and reactive inhibition have different loci of enactment and time courses: reactive stopping is more post-hoc and in response to an external signal, while proactive stopping is preparatory and enacted in accordance with internally maintained goals. Additionally, Aron (2011) postulates differential neural circuits for selective proactive and reactive inhibition: an inferior frontal cortex-caudate-striatum circuit

for reactive stopping and a DLPFC-caudate-striatum for proactive stopping. Given these separable profiles of inhibition, it stands to reason that the shift from reactive to proactive control during childhood may be related to a shift from reactive to proactive inhibition. Indeed, research in children supports that two different kinds of inhibition exist during childhood: monitoring-related inhibition (more proactive in nature) and motoric inhibition (more reactive in nature; Chevalier, Chatham, & Munakata, 2014). Given these separable systems, it seems likely that reactive and proactive cognitive control may rely on different inhibitory processes. Specifically, it is likely that reactive control would be more closely related to more motoric stopping utilizing a fronto-basal ganglia circuitry, while proactive control would be related to more context-monitoring-dependent and rely on fronto-striatal circuitry. To our knowledge, no studies have directly examined the relations between individual differences in proactive and reactive control and inhibitory control in children.

The relation between attentional control, or attention shifting, and cognitive control strategy is more heterogeneous. To broadly review, proactive control is thought to increase sustained attention and to optimally bias attentional processes for task demands, while reactive control relies more on automatic and conflict-based attentional processes (Miller & Cohen, 2001; Stuphorn & Emeric, 2012). Another way to think of differential attentional demands of proactive and reactive strategies is that proactive processes rely on predictive and more sustained action control, which requires sustained internal goal maintenance and top-down attention but less

bottom-up attention to external cues, while reactive control is associated with instantaneous attentional focus (i.e. orienting and alerting) to task-relevant stimuli (Petersen & Posner, 2012; Tops, Boksem, Quirin, IJzerman, & Koole, 2014). To our knowledge, no studies have directly examined the relations between individual differences in proactive and reactive control and attention shifting in children.

In sum, theory suggests that executive skills are integral to cognitive control. Given that both cognitive control and executive skills develop rapidly during childhood, it seems possible that individual differences in cognitive control strategy may be related to developmental differences in executive functioning. However, to our knowledge, no study has collected both a comprehensive assessment of individual executive functions (i.e. inhibition, working memory, and attention shifting) and proactive/reactive control in early and middle childhood in order to examine the relations between executive functions and cognitive control development. Without such a study, it is difficult to ascertain the relation between executive functioning and cognitive control – particularly in childhood when both skill sets are changing rapidly.

2.4 Summary and Conclusions

One of the hallmarks of the first decade of life is the emerging ability to maintain and complete increasingly complex goal-driven behaviors – due in large part to the development of cognitive control. As reviewed in this chapter, children become increasingly efficient at managing their cognitive resources through early

and middle childhood, with control becoming less externally-driven (reactive) and more planful and sustained (proactive; Munakata et al., 2012). While this transition has been documented in a number of studies, much is still unknown about the perceptual and cognitive mechanisms that support this change. For instance, although behavioral and pupillometric data suggests that children employ different control strategies, it is unclear whether neural activation related to the processing of task-relevant stimuli changes in relation to the cognitive control strategy they employ.

Studies examining the neural correlates associated with proactive and reactive control in adulthood have identified two candidate neural components that might provide insights into children's processes of cognitive control demands – the cue-locked P3b and the probe-locked N2. Modulations (or lack thereof) in these components are of particular interest since they would provide insight as to whether children encode cue stimuli (P3b) and detect conflict (N2) differently based on control strategy.

Additionally, this chapter reviewed relevant theories and evidence linking cognitive control and executive functions. Given that there is clear evidence of executive skills developing in concert with cognitive control, surprisingly little is known about the interaction of these domains during childhood. In sum, much is still to be understood concerning the development of cognitive control during childhood – particularly in regards to our understanding of neural markers of cognitive control strategy use and the relations between cognitive control and executive functions.

Chapter 3: The Current Study

3.1 Statement of the Problem

Childhood is characterized by a period of protracted cognitive development. To date, much of the research detailing the developmental changes associated with cognitive development during childhood have focused on individual cognitive skills, such as executive functions, and less on the interaction between multiple cognitive domains. However, given that real-world functioning requires rapid management and implementation of a wide array of cognitive skills, understanding how children learn to manage their cognitive resources throughout development is of increasing interest. As such, an expanding body of research in the area of *cognitive control* aims to understand how children prepare and employ cognitive resources in order to complete a goal.

While there are a number of theories of cognitive control, one model that has garnered a great deal of attention is the Dual Mechanisms of Control theory (DMC; Braver, 2012). The DMC postulates that there are two kinds of cognitive control: proactive control and reactive control. Proactive control requires that goal-relevant information actively is maintained in order to optimally bias attention and action systems in order to complete a goal. In contrast, reactive control is recruited on an as-needed basis in response to the detection of a goal-relevant event. While the DMC has received much attention in adults, only a few studies have examined the development of proactive and reactive control during childhood.

It has been theorized that children shift from a preferential reliance on reactive control strategies to a preferential reliance on proactive control strategies during the first decade of life (Munakata et al., 2012). Preliminary evidence suggests this transition from reactive to proactive control takes place in middle childhood (Chatham et al., 2009; Lorschach & Reimer, 2008, 2010; Lucenet & Blaye, 2014; Unger et al., 2016). However, only a few studies have concurrently measured proactive and reactive control strategies and shown evidence for this transition. As such, Aim 1 of the current study attempts to replicate prior findings suggesting that children transition from reactive to proactive control using an adapted version of an AX-CPT (Braver, 2012; Chatham et al., 2009).

Little is known about what developmental phenomena support the transition from reactive to proactive control during childhood. One hypothesis is that the rapid maturation of the neural networks supporting cognitive control may allow for more complex reasoning to come “online” during childhood and adolescence (Mahy & Munakata, 2015; Munakata et al., 2012). As such, children may begin to process stimuli and task goals differently. However, little is known about the neural correlates associated with the shift from reactive to proactive control during childhood. Aim 2 of the present study investigates whether the neural correlates associated with context updating and conflict detection change as a function of cognitive control strategy selection.

In addition to neural development, cognitive functioning also develops rapidly during early and middle childhood (Mahy & Munakata, 2015; Munakata et

al., 2012). Specifically, executive functions, which are thought to support cognitive control, have a protracted developmental timeline that spans into adolescence (Davidson et al., 2006). Two recent studies suggest that increases in cognitive control during childhood and adolescence are linked to working memory development (Amso et al., 2014; Unger et al., 2016). However, no studies have tested a comprehensive set of executive functions and their associations with proactive and reactive control during early and middle childhood. This question is addressed by Aim 3 of this study.

The goal of the present study is to apply the theoretical framework of the DMC to enhance our understanding of the development of cognitive control during childhood. More specifically, the current study aims to document the transition from reactive to proactive control during middle childhood as well as to investigate the cognitive predictors and neural correlates that support this transition. To date, there is little empirical support for the transition from reactive to proactive control during childhood. Thus, the overall aim of the present study is to elucidate the neural correlates and cognitive underpinnings of proactive and reactive control in a cross-sectional sample of children.

3.2 Overview of the Present Study

The present study investigates the behavioral and neural correlates of proactive and reactive cognitive control strategies in early and middle childhood. Additionally, this study is one of the first to examine the executive skills supporting

cognitive control strategies in childhood. This is accomplished by comparing two samples of children: one that, based on existing literature, we expect to rely heavily on reactive strategy use (5-year-olds) and one that, based on existing literature, we expect to rely more heavily on proactive strategy use (9-year-olds; Chatham et al., 2009; Chevalier et al., 2015; Lorscheid & Reimer, 2010; Lucenet & Blaye, 2014; Van Gerven et al., 2016). Children completed an adapted version of the AX-CPT as well as a battery of cognitive tasks indexing different executive skills.

3.3 Research Aims and Hypotheses

3.3.1 Aim 1: Examine whether development is associated with changes in cognitive control strategy use.

Hypothesis 1: The present study tested whether 5-year-olds rely more on reactive cognitive control strategies, while 9-year-olds rely more on proactive control strategies. It was hypothesized that 5-year-old children would rely much more on stimulus-driven reactive strategies resulting in poorer behavioral performance on BX trials relative to AY trials, while 9-year-old children would rely more on planful proactive strategy use resulting in poorer behavioral performance on AY trials relative to BX trials.

3.3.2 Aim 2: Examine whether development in cognitive control strategy is accompanied by altered patterns of neural activation.

Hypothesis 1: The present study tested whether the N2 is enhanced when participants are presented with high conflict trials, and whether N2 activation changes dynamically based on cognitive control strategy use. It was expected that N2 amplitude would be enhanced on trials that are high conflict for the participant. Given that the cognitive control strategy employed by a participant should alter what trial types are high conflict, it was expected that 5-year-old children utilizing reactive strategies would exhibit larger N2 amplitude on BX trials relative to AY trials, while 9-year-old children using proactive strategies would exhibit larger N2 amplitudes on AY trials relative to BX trials.

Hypothesis 2: This study tested whether the P3b is enhanced when participants utilize a proactive strategy. It is expected that P3b amplitude would be enhanced when the cue elicits context updating. Specifically, we expected that 'B' cues would be associated with larger P3b amplitudes as compared to 'A' cues when participants employed a proactive strategy, but not when they used reactive strategies. Given this hypothesis, we expect that 9-year-old children would show an enhanced P3b to 'B' cues when compared to 'A' cues, while 5-year-old children would not show this differentiation.

3.3.3 Aim 3: Examine which executive skills are associated with proactive and reactive strategy use.

Hypothesis 1: The present study examined which executive skills are associated with both proactive and reactive strategy use. It was expected that proactive and reactive strategy use would be associated with different underlying executive skills.

Specifically, based on prior research, we expected that proactive control would be most strongly associated with working memory, while reactive control would be most strongly associated with inhibitory control.

Chapter 4: Methods

4.1 Procedures and Methods

4.1.1 Participants

Seventy-nine children – forty-one 5-year-olds and thirty-eight 9-year-olds – were recruited for participation in this study. Following IRB approval, participants were recruited using referral and the University of Maryland Infant and Child Studies Consortium database.

