The Impact of Executive Function on Reward Processing in Children: Neural Correlates and Individual Differences.

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Abstract

Executive function (EF) involves the integration of cognitive processes in order to support and sustain goal-directed behaviors that are crucial in the development of behavioral regulation (Sergeant, Geurts, & Oosterlaan, 2002). Motivational and rewarding information may alter the underlying cognitive processes surrounding the implementation of these goal-directed behaviors. Previous research indicates that both behavior and brain systems associated with reward and executive function (EF) processes may be interacting in children with ADHD (Luman, Van Meel, Oosterlaan, Sergeant, & Geurts, 2009b; Scheres, Milham, Knutson, & Castellanos, 2007). However, little research has been conducted within middle childhood to explore the intersection of EF and reward processing in typical development. Furthermore, little is know about the degree to which reward processing may be interacting with low EF ability on a behavioral and neural level during middle childhood.

The current study examined behavioral performance as well as functional and structural Magnetic Resonance Imaging (MRI) data to address the degree to which executive function (EF) ability may be related to reward processing behaviors and brain circuitry in middle childhood. Chapter 2 addresses the overlap of EF and reward processing in behavioral task performance and parent questionnaire measures. Chapter 3 describes brain activation pattern differences in children with high versus low EF ability in a reward processing task. This portion of the study was conducted to determine whether children with lower EF ability process reward information similarly to children with high EF ability. In Chapter 4, the links between behavioral performance on EF and reward processing measures and structural volumes of related brain areas are discussed.

Finally, in Chapter 5, general conclusions, limitations and future directions are outlined.

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Chapter 1: General Introduction

The ability to integrate information regarding the positive or negative consequences associated with a particular stimulus or behavior, is vital for the development of approach and avoidance behaviors in humans and animals alike (Schultz, 2002). Similarly, executive functions (EF), or higher-order cognitive processes that control and alter thoughts and behaviors in the interest of pursuing goals, are necessary for the development of behavioral control and regulation (Sergeant, et al., 2002). It is likely that on a daily basis these two overarching processes occur in tandem with one another to inform decision-making as well as direct behaviors. However, little research has been done to explore the intersection of EF and reward processing in order to discern how they might be linked both in terms of cognitive processing and in the underlying neural circuitry of the brain (Luman, Tripp, & Scheres, 2010).

The most prominent insight into this question of how reward processing and EF interact comes from the ADHD literature. Findings from this literature suggest that executive functions affective processing and motivational behaviors are impaired in children with ADHD (Barkley, 1997; Biederman, 2005; F. X. Castellanos, Sonuga-Barke, Milham, & Tannock, 2006; Luman, et al., 2009b; Nigg, Blaskey, Huang-Pollock, & Rappley, 2002; Sagvolden, Johansen, Aase, & Russell, 2005). For example, behavioral studies have shown that children with ADHD tend to make more errors and are less sensitive to reward and punishment contingencies than their typically developing counterparts (Gomez, 2003; Luman, et al., 2009b). Alternatively, some research suggests that children with ADHD are more motivated by rewards and subsequently perform better on tasks that involve a strong reward component than children without ADHD (Huang-Pollock, Mikami, L., & McBurnett, 2007; Luman, et al., 2009a). It is not entirely clear to what extent motivation and reward may play a role in buffering or hindering performance on cognitive tasks for children with ADHD.

Physiologically, children with ADHD show lower levels of response to reward and punishment conditions (Crone, Jennings, & van der Molen, 2003; Masunami, Okazaki, & Maekawa, 2009). In one study conducted by Crone and colleagues (2003), children with ADHD showed less of an increase in heart rate than control children after rewarding feedback. In another study examining skin conductance responses, researchers found that unlike control children, the ADHD group did not show differences in skin conductance responses between reward and punishment information (Masunami, et al., 2009). Additionally, fMRI and PET scans of the functioning of brain systems thought to be involved in EF and reward processing often show differences in activation patterns in between children with ADHD and typically developing controls (Durston, 2003b; Durston, et al., 2003a; Scheres, et al., 2007; Ströhle, et al., 2008). For example, children and adults with ADHD show lower levels of activation in the ventral striatum, which is usually highly activated for high magnitude rewards (Scheres, et al., 2007; Ströhle, et al., 2008). Overall, measures of physiological and neurological function imply that children with ADHD show atypical response patterns to rewarding situations than do typically developing children.

One explanation for why there are atypical patterns of reward processing on a behavioral and neural level in children with ADHD may be related to the heavy reliance of both reward processing and executive function on dopamine rich fronto-striatal circuits in the brain (Barkley, 1997; Luciana, 2001; Sagvolden, et al., 2005). Dopamine has been implicated in a number of behaviors including reinforcement learning, movement, behavioral inhibition, emotion, attention and mood (Sagvolden, et al., 2005; Staller & Faraone, 2007). Functional neuroimaging studies suggest that there are areas of dopamine-rich fronto-striatal circuitry that are involved in both reward processing and EF (Durston, et al., 2003a). Research in the animal literature has found that dopamine neurons in the midbrain respond to cues indicating reward and are also sensitive to reward timing (Schultz, 2001). Unlike midbrain dopamine neurons, dopamine neurons in the striatum and orbitofrontal cortex more readily adapt to current information about reward, and show differential responses to specific types of rewards (Schultz, 1998; Schultz, Tremblay, & Hollerman, 2000). These results are mirrored by studies with human subjects. The ventral striatum, or nucleus accumbens, shows increased activation as a function of reward magnitude in humans (Galvan, et al., 2005; Knutson, Adams, Fong, & Hommer, 2001a). The orbitofrontal cortex has been implicated in processing both reward and punishment information, and may link to other prefrontal regions important for planning and problem solving (O'Doherty, Kringelbach, Rolls, Hornak, & Andrews, 2001; Watanabe, 2002).

Regions of the prefrontal cortex, such as the dorsal lateral prefrontal cortex (DLPFC), a primary neural substrate for executive functions like response inhibition, attention modulation, planning, and working memory, are densely populated with dopamine receptors as well (Staller & Faraone, 2007). Successful dopamine transmission is crucial for the function of these cognitive processes (Staller & Faraone, 2007). Additionally, striatal circuits are high in dopaminergic activity and are important in modulating motor activity (Schultz, 2002). There is also research to suggest the importance of fronto-striatal circuits in coordinating attention and working memory functions (Staller & Faraone, 2007). Similarly, inhibitory control tasks have been found to activate areas such as the caudate nucleus and anterior cingulate cortex (Durston, 2003b), while task switching and working memory tasks have been found to activate areas of the ventrolateral and dorsolateral prefrontal cortex (Best, Miller, & Jones, 2009; Zelazo, Carlson, & Kesek, 2008).

This overlapping reliance on dopamine function for success in both reward processing and EF is compelling and may explain to some degree the underlying factors at work in the disruption of cognitive function in ADHD. However, less is known about how EF and reward processing specifically are related in typically developing children (Best, et al., 2009). It is unclear what the potential functional overlap in neural systems that are recruited for both EF and reward processing tasks might mean for typical development. There are only a few studies that address the potential neural overlap of EF and reward sensitivity and motivation. One study with adolescents found that reward and sustained attention processes seemed to both use similar areas of the brain, specifically the dorsal lateral prefrontal cortex, ventrolateral prefrontal cortex, and parts of the striatum (Smith, Halari, Giampietro, Brammer, & Rubia, 2011). Another study found similar patterns of overlap in processing of reward information and a working memory task in the DLPFC, and right superior sulcus (Taylor, et al., 2004). These studies provide the first compelling evidence that the processes of executive function and reward processing are utilizing overlapping portions of the brain.