Given that this study aimed to recruit typically developing children, participants were excluded from participation if parents reported any current psychiatric disorders, previous brain injury, significant birth defects, significant or uncorrected visual impairments, any physical disability that may impede their ability

to complete the task, and/or any prescribed medication for neurological or mental health issues. One child (age 5) was excluded after consent due to a previously undisclosed autism diagnosis, which prohibited the child from completing the experimental visit. As such, our final sample consisted of forty 5-year-olds ($M_{\text{age}} = 5.35$ years; $SD = .37$ years) and thirty-eight 9-year-olds ($M_{\text{age}} = 9.05$ years; $SD = .43$ years).

4.1.2 Procedure

Upon arrival at the laboratory, parents were informed of all procedures and informed consent was obtained. Children were also informed of the study procedure and assent was obtained when applicable. Following consent, parents completed questionnaires. Following assent, children were led to a physiology collection room where they were fitted with an EEG net and asked to perform the AX-CPT task. Following the completion of the AX-CPT, the child completed the NIH toolbox assessment. Finally, all families were compensated \$20 and children selected a small prize.

4.1.3 Questionnaires

Demographics Questionnaire: Parents completed one standard demographics questionnaire. Information collected included age of participant, race, maternal and

paternal education, household income, number of siblings, current medications, and other relevant information.

4.1.4 Experimental Design

4.1.4.1 Laboratory Task

An adapted version of the AX Continuous Performance Task (AX-CPT; Barch et al., 1997; Braver, 2012; Braver et al., 2001; Cohen et al., 1999) was administered using e-prime stimulus presentation software (Psychology Software Tools, Inc., Sharpsburg, PA). The AX-CPT was comprised of 4 trial types – AX, AY, BX, BY (see Figure 3 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.

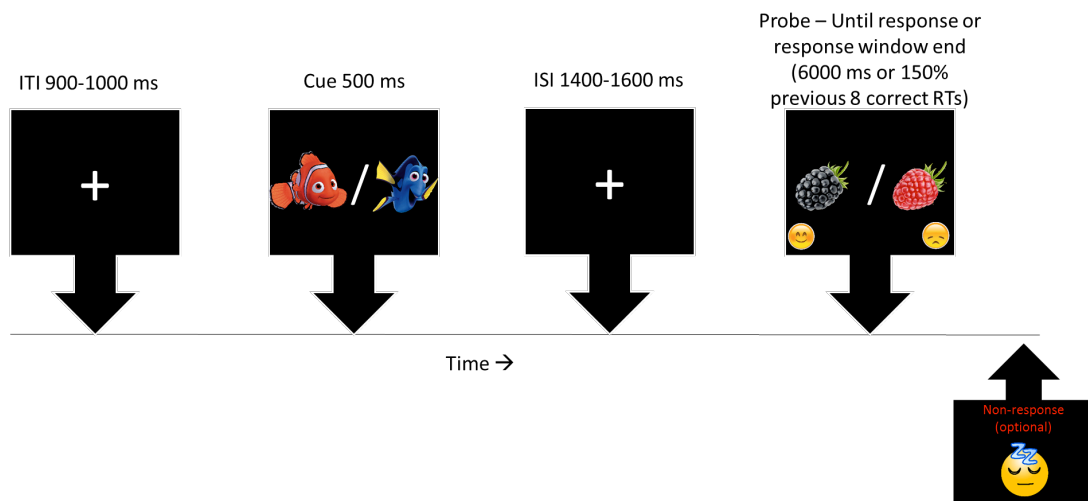


Figure 3. Child AX-CPT Schematic.

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, as opposed to responding after both the cue and probe in the adult versions of the task. Each trial began with a centrally located fixation cross followed by one cue stimulus (A or B), which was presented for a duration of 500 ms. The cue stimulus was followed by a randomized interstimulus interval of 1400 to 1600 ms. Finally, one of two probe stimuli (X or Y) was presented until the participant responded or until the conclusion of a predetermined response window. To encourage sustained attention, participants were encouraged to respond as quickly as possible and a dynamic response window was used. Consistent with past research (Chatham et al., 2009), the initial response window was set to 6000 ms, but was adjusted to be a maximum of 150% of the previous 8 correct responses. Eight versions of the task were programmed to ensure that cue and probe pairings were counterbalanced across participants.

Prior to beginning the task, participants completed a practice block of 12 trials, which had to be completed at 70% accuracy or greater in order 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 8 blocks (320 stimuli pairs), although participants only completed around 6 blocks on average ($M_{\text{trials}} = 236.13$; $SD = 52.07$). Trials with response times faster than 100 ms were removed all from analyses. Additionally, reaction times (RTs) from correct trials for each trial type were z-transformed with respect to each subject's grand mean RT across all correct trials to increase statistical power and correct for individual differences in overall processing speed (Chatham et al., 2009; Paxton, Barch, Racine, & Braver,

2008). Accuracy was calculated as the number of correct trials divided by the total number of trials. Accuracy and response times were separately averaged for AX, AY, BX, and BY trials for each participant in each condition. To ensure participants understood task instructions, participants with <60% accuracy on BY trials were excluded from all analyses (N=1 ;Chatham et al., 2009). Additionally, two behavioral composites were computed – the PBSI and d' context. The first composite, known as the PBSI (Braver et al., 2009), compares performance on AY trials relative to BX trials. Higher scores indicate increased use of proactive control and lower scores indicate more reactive strategy use. The PBSI was computed for both errors and RT. In addition, a PBSI sum was computed by adding the PBSI for errors to the PBSI for RT. The equation used to compute the PBSIs was as follows:

$$PBSI = \frac{(AY - BX)}{(AY + BX)}$$

Consistent with past research (Braver et al., 2009), the following correction was made for the PBSI accuracy computation to avoid errors equaling to zero: (error+0.5)/(frequency of trials+1). The second composite computed was the d' context (Cohen et al., 1999; Swets & Sewall, 1963), which compares the sensitivity to the X in the presence and absence of an informative contextual cue, and thus provides a measure of sensitivity to context. To do this, we examine performance on two trial types -- AX and BX. These trial types have the same probe (X) but different cues (A vs B). To calculate the measure, we take hits on AX trials and subtract the false alarms on BX trials. For instance, if the participant guessed every time they saw

an 'X' probe because they did not remember the cue, they would have approximately 50% AX hits and 50% BX false alarms -- a score near 0. The more a participant remembers the cue identity (A vs B) the more accurate they should be on AX and BX trials, which increases the AX hit rate and decreases the BX false alarm rate, thus yielding a higher d' context score. The higher the score you have, the more you used cue identity to inform your response. The d' context was computed using the following SPSS syntax:

```
d' context= idf.normal(AX hit rate, 0,1)-idf.normal(BX false alarm rate, 0,1)
```

Hit rates and false alarms with a value of zero or one were corrected with methods consistent with past research (Nuechterlein, 1991).

To ensure that participants understood the task and that substantial task learning did not take place during the earlier blocks, performance was examined block-by-block within each age group (see Figure 4). For both the 5-year-olds and 9-year-olds, performance on any single block did not significantly differ from either neighboring block (5-year-olds: $ps > .092$; 9-year-olds: $ps > .097$). Importantly, there also did not appear to be any learning effect between Block 1 and 2 (as evidenced by no increase in accuracy), which suggests that the practice trials were sufficient for learning task rules.

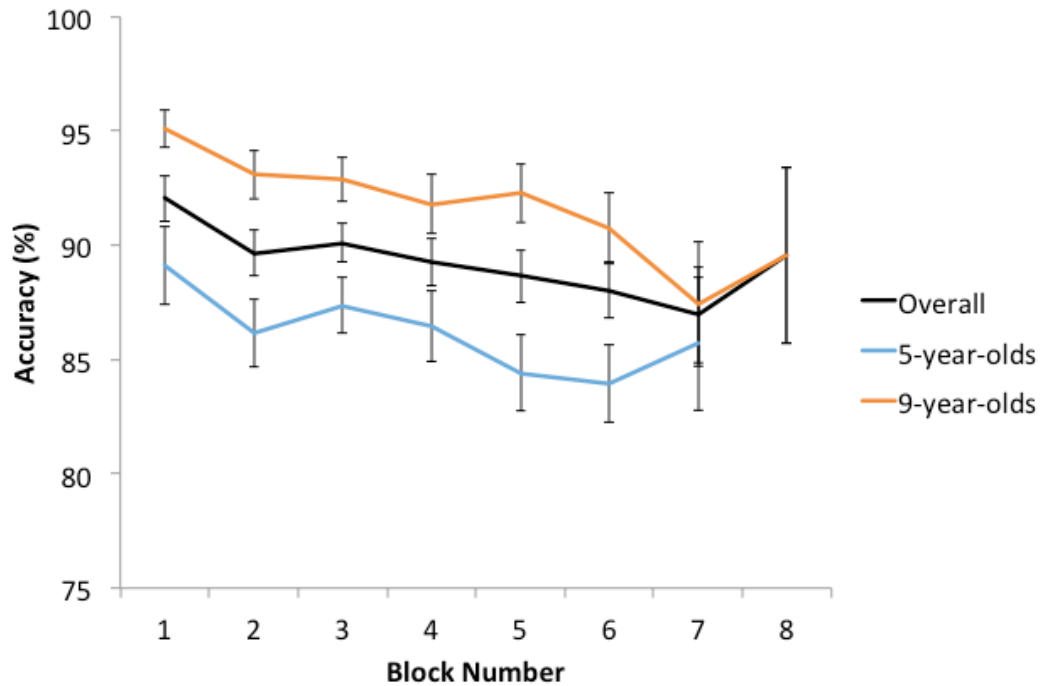


Figure 4. Performance by block and age group. Error bars reflect the standard error of the mean.