The overlap in neural systems and the mutual dependence on dopamine function for both reward processing and EF might lead one to hypothesize that a difficulty in one of these domains may be directly linked to difficulties or atypical processing in the other. Outside of the ADHD literature, little is known about the impact of poor executive function on behavioral measures of reward processing or motivation, or the potential effects of poorer EF on the brain response to rewarding stimuli. Exploring the intersection of reward and EF processes in the brain may provide insight into how these constructs interact to initiate the disruptive behaviors exhibited in children with ADHD.

The overarching goal of this paper is to examine the degree to which executive function and reward processing are behaviorally and neurologically related in middle childhood. Specifically, the focus will be on a range of typically developing 9- through 11-year-old children who show a range of performance levels on a variety of executive function and reward sensitivity or motivation tasks. In the first study, we examine whether behavioral performance on EF tasks is linked to behavioral performance on reward sensitivity or motivation tasks. To examine questions about the interaction between EF ability and the brains response to reward information, we examine both functional and structural neuroimaging data in a second study. In the two parts of this second study we address whether children with poorer EF ability show atypical brain activation patterns to rewarding information and whether there are any differences in brain size based on individual differences in EF and reward task performance. The following section describes the specific aims and hypotheses associated with each study.

Aims & Hypotheses

Aim 1: To examine the degree to which children with executive function difficulties also exhibit problems in tasks that involve a motivational or reward component. There are three underlying goals to this aim. 1) To examine executive function performance in order to obtain a better understanding of executive function processes in typically developing 9-11 year old children. 2) To examine the potential inter-relationships among the reward sensitivity, risk taking, and delayed discounting tasks in order to understand the potential overlap of these separate constructs. 3) To ascertain to what degree EF ability is related to performance on the reward sensitivity, delayed discounting, and risk taking tasks.

The first goal involves determining whether the executive function tasks used in this study are related to one another. We expect that these tasks will be correlated with one another as they are thought to tap overlapping constructs of cognitive function (Best, et al., 2009; Brocki & Bohlin, 2004). This step is imperative for determining whether an overall metric of executive function in the form of a composite variable is a viable way to examine the data. In this section, correlations between the variety of accuracy and reaction time metrics of performance on the EF tasks will be examined to determine how well performance on different tasks holds together. From those correlations, we will select related variables and conduct reliability analyses to determine if these variables can be successfully composited into an overall metric of executive functioning. Furthermore, we will explore the relationship between EF task performance and parent-report questionnaire measures of children's behavior.

The second goal involves examining to what degree performance on the reward sensitivity, delayed discounting and risk taking tasks is related. Unlike the executive function measures, we do not necessarily expect strong correlations among the reward processing tasks as they are thought to be measuring different constructs of reward processing and motivation. However, we will examine those relationships to determine to what degree these tasks overlap in their measurement of motivational processing. Furthermore, we will examine to what degree parent-report measures of behaviors such as impulsivity and thrill seeking are related to reward task performance. We would expect that parent report measures of impulsivity would be positively correlated with risking taking and levels of discounting a delayed reward.

The third and main goal of this section is to examine to what degree EF ability is related to reward sensitivity, risk taking, and delay discounting. Specifically, we want to ascertain whether children who have lower scores on EF tasks also show less sensitivity to reward, higher discounting of delayed rewards, and higher risk taking tendencies. We would expect, given previous literature on ADHD, that children who show EF difficulties might also show higher levels of risk taking, and stronger discounting of a delayed reward (Luman, et al., 2010; Steinberg, 2005). Additionally, we might expect that children with lower EF skills might show less sensitivity or distinction in their responses to reward versus non-reward conditions than children with higher EF ability (Luman, et al., 2009b; Masunami, et al., 2009). However, there is some literature to suggest that children with ADHD are actually more motivated to complete a taxing task when a reward motivation is present (Huang-Pollock, et al., 2007; Luman, et al., 2009a). Thus, we may find that children with lower EF performance show heightened sensitivity to reward and higher accuracy on rewarding trials specifically.

Aim 2: To examine the effect of EF differences on functional activation patterns in the brain during the Monetary Incentive Delay (MID) reward processing task. The purpose of this aim is to ascertain whether children who show lower EF skills exhibit differences in the brain regions that are recruited to process reward information as compared to children with higher EF ability. We would expect children with lower EF to show weaker, less focal patterns of activation in areas associated with reward processing (such as nucleus accumbens, orbitofrontal cortex, and caudate nucleus), than children with higher EF based on previous studies of children with ADHD (Durston, et al., 2003a). Additionally, we expect that in some cases, especially when comparing the magnitude of reward that children with EF difficulties might show a more blunted response to smaller rewards than children with strong EF skills based on previous literature addressing children with ADHD (Scheres, et al., 2007; Ströhle, et al., 2008). However, it is also possible that children with EF difficulties may recruit different areas of the brain than children with strong EF during the processing of reward information (Durston, et al., 2003a).

Aim 3: To examine whether difficulties in EF and reward task performance are related to structural brain volumes of areas in fronto-striatal circuits that are thought to be involved in both EF and reward processing. We examine brain activity in the orbitofrontal cortex, caudate nucleus, anterior cingulate cortex and nucleus accumbens (Elliott, Dolan, & Frith, 2000a; Knutson, et al., 2001a; Knutson, Fong, Bennett, Adams, & Hommer, 2003; Knutson, Westdorp, Kaiser, & Hommer, 2000; O'Doherty, et al., 2001; Schultz, Tremblay, & Hollerman, 1998; Schultz, et al., 2000). Though we are conducting these analyses merely as an exploration of the potential correlation between brain and behavior, we would expect that any differences would show that children with lower EF ability would have smaller volumes in key areas such as the prefrontal cortex and caudate nucleus as has been previously documented in children and adolescents with ADHD (Ellison-Wright, Ellison-Wright, & Bullmore, 2008; Semrud-Clikeman, et al., 2000; Sowell, et al., 2003). There has been very little research on the link between structure of the brain and reward processing specifically, but given previous developmental work on the links between cognition and brain structure, we might expect that children with better performance on the reward processing tasks might show smaller volumes than children who performed more poorly (Toga, P., & Sowell, 2006).

Chapter 2

Study 1: The behavioral intersection of EF and reward processing

Introduction

The first step in understanding the nature of the interaction of EF and reward processing in behavior and the brain is examining executive function abilities in typically developing children. Extensive research on early childhood EF development has found that many of the basic foundational aspects of executive function seem to develop between ages three and five (Anderson, 2002; Best, et al., 2009; Brocki & Bohlin, 2004; Davidson, Amso, Anderson, & Diamond, 2006; De Luca, et al., 2003; Zelazo, et al., 2008). Tasks such as the Dimension Change Card Sort (DCCS) which requires flexible rule use and switching between different sorting tasks without becoming swayed by interfering information have highlighted the difficulties that young children often have with these types of abilities (Zelazo, 2006; Zelazo, et al., 2008; Zelazo, Frye, & Rapus, 1996). Much research has evaluated children's ability to flexibly switch between rules as well as inhibit prepotent responses (Anderson, 2002; Best, et al., 2009; Brocki & Bohlin, 2004; Davidson, et al., 2006; De Luca, et al., 2003; Diamond, Kirkham, & Amso, 2002). Additionally, tasks such as the Tower of London task that require higher level planning and problem solving abilities also exhibit a developmental change in performance across early and middle childhood (Luciana & Nelson, 2002; Luciana & Nelson, 2009).

Though much of early research with EF in children has focused on early childhood, more recent research has begun to examine the extension of EF development into middle childhood, adolescence and young adulthood (Best, et al., 2009; Brocki & Bohlin, 2004; Crone, 2009; Luciana & Nelson, 2002; Luciana & Nelson, 2009). Even later in development, children and adolescents often show less successful ability to switch flexibly between rules, successfully solve problems, control prepotent responses, keeping information in mind, and resolve conflicting information than adults (Brocki & Bohlin, 2004; Davidson, et al., 2006; De Luca, et al., 2003; Luciana & Nelson, 2002; Luciana & Nelson, 2009). Furthermore, many children show decrements in these EF abilities that disrupts other aspects of life and function and are often diagnosed with disorders such as Attention Deficit Hyperactivity Disorder (Biederman, et al., 2004; Spencer, Biederman, & Mick, 2007). However, even typically developing children can display a range ability in executive function tasks. Though not nearly as apparent as children who have been diagnosed with ADHD, typically developing children can show subtle difficulties in EF, which may be linked to difficulties in other areas of their lives (Best, et al., 2009; Zelazo, et al., 2008).

One of the major challenges in conducting executive function research is that there is no standard battery of tasks used to measure EF (Best, et al., 2009). Often researchers will use one or two tasks to measure the whole construct of EF. However, the term executive function encompasses a wide range of functions and behaviors. Inhibitory control, working memory, set shifting, and planning all fall under the umbrella term of executive function (Best, et al., 2009; Zelazo, et al., 2008). In recent years, researchers have been challenged to include more than one measure of the executive function construct in order to more accurately account for the variety of abilities that are subsumed under the term EF (Best, et al., 2009). Following this trend, in this study, we had participants complete four tasks that measure separate but overlapping constructs of EF (Best, et al., 2009; Zelazo, et al., 2008).

In this study, we used the classic color/word Stroop task, the Dimensional Change Card Sort (DCCS) task, the Go/Nogo task and the Tower of London (TOL) task. The Stroop is a classically used task that measures inhibitory and conflict processes by requiring participants to name the color that the letters of a color word are printed in (e.g. the word blue written in red ink) instead of automatically reading the word (Lansbergen, Kenemans, & van Engeland, 2007; Stroop, 1935). The Dimensional Change Card Sort task measures cognitive flexibility and rule use by requiring subject's to switch back and forth between two different sorting rules on a trial by trial basis (Zelazo, 2006; Zelazo, et al., 1996). The Go/Nogo task measures basic inhibitory control processes by participants to withhold a prepotent response (Best, et al., 2009; Casey, Tottenham, & Fossella, 2002). The Tower of London task is classically used to measure planning and problem-solving ability by requiring participants to match a pattern by moving a series of colored discs with the goal of completing the problem in as few moves as possible (De Luca, et al., 2003; Luciana & Nelson, 2002; Luciana & Nelson, 2009). All of these tasks have been extensively used in examining EF previously (Anderson, 2002; Best, et al., 2009; Brocki & Bohlin, 2004; Davidson, et al., 2006; De Luca, et al., 2003; Luciana & Nelson, 1998, 2002; Luciana & Nelson, 2009; Zelazo, 2006; Zelazo, et al., 2008). Thus, it is our hope that this combination of tasks that measure different underlying aspects of executive function will give us a coherent and comprehensive metric of executive function ability in these children. In addition, parents completed a number of questionnaires that measure different behavioral aspects of executive function that are seen in everyday life. We used the Child Behavior Checklist (CBCL), Conners' Parent Report Form, the Sensation

Seeking Scale for Children (SSSC), and the Behavior Regulation Index of Executive Function (BRIEF).

Furthermore, to more precisely understand the interplay of EF and reward processing in both behavioral and task performance manifestations, we needed to examine the performance on the reward tasks in this sample alone. In early childhood the primary task examining how children control behaviors in the face of rewarding situations is the delay of gratification task which requires to children to choose to wait for a larger reward at a later time instead of an immediate smaller reward (Mischel, Ebbesen, & Zeiss, 1972; Mischel, Shoda, & Rodriguez, 1989). The classic delay of gratification task administered to pre-school and elementary school-aged children usually involves some type of desirable food item (Mischel, et al., 1972; Mischel, et al., 1989). However, for the 9- through 11-year-old children, we did not feel that this task would be difficult enough to perform. Thus, we chose a hypothetical delayed discounting task to attempt to address questions about how long a child was willing to wait for hypothetical delayed rewards of varying magnitudes (Barkley, Edwards, Laneri, Fletcher, & Metevia, 2001; Olson, Hooper, Collins, & Luciana, 2007; Shiels, et al., 2009). Previous research using delayed discounting tasks with adolescents has found that degree of discounting decreases with age such that older children are more likely to wait longer for a larger reward (Olson, et al., 2007; Scheres, et al., 2006). Previous research has found higher levels of discounting (preferring the smaller reward now over the larger reward later) in individuals diagnosed with ADHD (Barkley, et al., 2001). However, other research has not found this effect in ADHD individuals (Scheres, et al., 2006). Thus it is unclear to what degree ADHD, and its associated behaviors, may be related to discounting of a delayed reward. In this study, we wanted to evaluate to what degree delayed discounting might be related to EF in typically developing children to help address the questions of this link in children with ADHD.

Another construct of interest in this sample given the previous literature in ADHD, is risk taking. Previous studies have reported increased risk-taking behaviors are often associated with ADHD symptomology (Barkley, 1997; Biederman, 2005; F. X. Castellanos, et al., 2006; Geurts, van der Oord, & Crone, 2006). Additionally, there is a measurable increase in risk-taking tendencies in adolescence (Steinberg, 2005). Thus, in this transitional period of middle childhood, we were especially interested in understanding how EF ability might interact with risk-taking tendencies. In this study, we used the Balloon Analogue Risk Task (BART), which is thought to measure risk taking propensity (Lejuez, Aklin, Zvolensky, & Pedulla, 2003; Lejuez, et al., 2002). In this task participants press a button to blow up a balloon in order to build up points. The larger the balloon is, the more points they accrue, and they can save their points at any time, but the balloon can also pop at any time. In other words, the risk for the balloon popping increases as the size of the balloon, and the number of points associated with it increases (Lejuez, et al., 2003; Lejuez, et al., 2002). Previous research with adolescents has found that riskyness measured by the BART was significantly related to increased levels of self-reported risk taking behaviors (Lejuez, et al., 2003). Given these findings and the link between risk-taking and ADHD, we wanted to examine whether lower EF performance in these children is related to increased levels of risky behaviors.