4.1.4.2 EEG Recording and Processing

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

Cue-locked P3b Processing

Data were filtered offline using a digital band-pass FIR filter from .3-50 Hz. Data were segmented separately for 'A' cue and 'B' cue trials from 200 ms before the presentation of the cue to 1000 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 than any neighboring channel. Channels were marked globally bad if the correlation between neighboring channels was less than .30 or if the channel was bad on greater than 20% of trials (A trials: 4.9% of channels, B trials: 4.9% of channels). Trials were marked bad if more than 20% of channels were determined to be bad (A trials: 27.7% of trials, B trials: 27.2% of trials). Bad channels on remaining good trials were replaced using spherical spline interpolation (Perrin, Pernier, Bertrand, & Echallier, 1989). Participants needed at least 10 artifact-free trials in each condition to be included in the analysis. The P3b was evaluated as the mean amplitude between 350-650 ms (Morales et al., 2015) following cue presentation at a grouping of parietal electrode at the midline surrounding electrode Pz (electrode numbers 54, 61, 62, 67, 72, 77, 78, 79,).

Probe-locked N2 Processing

Consistent with past AX-CPT studies examining the N2 (van Wouwe et al., 2011), data was filtered offline using a digital bandpass filter from 2-12 Hz in order to isolate the N2 and to filter out the low-frequency waves from the EEG stemming from the rising P3b (Donkers, Nieuwenhuis, & van Boxtel, 2005; Donkers & van

Boxtel, 2004; van Wouwe et al., 2011). Data were segmented separately for all four trials types: AX, AY, BX, BY. Segments began 200 ms before the presentation of the probe and ended at 1000 ms following probe presentation. Only trials that resulted in a correct behavioral response were analyzed. Channels were marked bad if electrode amplitude exceeded 150 μ V or when a channel differed by more than 40 μ V than any neighboring channel. Channels were marked globally bad if the correlation between neighboring channels was less than .30 or if the channel was bad on greater than 20% of trials (AX: 3.5% of channels, AY: 3.6% of channels, BX: 3.6% of channels, BY: 3.5% of channels). Trials were marked bad if more than 20% of channels were determined to be bad (AX: 5.1% of trials, AY: 5.2% of trials, BX: 5.5% of trials, BY: 5.3% of trials). Bad channels on remaining good trials were replaced using spherical spline interpolation (Perrin et al., 1989). Consistent with other studies examining the N2 in children, participants needed at least 15 artifact-free N2 trials to be included in the analysis (Espinet, Anderson, & Zelazo, 2012). The N2 was evaluated as the mean amplitude between 300-500 ms following probe presentation at a fronto-central electrode cluster at the midline surrounding FCz (electrode numbers 5, 6, 7, 11, 12, 13, 106, 112) where the N2 is maximally negative in children (Espinet et al., 2012).

4.1.4.3 NIH Toolbox Childhood Cognition Battery:

The NIH toolbox cognition battery (Weintraub, Dikmen, et al., 2013) is a validated cognitive assessment tool constructed by a team of scientists in

collaboration with the National Institute of Health (NIH). The NIH Early childhood cognitive assessment battery includes five short tasks aimed at assessing cognitive functioning in children (Weintraub, Bauer, et al., 2013; Zelazo et al., 2013). Three tasks are specifically aimed at assessing executive functions in young children: the Dimensional Change Card Sort (DCCS) as a measure of attention shifting (Frye, Zelazo, & Palfai, 1995; Zelazo, 2006), the Flanker as a measure of inhibitory control (Eriksen & Eriksen, 1974), and the List Sorting Working Memory test as a measure of working memory (Tulsky et al., 2013). As is standard for all NIH Toolbox assessments, task data was scored using the NIH Toolbox iPad app. All tasks have been normed and validated for longitudinal cognitive measurement from age 3 to 85 (Akshoomoff et al., 2013, 2014; Beaumont et al., 2013).

4.2 Data Analysis Plan

Prior to exploring the main study aims, multiple Pearson's correlations were conducted to explore the intercorrelations between age, performance on the AX-CPT, and executive functioning.

4.2.1 Behavioral Data Analyses

Behavioral analyses took place in three steps. The significance level was set at .05 for all analyses and Bonferroni corrections for multiple comparisons were utilized where appropriate.

First, accuracy and reaction times were analyzed separately using a 2 Group (5-year-old, 9-year-old) by 2 Condition (AY, BX) repeated measures ANOVA. Second, consistent with past studies utilizing the AX-CPT to assess cognitive control strategy use, three PBSI indices were computed (Braver et al., 2009) – one for PBSI accuracy, one for PBSI RT, and the combined PBSI sum. Group differences in the PBSI indices were tested using an independent sample t-test for each composite. Next, consistent with past studies utilizing the AX-CPT to assess cognitive control strategy use, one d' context index was computed (Cohen et al., 1999; Swets & Sewall, 1963). Group differences in d' context were tested using an independent samples t-test. Finally, to examine whether cue or probe relationships were driving responding within each age group, partial correlations, controlling for AX reaction times, were conducted for AY, BX, and BY trials.

4.2.2 ERP Data Analyses

ERP analyses took place in two steps. The significance level was set at .05 for all analyses. 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. Second, to evaluate the probe-locked N2, a 2 Group (5-year-old, 9-year-old) by 2 Condition (AY, BX) repeated measures ANOVA was conducted. 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. Greenhouse-Geisser corrections and Bonferroni corrections for multiple comparisons were applied when

necessary. Finally, relations between ERP components and cognitive control strategy were examined by correlating component amplitudes with the PBSI sum and the d' context scores. If a significant correlation exists, correlations will be run separately for each group and compared using a Fisher r -to- z transformation to examine if the association is stronger in the 5-year-old or 9-year-old group.

4.2.3 Executive Function Analyses

Given that we hypothesized that 5-year-olds would rely more heavily on reactive control while 9-year-olds would rely more heavily on proactive control, analyses of the relation between cognitive functioning and cognitive control strategy use took place in two steps.

First, separate linear regressions were conducted for the 5-year-old and 9-year-old groups. For each age group, uncorrected scores from all three of the NIH toolbox executive tasks (DCCS, Flanker, and List Sorting Working Memory) were regressed onto the d' context and PBSI scores. These analyses revealed the executive skills associated with proactive and reactive strategy use in each age group.

Second, differences in cognitive functioning between groups were investigated using linear regression. To ensure the appropriate statistical analyses were conducted, the distribution and kurtosis of the d' context and PBSI scores were examined. Given that both variables had a normal distribution, a series of linear regressions were performed. First, separate linear regressions were performed with the uncorrected score of each executive skill serving as a predictor variable. In each

of these regressions, age group (dichotomously coded), executive skill (attention shifting, inhibition, and working memory), and an age by executive skill interaction term was regressed onto the PBSI and d' context. Next, all three executive skills and the associated interaction terms were entered into a single model to examine which executive skills predicted cognitive control strategy while controlling for the other entered executive skills.

4.3 Participant Inclusion

Seventy-nine children – forty-one 5-year-olds and thirty-eight 9-year-olds were recruited for participation in this study (see Table 1 for participant exclusion for each measure). One child (age 5) was excluded after consent due to a previously undisclosed autism diagnosis, which prohibited the child from completing the experimental visit. As such, our final sample consisted of forty 5-year-olds ($M_{\text{age}} = 5.35$ years; $SD = .37$ years) and thirty-eight 9-year-olds ($M_{\text{age}} = 9.05$ years; $SD = .43$ years)

For all behavioral and ERP analyses, one additional 5-year-old excluded due to less than 60% accuracy on BY trials. Additionally, for the P3b analyses, one 9-year-old was excluded due to refusing the cap and a total of five 5-year olds were excluded – three for refusing the cap and two due to an insufficient number of correct and artifact-free B trials. For the N2 analyses, one 9-year-old was excluded due to refusing the cap and a total of thirteen 5-year olds were excluded – three for

refusing the cap and ten due to an insufficient number of correct and artifact-free 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. For the List Sorting Working Memory (LSWM) task, a total of five 5-year-olds were excluded – one due to time constraints and four due to an inability to understand the task.

Enrolled		Behavioral		P3b ERP		N2 ERP		Flanker		DCCS		LSWM	
5	9	5	9	5	9	5	9	5	9	5	9	5	9
40	38	39	38	34	37	26	37	38	38	38	38	34	38

Table 1. Participant exclusion by age for each measure of interest.

Chapter 5: Results

5.1 Intercorrelations between variables of interest

Table 2 presents the correlations between age, performance on the AX-CPT, and executive functioning as well as means and standard deviations.

	1.	2.	3.	4.	5.	6.	7.	8.
1. Age	1							
2. PBSI Accuracy	.500**	1						
3. PBSI RT	.252*	.374**	1					
4. PBSI Sum	.503**	.973**	.579**	1				
5. d' context	.613**	.639**	.182	.607**	1			
6. Flanker (uncorrected)	.760**	.437**	.356**	.473**	.516**	1		
7. DCCS (uncorrected)	.730**	.413**	.320**	.443**	.415**	.695**	1	
8. LSWM (uncorrected)	.792**	.401**	.202	.410**	.553**	.737**	.615**	1
M	7.1872	-.0375	.1490	.1115	2.5257	75.3421	78.2368	83.0139
SD	1.8934	.48013	.13692	.54627	.96255	21.3076	21.2112	18.3744

**<.01 *<.05

Table 2. Zero-order correlations, means, and standard deviations of measures of interest.

5.2 Aim 1: Examine whether development is associated with changes in cognitive control strategy use

Analyses examining how development is associated with change in cognitive control strategy used took place in three steps.

First, mean accuracy and RTs by condition are reported in Table 3. To examine whether there were developmental differences in accuracy and reaction time (RT) on the AX-CPT task, two 2 Group (5-year-old, 9-year-old) by 2 Condition (AY, BX) repeated measures ANOVAs were conducted. The model examining accuracy revealed a main effect for Group $F(1, 75) = 11.82, p = .001, \eta^2 = .136$ and a marginal main effect of Condition $F(1, 75) = 3.13, p = .081, \eta^2 = .040$, both of which were qualified by a significant group by trial interaction $F(1, 75) = 21.62, p < .001, \eta^2 = .224$. Bonferroni-corrected follow-up tests revealed that 5-year-olds performed better on AY ($M = 84.97\%, SD = 11.09\%$) trials relative to BX trials ($M = 72.13\%, SD = 16.81\%$), $F(1, 75) = 20.87, p < .001, \eta^2 = .218$. The reverse was true for 9-year-olds who showed better performance on BX trials ($M = 88.92\%, SD = 10.81\%$) relative to AY trials ($M = 83.16.2\%, SD = 12.22\%$), $F(1, 75) = 4.09, p = .047, \eta^2 = .052$. Finally, 5-year-olds ($M = 72.13\%, SD = 16.81\%$) performed significantly worse than 9-year-olds ($M = 88.92\%, SD = 10.81\%$) on BX trials $F(1, 75) = 27.031, p < .001, \eta^2 = .265$. The two groups did not differ in performance on AY trials $F(1, 75) = .467, p = .497, \eta^2 = .006$.