The last reward task utilized in this study is the Piñata reward sensitivity task. This task is very new (developed by Nathan Fox and colleagues) and created to use with children, but is based on the Monetary Incentive Delay (MID) task developed by Brian Knutson and colleagues (Knutson, et al., 2001a; Knutson, Fong, Adams, Varner, & Hommer, 2001b; Knutson, et al., 2003; Knutson, et al., 2000). In the Piñata task, children are asked to respond with a button press whenever a picture of a Piñata appears on the screen. The Piñatas have different levels of potential reward associated with them: no reward, small reward, and large reward. In this task, we wanted to see if children are more accurate and quicker to respond to the highly rewarding condition as compared to the small or no reward conditions. Previous research in children with ADHD in tasks similar to this one has reported mixed findings. Some research has found that children with ADHD seem to be less sensitive to the rewarding contingencies (Luman, et al., 2009b; Masunami, et al., 2009). However, other research has found that children with ADHD exhibit better performance on the higher reward contingencies, indicating that reward information may be buffering performance for some children with ADHD (Huang-Pollock, et al., 2007; Luman, et al., 2009a). Given these findings, we are interested to see whether the children with lower EF ability are more or less sensitive to the reward trials in this task.

The focus of this second section of this study is to expand our knowledge about the development of these reward-processing constructs in the middle childhood period. Little is known about the development of these constructs in middle childhood, and as such this study will provide a first look at these constructs within the middle childhood period. Furthermore, given previous literature on the connections between impulsivity, hyperactivity, inattention and these constructs, we will examine how parent-report measures of these types of behaviors are related to these constructs of reward processing (Lejuez, et al., 2002; Luman, et al., 2009a; Olson, et al., 2007).

Lastly, in this chapter, behavioral performance on both EF and reward tasks is examined to address the overlap of these two domains. As reviewed in the general introduction, several studies of ADHD have suggested a possible link between these behaviors. Children with ADHD often exhibit impairments in both executive function ability (planning, working memory, inhibition, etc) and less sensitivity to reward stimuli and higher levels or risk taking (Barkley, 1997; Sagvolden, et al., 2005; Sonuga-Barke, 2005). However, very little work has been done examining the potential link between these constructs in normative development. In this chapter, we address this gap in the literature by testing whether EF ability has an impact on performance in reward tasks. Specifically we address whether differential reward processing behaviors are exhibited by children at opposite ends of the normative EF continuum (highest and lowest quartiles) of EF performance.

The results of the current study are presented in three sections addressing the three goals outlined previously. The first goal is to examine task performance of this sample of typically developing 9 through 11 year olds in the executive function tasks, as well as how these performance measures relate to parent report measures of executive function, hyperactivity, inattention, and externalizing types of behaviors. The second goal is to address how these typically developing children perform on reward sensitivity, risk taking, and delayed discounting tasks. The third goal is to examine the intersection of these two processes to address whether EF ability impacts reward sensitivity and motivation in middle childhood.

In the first section, data from the various EF tasks and parent-report questionnaires will be reported. This section will include correlational analyses of the relationships among the EF tasks and among the questionnaire measures, as well as relationships between the behavioral tasks and questionnaires. In the second section, the reward task data will be examined to determine to what degree the reward tasks are related to one another, and to the questionnaire data. In the third section, we address the central question of the paper by examining the potential impact of EF ability on performance on the behavioral reward tasks.

Method

Participants

One hundred 9-11 year old children (mean age = 10.51, range 9.00-11.92, male = 50, female = 50) were recruited from Minneapolis, St. Paul, and the surrounding suburbs in Minnesota to participate in this study. The majority of these children were recruited via the Institute of Child Development's Participant Pool, which provides basic contact information for families who have agreed to be contacted regarding research opportunities at the Institute. Fliers were also placed in coffee shops, libraries and community centers in the Minneapolis, St. Paul, and surrounding suburban areas in an attempt to recruit a more diverse sample. Eighty-eight percent of the children were identified by parents as Caucasian, four percent as Asian/Pacific Islander, three percent as biracial or multiracial, two percent as African American and two percent as other minority groups. All participants were pre-screened prior to enrollment for any major health or mental disorders (e.g. cancer, pervasive learning disorders, autism, etc.).

Procedures

The research session was held at the Institute of Child Development at the University of Minnesota. Researchers explained the tasks that children and parents would be asked to complete, and parents and children provided informed consent and assent to participate. Children were paid $20 and parents were paid $10 for their participation. After the session, children and parents were mailed a thank you letter and a Junior Scientist Certificate as an additional thank you.

Participants were told at the beginning of the session that there were some activities (the reward tasks) in which they could earn tokens to exchange for a prize from a prize box. Children were told that if they earned 5 or more tokens over the course of the session that they would get to select a prize out of the “Big Prize” box, but if they earned fewer than 5 tokens, they would get to select a prize from the “Little Prize” box. The session was designed so that the minimum number of tokens a child could receive was 5, so that every child would be able to select a prize from the “Big Prize” box. The specific number of tokens possible for each task is described below. The prize boxes included small toys, craft items, and card games.

During the session, child participants were asked to complete a series of tasks including the four executive function tasks and three reward tasks described below. The participant’s Intelligence Quotient (IQ) was calculated using the Matrix Reasoning Subtest of the Wechsler Abbreviated Scale of Intelligence (WASI).

Additional measures were collected as a part of a collaborative data collection effort for another project. These tasks included the Developmental NeuroPsychological Assessment (NEPSY) Affect Recognition subtest, the Hostile Attribution Bias

Questionnaire, and the Word Reading and Numerical Operations subtests of the Wechsler Individual Achievement Test (WIAT). These data are not reported in the current paper.

While children completed the behavioral assessments, parents were asked to complete a series of questionnaires assessing their child's everyday behaviors as well as aspects of cognitive, social, and emotional functioning.

Measures

Tasks

Go/NoGo task. The Go/NoGo inhibitory control task measures the ability to withhold a prepotent response. The specific Go/NoGo task used was the Whack a Mole Go/NoGo paradigm (Stimuli courtesy of Sarah Getz and the Sackler Institute for Developmental Psychobiology). The task was programmed using EPrime software (Psychological Software Tools Inc., Pittsburgh, PA). In this game, the participant was asked to press the spacebar as fast as possible when the mole popped out of its hole. However, children were asked to refrain from pressing the button when an eggplant (with the same basic shape as the mole) popped out of the hole. The images of the mole varied in the "disguises" (e.g. hair, glasses, hat), but the eggplant image remained constant throughout the task. Approximately 75% of trials were Go trials. This ratio insured that children built up a prepotent tendency to response. The Go and NoGo conditions were manipulated such that a NoGo stimulus followed 1, 2, 3, 4 or 5 consecutive Go stimuli. The purpose of this manipulation was to examine the effect of a build up of a proponent response tendency across time. There were 15 of each of the NoGo1, NoGo3 and NoGo 5 trialtypes, with only 5 of each of the NoGo 2 and NoGo 4 conditions. The latter two conditions were used as foil conditions to keep participants from picking up on any overall patterns. Each trial lasted approximately 2 seconds, and each run contained 55 trials. With all four runs, the task lasted approximately 8 minutes.