	<u>5 Year</u> (N=39)	<u>9 Year</u> (N=38)	<u>5 vs 9</u>
Total Trials Completed	217.79 (50.00)	260.05 (33.37)	-4.458 (<.001)
AX Accuracy	88.67 (8.1)	94.08 (6.1)	-3.411 (.001)

AY Accuracy	84.97 (11.1)	83.16 (12.2)	.441 (.660)
BX Accuracy	72.13 (16.8)	88.92 (10.8)	-5.301 (<.001)
BY Accuracy	91.62 (7.1)	97.76 (3.7)	-3.221 (.002)
AX RT (not z-transformed)	1502.53 (426.13)	748.18 (347.23)	8.603 (<.001)
AY RT (not z-transformed)	1730.23 (423.95)	825.17 (329.54)	10.507 (<.001)
BX RT (not z-transformed)	1430.19 (635.46)	591.75 (312.62)	6.998 (<.001)
BY RT (not z-transformed)	1466.67 (405.45)	595.06 (302.30)	10.713 (<.001)

Table 3. Descriptive statistics for each age group (mean and standard deviation in parentheses) and group differences (t value and significance in parentheses).

Analyses examining group differences in reaction time revealed a main effect for Condition $F(1, 75) = 90.640, p < .001, \eta^2 = .547$ but no main effect of Group, which was not unexpected due to the z-transformation procedure $F(1, 75) = 2.07, p = .155, \eta^2 = .027$. A significant Group by Condition interaction also emerged $F(1, 75) = 8.55, p = .005, \eta^2 = .102$. Bonferroni-corrected follow-up tests revealed that both 5-year-olds and 9-year-olds were slower on AY trials (5: $M = .24, SD = .29$; 9: $M = .34, SD = .27$) relative to BX (5: $M = -.11, SD = .32$; 9: $M = -.32, SD = .24$) trials (5: $F(1, 75) = 22.04, p < .001, \eta^2 = .227$; 9: $F(1, 75) = 76.45, p < .001, \eta^2 = .505$). Additionally, 5-year-olds ($M = -.11, SD = .32$) were significantly slower than 9-year-olds ($M = -.32, SD = .24$) on BX trials $F(1, 75) = 10.041, p = .002, \eta^2 = .122$. The two groups did not differ in the z-transformed reaction time on AY trials $F(1, 75) = 2.589, p = .112, \eta^2 = .033$.

Second, group differences in the three PBSI indices – performance, RT, and sum – and d' context were examined using an independent sample t-test for each measure. For the PBSI accuracy measure, the test revealed that 9-year-olds ($M = .19, SD = .46$) used a more proactive strategy, while 5-year-olds ($M = -.26, SD = .38$) used a reactive strategy, $t(75) = -4.66, p < .001$. For the PBSI RT measure, the test revealed that 9-year-olds ($M = .18, SD = .11$) used a more proactive strategy than 5-year-olds

($M = .12$, $SD = .15$), $t(75) = -2.08$, $p = .041$. For the PBSI sum measure, the test revealed that 9-year-olds ($M = .37$, $SD = .51$) used a proactive strategy, while 5-year-olds ($M = -.14$, $SD = .37$) used a reactive strategy, $t(75) = -4.68$, $p < .001$. Finally, the t-test for the d' context measure of context sensitivity revealed that 9-year-olds ($M = 3.08$, $SD = .14$) had more context sensitivity than 5-year-olds ($M = 1.99$, $SD = .12$), $t(75) = -6.00$, $p < .001$.

Finally, to examine whether cue or probe relationships drove responding within each age group, partial correlations, controlling for AX reaction times, were conducted for AY, BX, and BY trials (see Figure 5). Consistent with the notion that reactive control is associated with probe identity, 5-year-olds showed a significant correlation between reaction times on the two trial types that share a probe -- AY and BY trials ($r(36) = .410$, $p = .010$). 5-year-old reaction times between AY and BX ($r(36) = -.118$, $p = .481$) and BY and BX ($r(36) = .007$, $p = .964$) were not significantly associated. Consistent with the notion that proactive control is associated with cue identity, 9-year-olds showed a significant correlation between reaction times on the two trial types that share a cue -- BX and BY trials ($r(35) = .631$, $p < .001$). 9-year-old reaction times between AY and BX ($r(35) = .123$, $p = .468$) and AY and BY ($r(35) = .161$, $p = .340$) were not significantly associated.

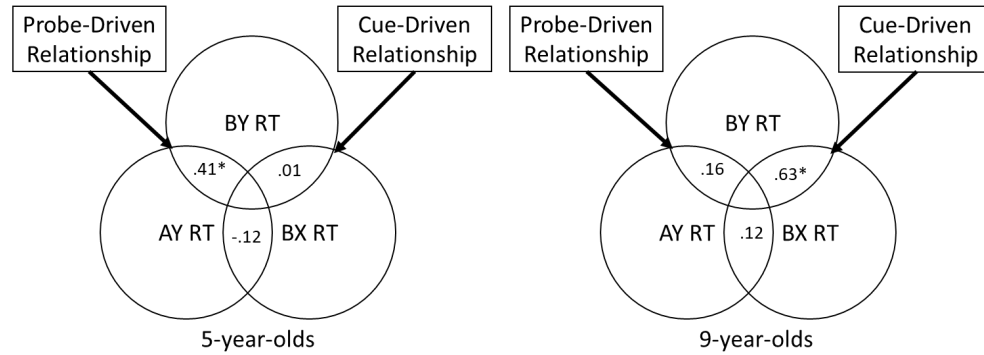


Figure 5. Partial correlations between AY, BX, and BY reaction times while controlling for reaction times on AX trials. Pearson's correlations are reported in circle overlaps and significant correlations are marked with an asterisk.

5.3 Aim 2: To examine whether development in cognitive control strategy is accompanied by altered patterns of neural activation.

5.3.1 Cue-locked P3b Processing

To examine differences in the P3b amplitude 2 Group (5-year-old, 9-year-old) by 2 Condition (A cue, B cue) repeated measures ANOVA was conducted (see Figure 6 for waveforms). The model revealed a main effect for Condition $F(1, 69) = 18.306$, $p < .001$, $\eta^2 = .210$, which was qualified by a significant Group by Condition interaction $F(1, 69) = 6.171$, $p = .015$, $\eta^2 = .082$. Bonferroni-corrected follow-up tests revealed that 9-year-olds had a larger P3b for B cues ($M = 7.9416$, $SD = 4.60614$) relative to A cues ($M = 4.9765$, $SD = 3.67452$; $F(1, 69) = 23.875$, $p < .001$, $\eta^2 = .257$), while 5-year-olds P3b did not differ by trail type (A cues: $M = 7.485$, $SD = 4.586$; B cues: $M = 8.271$, $SD = 5.377$; $F(1, 69) = 1.545$, $p = .218$, $\eta^2 = .022$). Additionally, on A cues, 9-year-olds had a significantly smaller P3b than 5-year-olds, $F(1, 69) = 6.158$,

$p = .013$, $\eta^2 = .086$. P3b amplitude on B trials did not differ between groups, $F(1, 69) = .077$, $p = .782$, $\eta^2 = .001$ ¹.

Relations between the P3b and cognitive control strategy use were examined using Pearson's correlations. 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 both the PBSI sum score ($r(69) = .346$, $p = .003$) and the d' context score ($r(69) = .294$, $p = .013$) suggesting that the larger the amplitude difference between the 'A' and 'B' cues, the more proactive or context-sensitive strategy was implemented. To further explore this finding, separate correlations were run within each age group and differences in the strength of correlation were compared using a Fisher r -to- z transformation. There was no significant correlation between the PBSI sum score and the P3 difference score for the 5-year-old age group ($r(32) = .117$, $p = .511$), but there was a significant association in the 9-year-old age group ($r(35) = .362$, $p = .028$). However, the correlations between the 5-year-olds and 9-year-olds were not significantly different in strength ($z = -.94$, $p = .347$). There was no significant correlation between and the d' context score and the P3b difference score in both the 5-year-old age group ($r(32) = .125$, $p = .482$) and 9-year-old age group ($r(35) = .213$, $p = .207$). Additionally, the correlations between the 5-year-olds and 9-year-olds were not significantly different in strength ($z = -.037$, $p = .711$).

¹ The interactive effects are still marginally significant after controlling for the number of trials completed by the participant.