Dimensional Change Card Sort (DCCS) task. The DCCS task measures flexible rule use in children (Zelazo, 2006). Though the DCCS has classically been administered to preschool age children, it has been adapted for use with children in this age group (Zelazo, Anderson, & Richler, 2011; Zelazo, et al., 2008). Children were asked to sort images of objects on the computer based on either the color dimension (yellow or blue) or the shape dimension (ball or truck) of the object. Children pressed either the left arrow key or the right arrow key to indicate in which "bin" they wanted to place the object. The two "bins" were represented by the intersection of the two dimensions, for example, a blue ball and a yellow truck. Children were then asked to sort yellow balls and blue trucks based on either the object's color, or the object's shape and press the button for the correct "bin". The children were told that the words "shape" or "color" would appear on the computer screen, instructing them of the relevant sorting dimension. The words were also presented in audio by the computer. After two practice rounds of sorting on each of the dimensions individually, the instructions were mixed together and subjects were required to flexibly switch between the two dimensions. Performance following a dimensional switch is used to index cognitive flexibility or task switching. For example, the child might be instructed to sort based on color for three or four trials, and then asked to sort based on shape. The "shape" trial in this case, would be considered a "post-switch" trial because the sorting rule switched from color to shape. Whether children sorted predominantly based on color or shape was randomized across the sample. This computer task is part of the NIH toolbox set of assessment of neurological and behavioral function (National-Institute-Of-Health, 2011; Zelazo, et al., 2011) and runs in Eprime software (Psychological Software Tools Inc., Pittsburgh, PA). The task was self-paced such that children could take as much time as they wanted to sort each stimulus. There were a total of 40 trials (32 pre-switch trials, and 8 post-switch trials) across the task. The task took approximately 2-4 minutes to complete, depending on the speed with which the child sorted the stimuli.

Tower of London (TOL) task. The TOL is a measure of planning proficiency and problem solving (Luciana & Nelson, 2009). The TOL task requires the participant to match a pattern of three colored discs within a required number of moves. The display was divided into two halves. A target arrangement was presented in the upper half of the screen. A starting arrangement was presented in the lower half of the screen. Children were instructed to plan out their moves ahead of time and move the colored discs in the lower half of the display to match the pattern in the upper half of the display while making as few moves as possible. The computer had a touch-screen enabled monitor so the children could touch the screen to move the colored discs. The starting pattern required one, two, three, four, or five moves to achieve the target arrangement. The patterns increased in degree of difficulty, beginning with one-move problems and ending with five-move problems. Three trials were presented for each difficulty level resulting in a total of 15 trials. This computerized version of the Tower of London task from the Psychology Experiment Building Language (PEBL) software package (Mueller, 2010) was self-paced, but on average took approximately 2-5 minutes to complete.

Color-Word Stroop task. The Color/Word Stroop Task is a measure of conflict monitoring and resistance to interference (Stroop, 1935). We created a computerized version of the Stroop task using Eprime software (Psychological Software Tools Inc., Pittsburgh, PA). The task parameters were selected to match the standard color-word Stroop included in the Delis-Kaplan Executive Function System (D-KEFS) standardized assessment. This task had four rounds. The first round required participants to name the colors of color patches presented on a white background. The second round required participants to read color words printed in black ink on a white screen. In the third round, color words were presented in different colored ink (e.g. the word blue printed in red ink), and participants were required to name the color of the ink that the letters were printed in and not read the word. The fourth round required participants to switch between naming the ink color as in the previous round, and reading the word whenever the word had a black box around it. Total time to complete each round and the number of errors committed in each round were recorded. The task was self-paced, but lasted approximately 3-6 minutes on average.

Piñata Reward Sensitivity task. Fourteen children did not complete the Piñata task due to difficulty in adjusting its design and implementation at the outset of the study. The Piñata reward sensitivity task required participants to press a button in response to different levels of symbolic reward to accumulate as many points as possible. Stimuli for this task were provided by Dr. Nathan Fox and his colleagues. Stimulus presentation and response collection were implemented in E-Prime software (Psychological Software Tools Inc., Pittsburgh, PA). In the task, a cartoon picture of an animal appeared, only partially visible, at the very top of the screen. After a random delay interval, the picture would become fully visible on the screen at which point participants were required to press the spacebar as quickly as possible to “whack” the piñata and break it open. Some piñatas had one star on them (indicating a small reward), some had four stars on them (indicating a large reward), and other had no stars (indicating a no reward condition). Participants were instructed to try to hit every piñata regardless of the number of stars they could earn. The first partially obscured image of the cartoon piñata was on the screen for 500ms, then there was a delay interval (750-1250ms) between when the cue disappeared and the target appeared. The randomly selected delay duration from the range of 750-1250ms was different for each trial and was used to prevent children from being able to accurately anticipate the occurrence of the target stimulus, therefore increasing the difficulty of the task. The participant’s reaction time on the previous experimental run was used to calculate the target duration. The process for determining the target presentation length is described below. After a 500ms post-target delay, feedback about whether participants were successful in opening the piñata was presented for 1650ms.

To obtain an accurate measure of the participant’s initial average reaction time on the task, participants completed a practice round of the game where they became familiar with the task. Each participant’s reaction times on each of the 12 trials were rank ordered, and the 2/3 (or 66% percentile) cut-point of the rank ordered times was entered into the first run of the actual task to set the target duration. The goal was to make the task difficult enough for the children to be challenged. Thus, the 66% percentile of their entire range of reaction times was used to specify the time frame for the delay interval preceding the target and for the target duration itself.

Following the participant's response to the target stimulus, the feedback screen was presented. The feedback was either the image of the cartoon animal swinging off the screen to indicate they had not successfully hit the button to receive the stars, or was an image of the broken piñata, with it's reward content spilling into a small basket at the bottom of the screen. There were 14 small reward trials, 14 large reward trials, and 14 no reward trials in each run. Participants received tokens based on the number of points they had earned over the course of the game. If participants earned 1-70 stars, they received 1 token, if they earned 71-140 stars, they received 2 tokens, and if they earned between 141-210 stars, they received 3 tokens. Most participants received either 2 or 3 tokens in this task.

Balloon Analogue Risk Task (BART). The BART measures risk-taking propensity (Lejuez, et al., 2002). Participants were required to press the "Pump" button on the touch screen computer monitor to inflate a balloon on the computer screen. As the balloon inflated, the number of points participants could earn increased. However, the risk that the balloon would pop, resulting in the loss of all the points in the balloon, also increased as the balloon grew in size. However, participants were told that the balloon could pop at any time. When the balloon popped, the computer made a startling explosion sound. Participants could choose to save, or "bank", their points whenever they wished by pressing the "Get $$$" button on the screen, at which point the points from the current balloon were placed in the participant's prize meter represented by a bar that increased as points were earned. When participants chose to save their points, they heard a sound like a casino slot machine jackpot. The prize meter had four levels indicated on the screen that were labeled as "Small Prize", "Medium Prize", "Big Prize", and "Bonus". These different levels stipulated whether children received 1, 2, 3 or 4 tokens. Participants were encouraged to try to earn as many points as possible in order to earn more tokens toward picking out a prize from the "Big Prize" box. There were a total of 30 balloons or trials total.

Delayed Discounting task. A delayed discounting task was used to assess participant's discounting of a hypothetical delayed reward over a hypothetical more immediate reward. The version used was based on a paradigm developed by Barkley (2001) that was adapted for use with younger children by Shiels et al., (2009). In this task, participants were asked a series of hypothetical questions about whether they would choose a smaller reward now or a larger reward later. The possible immediate dollar amounts ($1, $10, $20, $40, $50, $70, $90 and $100) were systematically compared to a fixed $100 amount at five hypothetical delay lengths (1 day, 1 week, 1 month, 6 months, 1 year). Children were presented with play money in the correct dollar amounts on the table as a visual representation of the hypothetical question. It was thought that this might increase the saliency of the question as compared to a verbal hypothetical question alone. The smallest immediate value chosen over the longer delayed fixed amount was coded for each delay length as the threshold at which the child would prefer the immediate reward more than the delayed reward (Shiels et al., 2009). All participants received 2 tokens for completing this task.