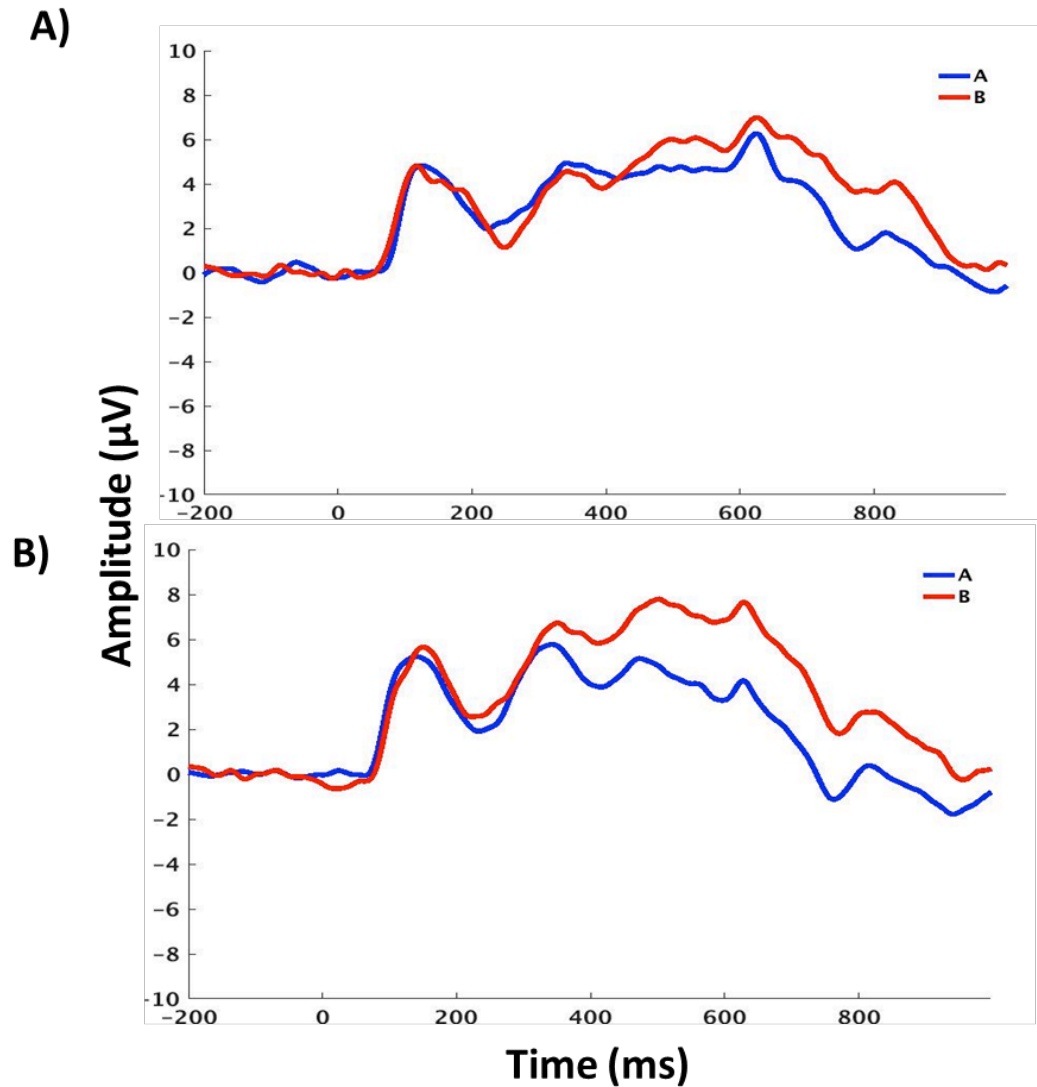


Figure 6. A) ERP waveforms for the P3b (top) for 5-year-olds. B) ERP waveforms for the P3b (bottom) for 9-year-olds.

5.3.2 Probe-locked N2 Processing

To examine differences in the N2 amplitude 2 Group (5-year-old, 9-year-old) by 2 Condition (AY, BX) repeated measures ANOVA was conducted (see Figure 7 for

task waveforms). The main effect for Condition, the main effect for Group, and the Group by Condition interaction failed to reach significance.²

Relations between the N2 and cognitive control strategy use were examined using Pearson's correlations. First, a difference score was created by subtracting the amplitude of the 'AY' trials from the 'BX' trials. The N2 difference score was not significantly and correlated with the PBSI sum score ($r(61) = .020, p = .875$) nor the d' context score ($r(61) = .063, p = .624$). Given no significant associations between behavioral measures and the N2, further group-level associations were not explored.

² These results remain insignificant after correcting for differences in the preceding positivity as well as after controlling for the number of trials completed by the participant.

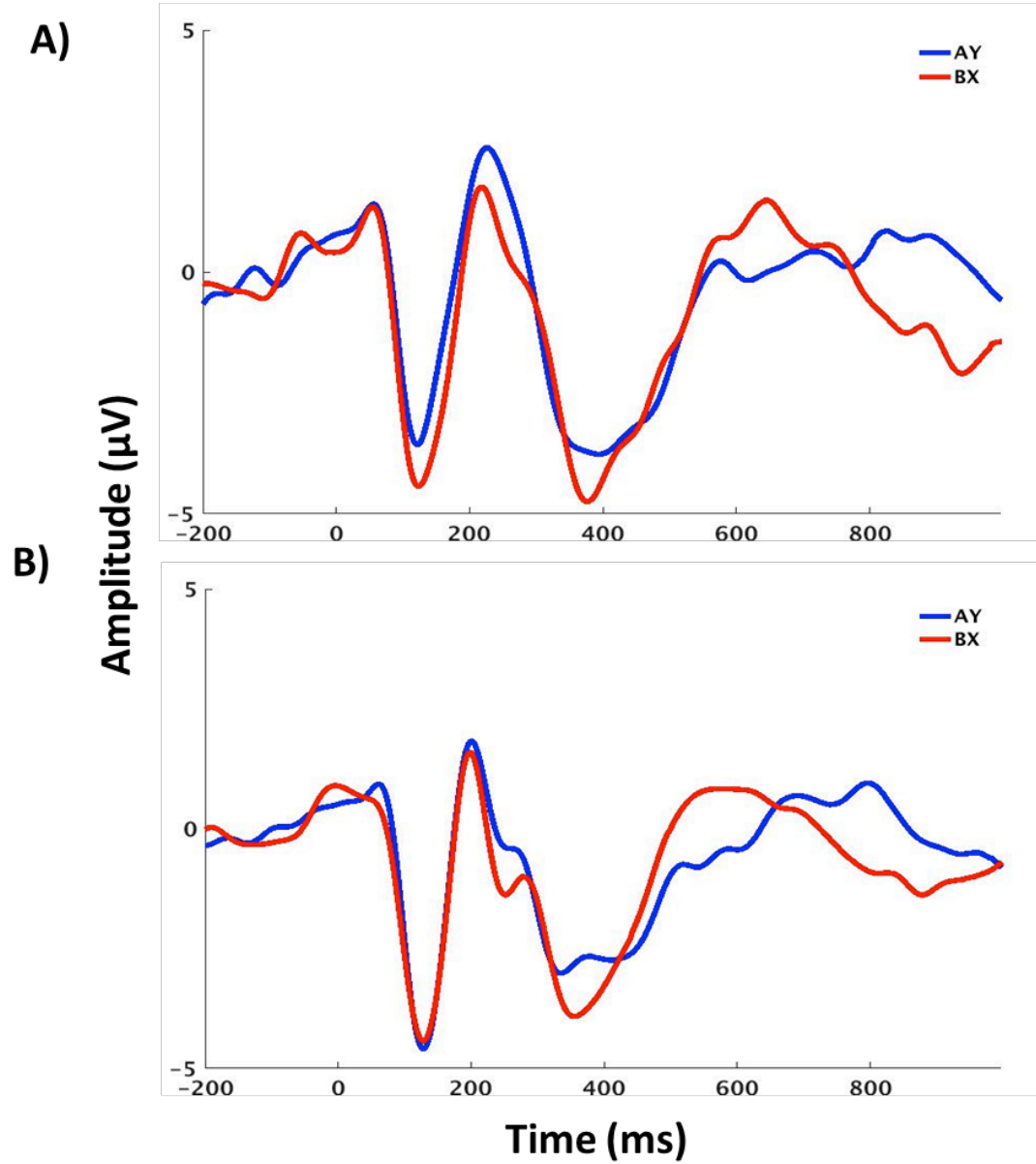


Figure 7. A) ERP waveforms for the N2 (top) for 5-year-olds. B) ERP waveforms for the N2 (bottom) for 9-year-olds.

5.4 Aim 3: To examine which executive skills are associated with proactive and reactive strategy use.

To examine whether age-related differences in cognitive functioning predict cognitive control strategy use, a series of regressions were conducted. First, to ensure that the proper test was conducted, the distribution of the outcome variables – the PBSI sum score and d' context – were examined. Both the PBSI sum score ($p=.528$) and context ($p=.792$) scores survived the Shapiro-Wilk test for normality, and as such all analyses were conducted assuming a normal, linear distribution.

To examine which executive functions (inhibitory control, attention shifting, and working memory) predicted cognitive control strategy use, separate linear regressions were conducted for the 5-year-old and 9-year-old groups. For each age group, uncorrected scores from all three of the NIH toolbox executive tasks (DCCS, Flanker, and List Sorting Working Memory) were regressed onto the PBSI sum and d' context scores. For the 5-year-old age group, the model predicting the PBSI sum score failed to reach significance $F(3, 30) = .099, p = .960$. The model predicting the d' context also did not reach significance $F(3, 30) = .138, p = .937$. For the 9-year-old age group, the model predicting the PBSI Sum composite failed to reach significance, $F(3, 34) = 2.253, p = .100$. The model predicting the d' context did reach significance, $F(3, 34) = 3.460, p = .027$. Working memory was positively related to d' context ($t(35) =$

2.217, $p = .033$), while attention shifting ($t(35) = -1.735$, $p = .092$) and inhibitory control ($t(35) = 1.139$, $p = .263$) were not significantly related to d' context.

Next, separate linear regressions were performed for each executive skill. In each of these regressions, age group (dichotomously coded), executive skill (attention shifting, inhibition, and working memory), and an age by executive skill interaction term were regressed onto the continuous PBSI sum score. The regression model examining the relations between inhibitory control (as indexed by the Flanker task) and age (dichotomously coded) reached significance $F(3, 72) = 9.8309$, $p < .0001$. When examining the individual predictors, it was found that neither performance on the flanker ($t(74) = .6023$, $p = .5489$) nor age group ($t(74) = 1.2692$, $p = .2085$) predicted performance on the PBSI sum. The interaction term between age and inhibitory control reached marginal significance ($t(74) = 1.7974$, $p = .0765$). To understand better how age and inhibitory control interacted to predict proactivity, follow-up analyses were conducted by examining conditional effects by Group. A graphical representation of the interaction is provided in Figure 8. Due to the marginal significance of the interaction, these data should be interpreted with caution. Follow-up analyses indicated that inhibitory control was not a significant predictor of proactivity for 5-year-olds ($t = .0623$, $p = .5489$), while it was a significant predictor of proactivity for 9-year-olds ($t = .2557$, $p = .0127$).

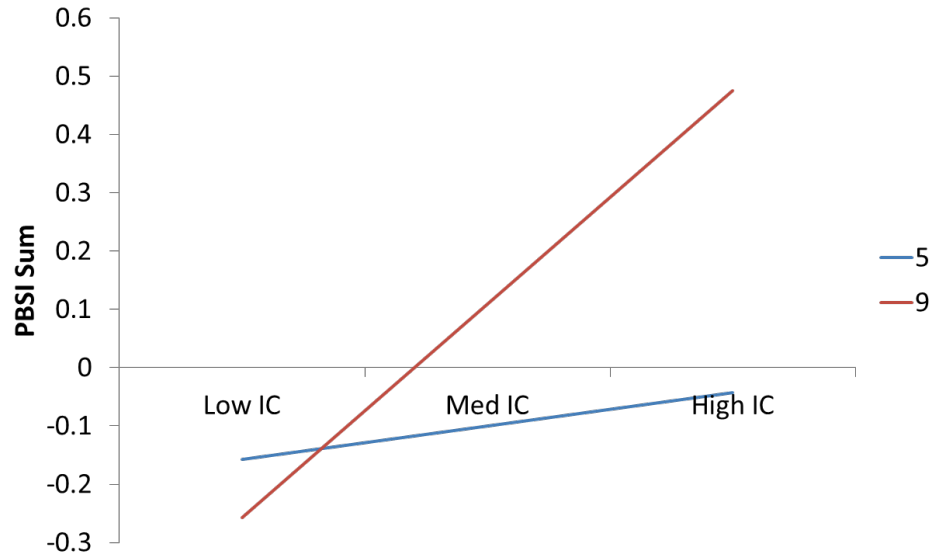


Figure 8. Marginal interaction between inhibitory control and age group.

The model examining how age and working memory predicted cognitive control strategy use also reached significance $F(3, 68) = 7.2233, p = .0003$. Follow-up tests showed that age group marginally predicted the PBSI Sum score ($t(70) = 1.9821, p = .0515$), while working memory did not ($t(70) = -.4289, p = .6694$). The interaction term between age and working memory only reached marginal significance ($t(70) = 1.7149, p = .0909$). To understand better how age and working memory interacted to predict proactivity, follow-up analyses were conducted by examining conditional effects by Group. A graphical representation of the interaction is provided in Figure 9. Due to the marginal significance of the interaction, these data should be interpreted with caution. Follow-up analyses indicated that working memory was not a significant predictor of proactivity for 5-year-olds ($t = -.4289, p = .6694$), while it was a significant predictor of proactivity for 9-year-olds ($t = 2.0016, p = .0493$).

Finally, the model examining whether age and attention shifting reached significance $F(3, 72) = 7.9689, p = .0001$. Follow-up tests showed that age group

marginally predicted the PBSI Sum score ($t(74) = 1.9307, p = .0575$), while attention shifting ($t(74) = .9120, p = .3648$) and the interaction between attention shifting and age ($t(74) = .5791, p = .5643$) did not reach significance.

Separate linear regressions were also performed for each executive skill in order to examine their relations to the d' context score. The regression model examining the relation between inhibitory control and age (dichotomously coded) reached significance $F(3, 72) = 13.3486, p < .0001$. It was found age significantly ($t(74) = 2.4611, p = .0162$) the d' context score, while performance on the flanker did not ($t(74) = .6584, p = .5124$). The interaction term between age and inhibitory control did not reach significance ($t(74) = 1.2359, p = .2205$) and was not probed further.

The model examining whether age and working memory predicted cognitive control strategy use also reached significance $F(3, 68) = 13.7773, p < .0001$. Follow-up tests showed that age group ($t(70) = 2.2684, p = .0265$) significantly predicted the d' context score, while working memory ($t(70) = .2563, p = .7985$) did not. The interaction term between age and working memory only reached marginal significance ($t(70) = 1.7721, p = .0809$). To understand better how age and working memory interact, follow-up analyses were conducted by examining conditional effects by group. A graphical representation of the interaction is provided in Figure 9. Due to the marginal significance of the interaction, these data should be interpreted with caution. Follow-up analyses indicated that working memory was not a significant

predictor of d' context for 5-year-olds ($t = .2563, p = .7985$), while it was a significant predictor of d' context for 9-year-olds ($t = 2.7725, p = .0072$).

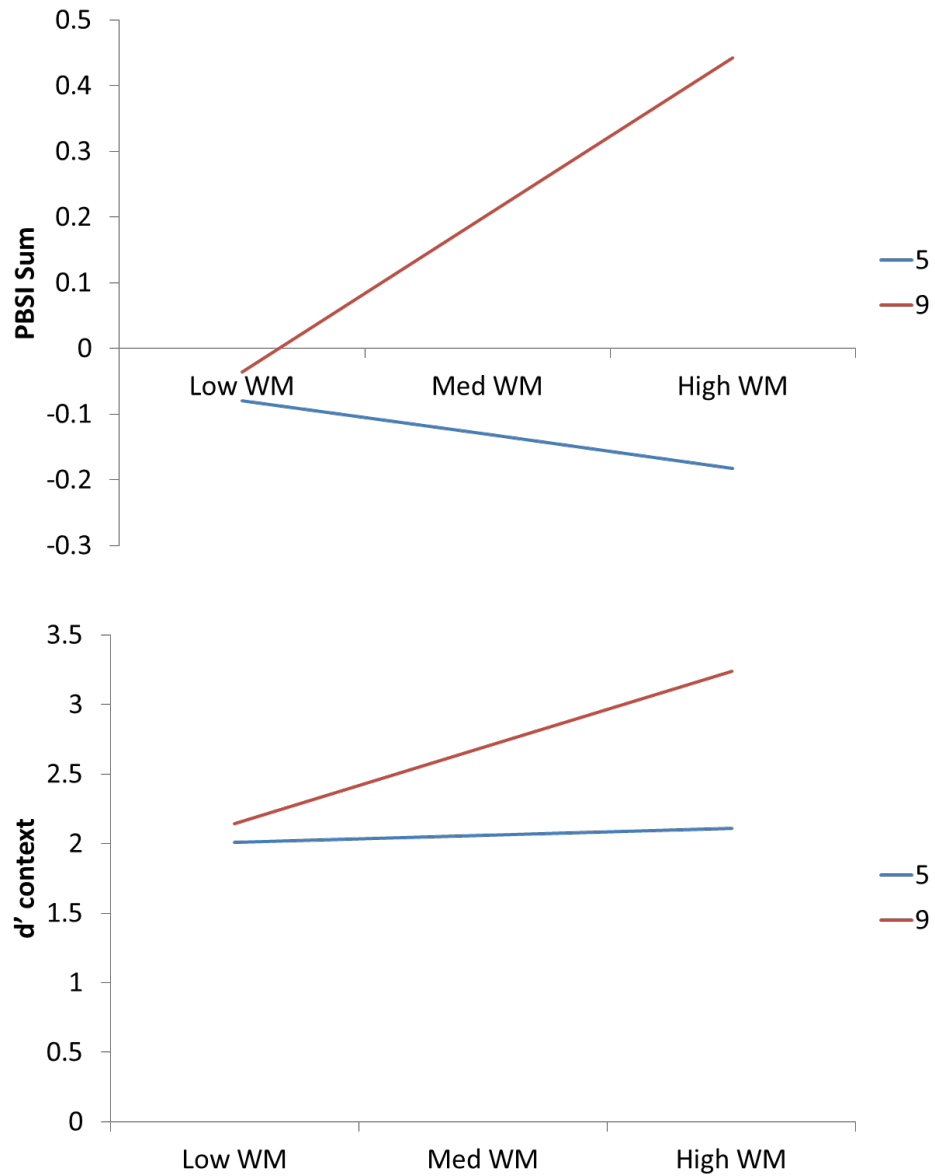


Figure 9. Marginal interaction between working memory (WM) and age group predicting context sensitivity (top) and proactivity (bottom).

Finally, the model examining whether age and attention shifting reached significance $F(3, 72) = 11.4041, p < .001$. Follow-up tests showed that age group significantly predicted the d' context score ($t(74) = 3.7200, p = .0004$), while

attention shifting ($t(74) = -.0688, p = .9454$) and the interaction between attention shifting and age ($t(74) = .3622, p = .7182$) did not reach significance.

Finally, two exploratory regression models were conducted with all three executive skills (inhibitory control, working memory, and attention shifting) and age were entered into the first block and the associated interaction terms between age and executive skill were entered into the second block were entered into a single model predicting the PBSI sum score and d' context score. For the model predicting the PBSI Sum Score, the first ($F(4, 67) = 4.924, p < .002$) and second ($F(7, 64) = 3.559, p = .003$) blocks did reach significance, however none of the individual predictor coefficients reached significance ($ps > .12$). For the model predicting the d' context score, both the first block ($F(4, 67) = 9.278, p < .001$) and second block ($F(7, 64) = 3.848, p < .001$) reached significance. In block 1, two predictors reached marginal significance – age ($t = 1.933, p = .057$) and working memory ($t = 1.704, p = .093$). In block 2, age significantly predicted d' context scores ($t = 2.236, p = .029$) with 9-year-old children having higher scores. Additionally, the age by working memory interaction term reached marginal significance ($t = 1.713, p = .092$) but was not followed up due to lack of power and the exploratory nature of these analyses.

Chapter 6: Discussion

The paramount goal of the present study was to examine the chronometry of cognitive control during childhood. As hypothesized, 5-year-olds preferentially relied on a reactive cognitive control strategy when performing an AX-CPT task, whereas 9-

year-olds preferentially relied on a proactive cognitive control strategy. 9-year-olds also exhibited more context sensitivity on the AX-CPT than their 5-year-old counterparts did.

In addition to examining behavioral patterns of cognitive control, continuous electroencephalography (EEG) was collected while the children completed the AX-CPT task and event-related potentials (ERPs) were computed offline in order to examine whether cognitive control strategy was associated with differential patterns of neural activation to the cue and probe stimuli. Consistent with our hypotheses, we found that greater discrimination (as indexed by P3b amplitude) between different kinds of task-relevant information given in advance of a response-event (cue stimuli) resulted in an increased likelihood of using a proactive strategy. However, counter to our hypotheses, we did not observe associations between cognitive control strategy and a neural component reflective conflict monitoring (N2).

The final goal of the present study was to examine associations between cognitive control strategy use and executive functions. Somewhat consistent with our hypotheses, we found preliminary evidence that cognitive control strategy use was differentially related to a number of executive skills. Specifically, we found preliminary evidence that proactive control and increased context sensitivity were positively associated with working memory and, surprisingly, inhibitory control. Counter to our hypotheses, there were no observed associations between reactive control and inhibitory control.