WASI Matrix Reasoning. The Matrix Reasoning subtest of the Wechsler Abbreviated Scale of Intelligence (WASI; (Axelrod, 2002)) was administered to all participants. In the subtest, participants were instructed to look at a picture that had a piece missing, and to choose the missing piece from the five choices at the bottom of the page. Children were required to meet a base of 2 correct items in a row before continuing. Once a child missed 4 in a row, or 4 out of 5 consecutive items, the task was ended and the child's score was calculated based on the number of items they correctly answered before discontinuing. The total score was then T-scored (Mean = 50, SD = 10) according to the age and gender of the child. The task was self-paced, but took approximately 5-8 minutes to complete.

Parent Questionnaires

Parent-report questionnaires included the Child Behavior Checklist (CBCL; (Achenbach, 1991)), Conners' Parent Rating Scale – Revised Long Form (Conners'; (Conners, 1994)), The Health and Behavior Questionnaire (HBQ; (Armstrong & Goldstein, 2003)), the Behavior Regulation Index of Executive Function (BRIEF; (Gioia, Isquith, Guy, & Kenworthy, 2000))the Sensation Seeking Scale for Children (SSSC; (Russo, et al., 1993)), life events questionnaires (Masten, Neeman, & Andenas, 1994), and a general demographics questionnaire. For the purposes of the questions being addressed in this thesis, only subscales from the CBCL, Conners' BRIEF, SSSC and subcomponents of the demographics questionnaire were used in these analyses. The HBQ and Life Events Questionnaires will not be described further in this paper.

The CBCL required parents to rate the frequency of a variety of behaviors their children may or may not exhibit, and it is normed to provide ranges of problem behaviors such as internalizing or externalizing symptoms. It consists of 120 questions covering behaviors and emotional problems within the last six months. Parents are asked to rate the behaviors on a three point scale ranging from "Not true" to "True or Often True". Items include behaviors such as: "Fails to finish things he/she starts" and "Doesn't get along well with other kids". The CBCL is clinically validated for use in 6-18 year old children. T-scores (Mean = 50, SD = 10) for ten subscales are provided based on the age and gender of the child. For the purposes of the questions addressed in this paper, only the Attention Problems, Externalizing Behaviors, and ADHD Problems subscales of the CBCL were used in analyses given our interests in executive function.

The Conners' Parent Report is similar to the CBCL in that it asks parents about the frequency of certain behaviors, but it is most often used as a metric of inattentive, impulsive, and hyperactive behaviors. The Conners' parent report form has 80 items and asks parents, on a four point scale (ranging from "Not true at all" to "Very much true"), to rate the frequency or severity of various problem behaviors over the course of the past month (Conners, 1994). Items on the Conners' include: "Restless or overactive" and "Needs close supervision to get through assignments". This questionnaire has been validated for use with 3-17 year olds, and provides T-scores (Mean=50, SD=10) based on age and gender for nine subscales. Given our interest in the prevalence of ADHD-type behaviors, the cognitive problems/inattention, hyperactivity, and ADHD subscales were used in these analyses.

The BRIEF is an 86-item questionnaire that was used to assess the observable characteristics of behaviors associated with executive function. There are eight non-overlapping scales of EF including scales of inhibition, shifting, working memory, and monitoring behaviors. Parents are asked to rate the frequency of behaviors on a three point scale ("Never" to "Often"). Items on the BRIEF include: "Is easily distracted by noises, activity, sights, etc." and "Does not take initiative". The measure has been validated for use with 5-18 year olds (Mean = 50, SD = 10). All of the scales on the BRIEF were included in initial analyses.

The SSSC provides a metric of children's general tendencies toward risk taking (Russo, et al., 1993). The SSSC has been shown to have good reliability and validity (Russo, et al., 1993). There are 19 items on this adapted version of the SSSC. We removed items that made references to drug and alcohol use as those questions were not appropriate for the age range in our study. Traditionally, the SSSC is administered to children, but we adapted wording of the items to make it a parent-report questionnaire. Items presented two options and parents were asked to select the option that was most like their child. For example, parents were asked to choose which of the following was most like their child: "My child would want to try mountain climbing" and "My child thinks that people who try dangerous things like mountain climbing are foolish." Two subscales of interest were calculated: the Thrill and Adventure Seeking (TAS) scale and the Social Disinhibition (SD) scale. In the original SSSC, there is a third scale relating to drug and alcohol use, but as previously described, those items were not included in this questionnaire.

The general demographic questionnaire asked basic questions about parent age, marital status, education, socio-economic status, and race. It contained 30 questions, but only basic information about the child's race was used in these analyses.

Data Analysis

Outliers and Analysis. Statistical outliers were excluded from individual variables in cases where a data point was greater than 3 standard deviations above or below the mean. In the Piñata task, there was one outlier in both the reaction time data and accuracy data; in the dimensional change card sort task, there was one outlier in reaction time data; and in the Go/Nogo task, there was one outlier in NoGo accuracy. All of these outliers were excluded from subsequent analyses of these variables.

Data were analyzed using PASW Statistics 18, Release Version 18.0 (SPSS, Inc., 2009, Chicago IL, www.spss.com) computer software. Linear regressions, bivariate correlations, univariate and repeated measures ANOVAs were used. In cases where sphericity assumptions were violated, Greenhouse-Geisser correction was used. In cases of correlational analysis where data did not display a normal distribution, a Spearman's Nonparametic correlation was used in place of a Pearson's correlation.

EF Task Missing data. Ninety-eight participants successfully completed the Go/NoGo task, with two participants refusing to complete the task. All 100 participants completed the DCCS task. Ninety-eight participants completed the Tower of London task. Two participants were unable to complete the task due to a computer malfunction. In the Stroop task there were a few cases in which the children accidentally pressed the computer screen when they were tracking which word they were reading, and because the screen was a touch screen monitor, the screen would advance incorrectly, thus providing us with an inaccurate condition completion time. Additionally, there were a few cases for which the experimenter's lost track of the child's naming or reading and did not code the errors correctly. For each of these reasons, the Stroop task conditions have different numbers of excluded subjects per condition.

The number of errors was recorded for each condition (naming color, reading words, inhibiting reading, conflict/switching). There were four subjects excluded from the color naming condition (n=96), two from the word reading condition (n=98), five excluded from the inhibition condition (n=95), and four from the conflict condition (n=96) for the reasons stipulated above. In the completion time scales, four subjects were excluded in the naming condition (n=96), two were excluded in the reading condition (n=98), three were excluded in the inhibition condition (n=97), and three were excluded in the conflict condition (n = 97) for the reasons stated above.

Reward Task Missing Data. All one hundred children completed the BART task. Fourteen participants did not complete the Piñata task due to difficulties with implementation of the computer program early on in data collection. Because there was no statistical benefic gained by imputing the missing data, we used the more conservative approach of using only the observed data from this task. In the Delayed Discounting task, only 98 participants were included in the analysis, because two participants were excluded because of experimenter error.

Questionnaire Measures Missing Data. Additionally, there were six statistical outliers on the CBCL ADHD problems subscale. The function of the CBCL, is to measure atypical behaviors. Given that this population of typically developing children would be expected to show low incidences of atypical and disruptive behaviors, it is not unexpected for statistical outliers to occur on these subscales. However, given that all were extreme outliers that might affect conclusions based on the assumptions made by the statistical methods used in this paper, they were excluded from further analyses. For the purposes of this paper, only the Attention Problems, Externalizing Behaviors, and ADHD Problems subscales of the CBCL were used. Ninety-nine participants had CBCL subscale scores. The remaining CBCL questionnaire was not fully completed by the parent (see Table 2). Ninety-four participants had complete Conners' questionnaire data.

The remaining six participants did not have complete data because the questionnaires were not fully completed by the parent. For the purposes this paper, only three subscales will be used. The cognitive problems/inattention, hyperactivity, and ADHD subscales are reported here (see *Table 2*). All one hundred subjects had complete BRIEF data. Because the research questions presented here surrounded measures of Executive Function, all of the BRIEF subscales are explored here (see *Table 2*). Ninety-four parents completed the SSSC questionnaire. Six participants had missing data due to missing questionnaire data. The SSSC has four subscales. Only three were used here as the fourth subscale contained questions about alcohol use that were not administered given of the age of the child participants. The three scales included were the Thrill and Adventure Seeking (TAS) subscale, the Social Disinhibition (SD) subscale and a Total scale, which assesses overall sensation seeking and is merely a combination of the TAS and SD scores. Given that the Total subscale is redundant with the TAS and SD subscales, it will not be used in analyses here (see *Table 2*).

Results

The results section is split into the three goal sections as described above in the hypotheses and aims section. The first section reports the basic task findings of the EF tasks to examine the profile of EF in this sample. The basic EF task descriptives are presented in *Table 1*. The second section reports the basic findings from the reward processing tasks to examine the profile of reward processing in this sample. The reward task descriptives are presented in *Table 6*. The third section examines how these two processes may interact behaviorally, to determine whether there are any effects of EF ability on reward sensitivity and risk taking behaviors in this sample.

Goal 1: Executive Function Task Performance and Parent Report

Executive Function Tasks

Go/NoGo task. Participants showed significantly better accuracy on Go trials than NoGo trials ($F(1, 97) = 156.53$, $p < 0.001$; Go mean = 1.00, NoGo mean = .85, see *Table 1*). NoGo trial accuracy also varied as a function of load ($F(2,194) = 27.52$, $p < 0.001$). Tukey's HSD post-hoc analyses were calculated. Comparisons between load levels indicated that NoGo 1 accuracy was significantly worse than NoGo 3 accuracy ($t=8.522$, $p < 0.05$) and NoGo 5 accuracy ($t = 9.518$, $p < 0.05$), but NoGo 3 trials were not significantly different from NoGo 5 trials. However, for the sake of simplicity, we only wanted one measure of inhibitory control from this task in the form of NoGo accuracy. Thus we will not be examining the effects of load further in this paper.

Dimensional Change Card Sort (DCCS). Participants performed significantly better on pre-switch trials than on post-switch trials ($F(1,99) = 52.01$, $p<0.001$; pre-switch = 0.96, post-switch = 0.84). Reaction times were also significantly different between pre and post switch trials, with longer reaction times on average for post-switch trials ($F(1,99) =11.13$, $p < 0.01$; pre-switch = 844.21ms, post-switch = 892.93ms, see *Table 1*).

Tower of London task. The number of problems that were solved in the minimum number of moves (i.e. 2 moves, 3 moves, 4 moves) was calculated for each participant (maximum = 15). In addition, accuracy for each level of problem difficulty (i.e. 2 move, 3 move, 4 move problems) was calculated. The mean number of problems solved in the minimum number of moves for this sample is 9.92, with a range of 5 problems to 14 problems (see *Table 1*). Not surprisingly, accuracy significantly decreased across problem difficulty level ($F(4, 348) = 146.85$, $p < 0.001$). However, because we wanted to use the number of problems solved in the minimum number of moves as our metric of successful planning, we did not perform any further analyses on the effects of problem difficulty in this paper.

Stroop task. The Stroop task was designed such that each condition completion time for each condition was recorded via the computer using the time between the condition onset and the time at which the researcher clicked the button to advance the screen at the completion of the round. The number of errors was scaled by age according to the Delis-Kaplan Executive Function System (D-KEFS) standard scale. For the naming and reading conditions, the raw scores were transformed into cumulative percentile ranks corrected for age. For the inhibition and conflict conditions, the raw score was converted to a scaled score based on age ($M=10$, $SD=3$). The number of seconds it took to complete each condition was also recorded and then scaled by age using the standard scale on the D-KEFS. For each of the four conditions, the raw seconds to complete were converted to a scaled score ($M=10$, $SD = 3$) according to age.

An individual's scaled scores on each condition gave an indication as to his or her overall performance on each of the conditions of the Stroop. Within the whole group, the completion time scores on the naming, reading, inhibition and conflict conditions all fell within the normal ranges expected for this group of children (see *Table 1*). The error percentiles on the naming, and reading, and the error scales on the inhibition and conflict conditions also fell within the typical values expected (see *Table 1*). For the purposes of the questions addressed in this paper, we focused on the inhibition and conflict conditions of the Stroop task. In comparing the completion time scaled scores on the inhibitory control condition to the conflict condition, we found that children tended to perform better on the inhibitory control condition than on the conflict condition ($F(1,95) = 10.045$, $p < 0.005$; Inhibition = 11.454, Conflict = 10.732).

Effects of Age, Gender and IQ on EF Tasks & Questionnaire Measures

Age. Age was significantly related to performance on a number of EF tasks and questionnaire measures. Specifically, age was positively correlated with the number of problems solved in the minimum number of moves on the Tower of London task ($r = .27$, $p < 0.01$), such that older children performed better overall on this task. Age was also significantly negatively correlated with reaction time on the DCCS task for both the pre and post switch dimensions ($r = -.41$, $p < 0.001$; $r = -.34$, $p < 0.01$ respectively). Though age was accounted for in the standard scoring for the Stroop task, there was still a significant negative correlation between age and the standard score for the completion time in the conflict condition ($r = -.23$ $p < 0.05$). In other words, the older children were slower on the completion time for the conflict condition in the Stroop task even though age is accounted for in the standard scoring.

For the BRIEF parent-report questionnaire, the working memory and planning/organization subscales were both positively correlated with age ($r = .246$, $p < 0.05$, $r = .199$, $p < 0.05$ respectively), indicating that though these standardized scores account for age, older children tended to show higher incidences of parent-reported difficulty in everyday working memory and planning/organization. Additionally, the Thrill and Adventure seeking scale on the SSSC was significantly negatively correlated with age ($r= -.234$, $p < .05$), such that younger children tended to show higher scores on the TAS subscale than older children. There were no other effects of age on task performance or parent-reported behaviors.

In all further analyses, age was controlled for in cases where there was a significant correlation between age and a variable of interest. If age was not significantly related to the variables of interest, it was not controlled for unless otherwise explicitly stated.

Gender. Accuracy on these EF tasks differed by gender in two cases: accuracy on the pre-switch trials of the DCCS task ($t = 2.22$, $p < 0.05$), and completion time scaled score in the conflict condition of the Stroop task ($t = -2.15$, $p < 0.05$). Girls performed better in both cases. There were significant differences between males and females on both of the SSSC subscales, with males showing higher overall scores on the three subscales than females (TAS: $t=2.68$, $p < 0.01$, males = 8.15, females = 6.41; SD: $t=3.06$, $p < 0.01$, males = 3.44, females = 2.37). However, across all other metrics of task accuracy and parent report, there were no significant gender differences.

As with age, gender was only controlled for in further analyses when there was a significant effect of gender on a variable of interest. If gender was not significantly related to the variables of interest, it was not controlled for unless explicitly stated.