The goal of this chapter is to discuss these findings in more detail as well as relate them to the broader literature. Additionally, we will highlight some of the limitations of the present study and suggest avenues for future research.

6.1 Developmental differences in cognitive control strategy use

Findings from the present study suggest that there is a developmental transition from more a stimulus-driven control strategy in early childhood to a more sustained and planful cognitive control strategy in later childhood. This data fits nicely with the Dual Mechanisms of Control (DMC; Braver, 2012) theory, which postulates two separable cognitive control strategies with temporally distinct profiles: proactive control and reactive control. Proactive control is more planful in nature and is enacted prior to a control-anticipated event, whereas reactive control is recruited on an as-needed basis in response to the detection of conflict. Findings from this study also complement both theoretical and empirical evidence suggesting that the ability to implement proactive cognitive control strategies emerges during the first decade of life (Chatham et al., 2009; Chevalier et al., 2015; Munakata et al., 2012).

Examination of the behavioral data from the present study reveals a number of nuanced relations between cognitive control strategy and development. First, as hypothesized in Aim 1, we see that 5-year-olds relied on probe-driven reactive strategies as evidenced by a variety of measures including poorer behavioral performance on trials that shared the same probe as the target trial (BX) relative to

trials that shared the same cue as the target trial (AY), reactive scores (e.g. negative scores) on the proactive behavioral shift indices for accuracy and the composite for accuracy and reaction time, low scores on a measure of context sensitivity (e.g. d' context), as well as significant correlations in RT between trial types that share probes (BY, AY) and insignificant correlations between trial types that share cues (BY, BX). Together, these data suggest that 5-year-olds, on average, preferentially used a reactive strategy on the AX-CPT and relied heavily on probe identity for responding. However, it is worth noting that one measure in the 5-year-old sample, the PBSI for RT, did not reflect reactive strategy use. This measure, which compares RTs on AY trials relative to BX trials, showed that 5-year-olds slowed more on AY trials relative to BX trials – a pattern more consistent with proactive control. However, evidence that children relying on reactive control do not slow on BX trials relative to AY trials has been observed in a sample of 3.5-year-olds who completed a very similar AX-CPT (Chatham et al., 2009). One reason that has been postulated as to why young children do not show more slowing on BX relative to AY trials is that 'Y' probes are rare (30% of trials for the present study), thus they may still disproportionately capture the attention of the reactive subjects (Chatham et al., 2009). Of course, another reason that 5-year-olds may slow on AY trials relative to BX trials is that they may be beginning to implement some aspects of proactive strategy use. Indeed, previous research has shown that, although 5-year-olds preferentially rely on reactive control when possible, they can enact proactive strategies when they are encouraged to via task demands (Chevalier et al., 2015).

In contrast to the 5-year-olds, 9-year-olds relied on cue-driven proactive strategies as evidenced by a variety of measures including worse behavioral performance on trials that shared the same cue as the target trial (AY) relative to trials that shared the same probe as the target trial (BX), proactive scores (e.g. positive scores) on all three proactive behavioral shift indices, high scores on a measure of context sensitivity (e.g. d' context), and significant correlations in RT between trial types that share cues (BY, BX) and insignificant correlations between trial types that share probes (BY, AY). These data contribute to a growing body of literature showing an increasing preferential reliance on proactive cognitive control strategies as well as increased proactive strategy efficiency emerges in the latter half of the first decade of life (Church et al., 2016; Lorschbach & Reimer, 2008; Lucenet & Blaye, 2014).

In sum, our hypotheses for Aim 1, which contended that 5-year-olds would rely on reactive control while 9-year-olds would rely on proactive control, were confirmed. These findings were particularly important given that the present study designed the first developmental and EEG-friendly version of the AX-CPT, which required slight alterations to task timings and trial proportions. Given that within-task relations and between-group relations were in-line with the existing literature, it appears the EEG version of the task is indeed valid and as such, developmental changes in neural activation can be examined both in the present and future studies.

6.2 Neural activation during Cognitive Control

Given that the behavioral data suggested that 5-year-olds and 9-year-olds used different cognitive control strategies, the present study aimed to identify different patterns of neural activation associated with cognitive control strategy use. Two time periods were examined: the period immediately following the presentation of the cue stimulus (A or B, which required no response) and the period following the probe presentation (X or Y, which required a response).

6.2.1 Cue-locked neural processes and Cognitive Control Strategy Use

The cue-locked P3b is a parietal positivity that is thought to reflect target categorization, context updating, and memory activation of task-relevant information. Consistent with other studies in children examining the P3b (Davis et al., 2003; Ridderinkhof & van der Molen, 1995; Rueda et al., 2004), the component was reliably evoked by the cue stimulus and detectable in both the 5-year-old and 9-year-old groups. Studies in adulthood have shown that, when using a proactive strategy, P3b amplitudes are larger for 'B' cues relative to 'A' cues (Morales et al., 2015; van Wouwe et al., 2011). Given the existing evidence that children transition from more reactive strategies to more proactive strategies over the first decade of life (Chatham et al., 2009; Chevalier et al., 2015; Munakata et al., 2012), we hypothesized that amplitude of the P3b for 'A' relative to 'B' cues may be altered during this time. Indeed, our data confirmed this hypothesis. Specifically, we saw that 9-year-olds showed the adult-like pattern of having a larger P3b amplitude to

'B' cues relative to 'A' cues, while 5-year-olds did not show differential P3b amplitudes by trial type. This pattern was driven by a reduction in P3b amplitude to 'A' cues in the 9-year-olds. To our knowledge, this is the first study examining the P3b on an AX-CPT task during childhood and our findings suggest that the differential magnitude of the cue-locked P3b may provide a valuable neural marker of proactive control recruitment.

In addition to P3b amplitude differences by age group, an even more interesting pattern emerged when examining the relation of P3b amplitude to behavioral performance. The data suggest that the more a participant's neural activity differentiates between 'A' and 'B' cues, the more likely they are to utilize a proactive strategy. This is particularly interesting since the cue-locked P3b precedes the probe presentation and response. To our knowledge, this is the first study to demonstrate that individual differences in P3b amplitude to 'A' and 'B' cues predicts cognitive control strategy. Future research should aim to examine whether this relationship holds on a trial-level basis.

6.2.2 Probe-locked Neural Processes and Cognitive Control Strategy Use

The probe-locked N2 is a fronto-central negativity that peaks between 150-300 ms following probe presentation (Van Veen & Carter, 2002b) and it is thought to index conflict detection with larger amplitudes for less frequent responses, inhibiting prepotent responses, and reconciling response conflict. Given the differential patterns of conflict elicited by the probe stimulus in proactive and

reactive control, we hypothesized that children would show alterations in N2 amplitude as they transition from reactive to proactive control. This hypothesis was not supported by the data. In fact, there were no differences between 5-year-olds and 9-year-olds and no differences in amplitude between AY and BX trials, although an N2 was identifiable via visual inspection (see Figure 7) and looked similar to other developmental populations (e.g. Davis et al., 2003; Rueda et al., 2004).

While the lack of findings was unexpected, there are a number of reasons why the expected effects may not have emerged. One reason is the different features and probabilities of the 'X' and 'Y' probes may have obviated the expected effects. Studies have shown that the N2 amplitude and latency is sensitive to stimulus probability as well as featural properties of the stimulus (for review see Folstein & Van Petten, 2008). Given that in the AX-CPT 'Y' probes are rarer (30% of trials in this version) and perceptually dissimilar from 'X' probes (70% of trials in this version), the lack of effects may be attributable to factors besides cognitive control strategy. Another reason we may not have seen the expected N2 effects is due to the within-age group variability in cognitive control strategy use. While 5-year-olds did, on average, rely on reactive control and 9-year-olds, on average, relied on proactive control, there were a fair number of 5-year-olds who used proactive strategies (based on a positive PBSI sum score, N=15) and a number of 9-year-olds who used reactive strategies (based on a negative PBSI sum score, N=9). As such, the within-group variability in cognitive control strategy employed may reduce our ability to detect the expected N2 effects. Finally, given the lack of N2 amplitude

findings, it was unsurprising that there were no significant associations between the N2 difference score and measures of task performance.

6.2.3 Summary of ERP findings

To our knowledge, this study is the first to examine neural components of cognitive control strategy using an AX-CPT task during childhood. Consistent with studies examining ERPs derived from an AX-CPT in adulthood (Dias et al., 2013, 2011; Tekok-Kilic et al., 2001; van Wouwe et al., 2011), this new child AX-CPT does appear to elicit a cue-locked P3b and probe-locked N2. Consistent with our hypothesized results, 9-year-old children showed a more adult-like pattern of activation with an enhanced P3b to 'B' cues when compared to 'A' cues, while 5-year-old children did not show this differentiation. Additionally, we showed that individual differences in P3b amplitude on 'B' cues relative to 'A' cues were significantly associated with the cognitive control strategy utilized by the participant. However, our findings related to probe-locked N2 activation did not confirm our hypothesis. We saw no differences in N2 amplitude based on trial type or age group.

6.3 Relations between Executive Functioning and Cognitive Control

This study also examined associations between executive skills and cognitive control strategy use. Based on past literature, we hypothesized that proactive and reactive strategy use would be associated with different underlying executive skills.

Specifically, based on prior research, we expected that proactive control would be most strongly associated with working memory, while reactive control would be most strongly associated with inhibitory control. Data from this study only moderately supported these hypotheses.

First, 5-year-olds and 9-year-olds were examined separately to determine which executive skills were closely associated with the strategy implemented by an individual. For the 5-year-olds, neither the model predicting proactivity nor the model predicting context sensitivity reached significance, which was counter to what we hypothesized. One reason that our models may not have reached significance is that many of the executive function measures entered into the model were significantly associated with each other, thus introducing multicollinearity into the model. To add credence to this idea, there is an emerging body of work suggesting that the postulated three components of executive functioning in adulthood (Miyake et al., 2000) may not be separable, independent constructs during early childhood (e.g. Brydges, Reid, Fox, & Anderson, 2012). An additional reason we may not have seen the association between reactive control and inhibitory control in 5-year-olds may be that the flanker task on the NIH toolbox does not cleanly assess inhibitory control in young children. As we reviewed in Chapter 2, it has been postulated that there are different kinds of inhibitory control – proactive inhibition and reactive inhibition – which have temporally distinct profiles and different underlying neural circuitry (Aron, 2011). It may be that the Flanker task on the NIH Toolbox more accurately taps proactive rather than reactive inhibition since the

flanker task requires the upregulation of executive attention in order to ignore flanking stimuli. As such, future studies may have more success finding relations between reactive control and inhibitory control if they utilize a task that more cleanly taps reactive inhibition.

The relations between cognitive control and executive functioning in 9-year-olds were also mixed. The model examining proactivity (PBSI sum) did not reach significance, but the model predicting context sensitivity did. Results from the significant context sensitivity model confirmed our hypothesis that increased working memory capacity predicted higher context sensitivity. Given that the d' context and PBSI sum are highly associated ($r=.607$), it is hard to decipher why only one model reached significance. One reason may lie in how the PBSI and d' context measures are computed. For the d' context measure, two trial types that share a probe are compared (AX and BX trials), while the PBSI sum score compares two trial types that do not share a cue or probe (AY vs BX). Since AX and BX trials share a probe, memory of the cue identity (maintained by working memory) is integral to discriminating between AX and BX trials. In contrast, since AY and BX trials do not share a probe, remembering the cue identity is less critical to discriminate between these two trial types.

In addition to the within-age analyses, separate sets of analyses were conducted in order to examine whether age group, executive skill (inhibitory control, attention shifting, and working memory), or an interaction of the two predicted proactivity (PBSI sum score) and context sensitivity (d' context). For analyses

examining the predictive nature of inhibitory control, a marginal age by inhibitory control interaction emerged when predicting proactivity. While this finding should be interpreted with caution, the data suggest that inhibitory control is a stronger predictor of proactivity for 9-year-olds than it is for 5-year-olds. Additionally, better inhibitory control skills predicted increased proactivity for 9-year-olds. Given prior work suggesting that children use two different kinds of inhibition – monitoring-related inhibition (more proactive in nature) and motoric inhibition (more reactive in nature; Chevalier, Chatham, & Munakata, 2014) – this finding was not unexpected. Additionally, given that the NIH Flanker task indexes executive attention as well as inhibitory processes, it is likely that behavior on this task indexes monitoring-related inhibition (or proactive inhibition).

The relations between working memory, age, and cognitive control tentatively suggest that both development and working memory skill influence cognitive control strategy use. Indeed, in both the model predicting proactivity and the model predicting context sensitivity, a marginal age by working memory interaction emerged. Due to the marginal significance of these interactions, these results should be interpreted with caution. However, it appears that that working memory is a stronger predictor of proactivity and context sensitivity for 9-year-olds than it is for 5-year-olds. Additionally, for 9-year-olds, better working memory predicted more proactivity and context sensitivity. These tentative findings are in-line with both our hypotheses and a growing body of literature suggesting that more planful cognitive control strategies are associated with working memory skills –

particularly since the dorsolateral prefrontal cortex (DLPFC) has been implicated in both working memory and proactive control paradigms (Amso et al., 2014; Aron, 2011; Braver et al., 1997, 2009; Bunge et al., 2001; Unger et al., 2016).

This study found no evidence for relations between attention shifting, age, and cognitive control strategy use. This is not very surprising given that the literature linking attention shifting to cognitive control is scant and we did not have any specific hypotheses regarding the role of attention shifting and the chronometry of cognitive control.

Finally, we attempted to examine the relations between age, all three executive functions, and the associated interaction terms predicting proactivity and context sensitivity. While both models reached significance, only the model predicting context sensitivity had significant coefficients. Particularly, it showed that older children were more likely to show more context sensitivity. Additionally, the age by working memory interaction term reached marginal significance and again very tentatively suggesting that working memory is a stronger predictor of context sensitivity for 9-year-olds than it is for 5-year-olds (see Figure 9). While these findings were not as robust as predicted, it is important to note that again multicollinearity was likely a problem in these models due to significant associations between some of the executive function measures. Additionally, given the large number of predictors in the model and the modest sample size, we were likely underpowered to detect many of the effects of interest.

Altogether, this data only moderately confirmed our hypotheses that executive functioning would differentially predict cognitive control strategy use. Consistent with existing literature and our hypotheses, there was a smattering of evidence suggesting a close link between working memory and more planful control strategies. Contrary to our hypotheses, inhibitory control also appeared to be tentatively related to more planful control strategies in 9-year-olds. Attention shifting was not related to cognitive control strategy use in this study. There were also a number of marginally significant findings suggesting that working memory and inhibitory control were better predictors of cognitive control in 9-year-olds than in 5-year-olds, although these results should be interpreted with caution.

6.4 Limitations and Future Directions

The present study has a number of limitations that should be addressed. First, and most notably, the sample size for the present study was modest at best. Indeed, due to the small sample size, we were likely underpowered to detect some of the expected effects – particularly when examining the complex relations between age and multiple executive functions. While a-priori power analyses were conducted to ensure that there was enough power to detect expected behavioral effects, the relations between the AX-CPT and executive functioning in children had not been previously investigated. As such, a number of the expected interactions only reached marginal significance. Future studies should aim to replicate the

findings reported here in a larger sample in order to better understand the relations between cognitive control and executive functioning.

Another limitation is that 5-year-olds, on average, completed less of the AX-CPT task and were disproportionately more likely to be excluded from analyses. While this is a problem endemic to developmental research, it is still worth noting. 5-year-olds also had significantly more movement artifact in their EEG data. Additionally, while 9-year-olds completed more trials on average, it is important to note that blocks were significantly longer for 5-year-olds due to their slower reaction times and the adaptive response window. While similar confounds have existed in other child AX-CPT studies comparing two age groups (e.g. Chatham et al., 2009), future studies should aim to reduce these confounds whenever possible.

Future studies should aim to replicate and expand upon the present study in a number of different ways. Future avenues of research may include the investigation of other neural components known to be modulated by cognitive control strategy use in adults. Candidate components may include the P1 (Dias, Bickel, Epstein, Sehatpour, & Javitt, 2013; Dias, Butler, Hoptman, & Javitt, 2011), N1 (Dias et al., 2013, 2011; Umbricht et al., 2003), P2 (Umbricht et al., 2003), error-related negativity (ERN; Suchan, Zoppelt, & Daum, 2003; van Wouwe et al., 2011), contingent negative variation (CNV; Bickel, Dias, Epstein, & Javitt, 2012; Dias et al., 2013, 2011; van Wouwe et al., 2011), and late positive potential (LPP; Chevalier et al., 2015). Additionally, time-frequency analyses may provide important insights into how children processes and sustain task-relevant information. To date, no

longitudinal assessment of cognitive control strategy use has been conducted. Such a study is necessary to confirm many of the insights that have been gained through cross-sectional studies like the present study. Finally, there is a growing body of work suggesting that cognitive control strategy use is related to socioemotional functioning in adulthood – including disorders like anxiety and schizophrenia (Braver, 2012; Cohen et al., 1999a; Henderson et al., 2014; Sheffield et al., 2014). As such, future studies should examine both concurrent relations between cognitive control in childhood and socioemotional functioning as well as longitudinal relations between cognitive control strategy use and later psychopathology.

6.5 Conclusion

Childhood is characterized by a period of protracted cognitive and neural development. Over the first decade of life, children acquire the cognitive skills necessary for real-world functioning such as the rapid management and implementation of a wide array of cognitive skills and the ability to prioritize cognitive demands in order to complete a goal – a collection of skills known as cognitive control. Theoretical models have posited the existence of two kinds of cognitive control with temporally distinct profiles: proactive control and reactive control (Braver, 2012; Munakata et al., 2012). Proactive control is enacted prior to a control-anticipated event and requires that goal-relevant information be actively maintained in order to optimally bias attentional and activation systems in order to complete a goal. In contrast, reactive control is commonly recruited on an as-needed

basis in response to the detection of conflict. Developmental theory and a few empirical studies have suggested that children shift from a heavy reliance on reactive control to a more proactive strategy during the first decade of life (Munakata, Snyder, & Chatham, 2012). This shift is characterized by children starting to plan their behaviors in advance of a goal-relevant event instead of reacting to external cues in order to enact goal-relevant behaviors. However, to date only a few studies have documented this transition and the neural and cognitive factors that support this transition have been largely uninvestigated.

Data from the present study showed that children transition between a preferential reliance on reactive cognitive control strategies in early childhood to proactive cognitive control strategies use in later childhood. More specifically, 9-year-olds were able to observe and sustain environmental cues to in order to complete a goal, while 5-year-olds used stimulus-driven information to drive their responding. These behavioral differences were also accompanied by interesting differences in neural activation in a neural component known as the cue-locked P3b, which is thought to be reflective of a number of processes including target categorization, context-updating, and memory activation of task-relevant information (Morales et al., 2015; van Wouwe et al., 2011). This study demonstrated that the more the brain discriminated (as indexed by P3b amplitude) between different kinds of task-relevant information given in advance of a response-event ('A' versus 'B' cue), the more likely that child was to use a proactive strategy. 9-year-olds were more likely to discriminate between different kinds of task-relevant

information given in advance of a response-event ('A' versus 'B' cue) than 5-year-olds. This study was the first study to show links between cognitive control strategy use and differential patterns of neural activation on an AX-CPT task during childhood.

This study also showed preliminary evidence that cognitive control strategy use was differentially related to a number of executive skills. Specifically, proactive control and increased context sensitivity appear to be positively associated with working memory performance and inhibitory control (particularly in 9-year-olds), but not with attention shifting – even after controlling for the effects of age. Additionally, exploratory analyses of marginally significant interaction terms suggested that both working memory and inhibitory control are more strongly associated with proactivity in 9-year-olds than they are in 5-year-olds, although these results should be interpreted with caution.

In sum, the present study provided important insight into how children prepare for and complete goals. To our knowledge, the present study is one of the first to document the neural correlates associated with proactive and reactive control in childhood and the executive skills that support these functions. This line of research is important not only for furthering our understanding of the development of goal-relevant behaviors, but also may have implications for child mental health, particularly anxious cognition, as the development of cognitive control has been implicated in the development of anxiety in children (Henderson, Pine, & Fox, 2015).

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