IQ. None of the metrics of accuracy on these EF tasks, or ratings on the parent-report questionnaires were significantly correlated with WASI IQ T-score on the matrix reasoning subtest.

EF Task Relatedness

In order to determine how well these separate tasks measure a similar construct of executive function, measures of task performance were correlated to determine task relatedness. Specifically we were interested in how the variables of NoGo accuracy, problems solved in the minimum number of moves on the TOL task, the post-switch trial accuracy and reaction time on the DCCS and the completion time and error standard scores from the Inhibition and Conflict conditions of the Stroop are related in this sample. Generally we expect to find correlations between most or all of these EF variables. We especially expect to find significant positive correlations between NoGo accuracy and Stroop completion time and errors in the Inhibition and Conflict conditions as they are thought to both measure inhibitory control processes. Additionally, we expect both DCCS post-switch accuracy and problems solved in the minimum number of moves on the Tower of London task to be related to NoGo accuracy. All EF task variable correlations can be found in *Table 3*. Only the correlations of primary interest are addressed below.

Tower of London. The number of problems correctly solved in the minimum number of moves was positively correlated with NoGo accuracy (Go/NoGo) ($r = 0.267$, $p < 0.05$). The number of problems solved in the minimum number of moves on the Tower of London task was also positively correlated with performance (both accuracy and completion times) on all of the conditions on the Stroop task (see *Table 3*).

DCCS. Post-switch trial accuracy on the DCCS was positively correlated with NoGo accuracy on the Go/NoGo task ($r = .386$, $p < 0.01$) indicating that children who performed better on the more difficult post-switch trials also performed well on the NoGo inhibitory control trials. Post-switch reaction time on the DCCS task was negatively correlated with both the inhibition ($r = -.355$, $p < 0.01$) and the conflict ($r = -0.330$, $p < 0.01$) completion time conditions of the Stroop task indicating that children who were faster at the post-switch DCCS trials were also faster at completing the Stroop Inhibition and conflict conditions.

Go/NoGo. NoGo accuracy on the Go/NoGo task was significantly positively correlated with the standard scores for condition completion times for both inhibition and conflict conditions ($r = 0.217$, $p < 0.05$; $r=0.346$, $p < 0.01$ respectively) in the Stroop task. The remainder of the significant findings can be found in *Table 3*.

Questionnaire Correlations. Within the questionnaires, we expected the CBCL, Conners' and BRIEF subscales of interest to be correlated as they are all thought to measure overlapping constructs related to EF difficulties. Conversely, the SSSC subscale was not expected to be as related to the other questionnaire measures as it is thought to address risk taking and motivation processes. As expected, the CBCL, Conners' and BRIEF subscales of interest are all highly correlated with one another (see *Table 4*). However, the subscales from the Sensation Seeking Scale for Children (SSSC), are only moderately correlated with the other questionnaire subscales (see *Table 4*).

EF Tasks and Questionnaire Measures

The CBCL Attention Problems subscale was negatively related to pre-switch trial accuracy on the DCCS task ($r = -.237$, $p < 0.05$). However, no other relationships were found between CBCL subscales and EF task performance. Scores on the Conners' Hyperactivity subscale were negatively correlated with DCCS post-switch trial accuracy, indicating that children with higher parent-reported hyperactivity showed poorer accuracy for the post-switch trials ($r = -.242$, $p < 0.05$). There were no other significant relationships between task performance and Conners' questionnaire subscales.

Many of the BRIEF subscales were significantly related to our EF task performance measures (see *Table 5*). The number of problems solved in the minimum number of moves in the Tower of London task was related to BRIEF Inhibit, Working Memory, Planning and Organization, Organization of Materials and Monitoring subscales (see *Table 5*). The Stroop Inhibition and Conflict completion times were related to Working Memory, Planning and Organization, and Monitoring subscales (see *Table 5*).

The TAS subscale on the SSSC was negatively correlated with post-switch reaction time on the DCCS ($r = -.298$, $p < 0.01$), indicating that children with faster reaction times on post-switch trials also showed higher levels of thrill and adventure seeking. There were no other significant relationships between SSSC subscales and behavioral performance on EF tasks.

Goal 2: Reward Tasks and Parent Reports

Balloon Analogue Risk Taking (BART) task. The average number of pumps was calculated across the 30 trials. However, trials in which the balloon popped were not included in the averages as they were not indicative of the child making a decision to cease pressing the pump button. The mean number of pumps for the entire sample was 26.46 (see *Table 6*). The number of explosions was totaled for each individual subject as an indicator of impulsivity. There were a total of 30 explosions possible, one per trial. The average number of explosions in this sample was 7.01. In addition, we calculated the average number of pumps for the trials following those in which the balloon exploded (mean = 24.14) as we expected those might be slightly lower than the overall average number of pumps. However, when controlling for effects of age, and restricting the post-pop average to only those participants who had more than 5 pumps, we did not find a significant difference between the average number of pumps, and the number of pumps following a balloon pop. Thus, for the purposes of this paper, we used only the average pumps measure for the BART task.

Delayed Discounting task. The smallest amount of money chosen in each time condition (day, week, month, 6 months, year) was recorded for each participant. Subjects had a choice of $1, $10, $20, $40, $50, $70, $90, $100 now or $100 at a later time. Some subjects always chose $100 later instead of any of the dollar amounts now. When this was the case, the data were recorded as $0 now in favor of $100 later. The mean for each time condition was calculated. The mean for the one day condition was 71.57; the one week condition was 64.45; the one month condition mean was 56.39; the six month condition mean was 43.98; and the one year condition mean was 38.88 (see *Table 6*). A repeated measures ANOVA revealed that there is a significant difference between the time conditions ($F\ (2.84, 275.74) = 30.97$, $p < 0.001$). Tukey HSD post-hoc follow-up analyses for these conditions are found in *Table 7*. Additionally, there was a significant linear trend across the time conditions ($F(1,97) = 70.94$, $p < 0.01$).

In addition, an overall delayed discounting score was calculated based on previous work by Myerson, Green & Warusawitharana (2001), which computes a curve for each subject based on the smallest amount of money selected across the different delay types and calculates the area under that curve as a metric of discounting for each subject. Delay and value were normalized as a proportion of the maximum delay (e.g. 7 days in a week divided by 365 days in a year) or the maximum value (e.g. $20 divided by $100 maximum value). Essentially, these normalized values provide points on a graph of subjective value and delay length. By calculating the area under the curve between those points and then adding those areas together, we get the area under the individual's discounting function (Myerson, et al., 2001). To calculate the area under the curve between each delay period, the following equation was used: (x2 – x1)[(y1+y2)/2), where x1 and x2 are the proportional successive delays (e.g. week – day), and y1 and y2 are the proportional subjective values associated with those delays (Myerson, et al., 2001). The areas for each delay window were then summed to obtain the total area under the individual's discounting function. Because all the values were previously normalized, the scale goes from 0.0, which indicates the most possible discounting, (e.g. always picking the smallest value now) to 1.0, which indicates the presence of no discounting (e.g. always picking only the highest value now). The means and standard deviations of the total area calculation for the whole group are presented in *Table 6*. We will be using this overall discounting measure in all further analyses of the Delayed Discounting task.

Piñata Reward Sensitivity task. Reaction time and accuracy were calculated for each subject for the three reward conditions: Large Gain, Small Gain, and No Gain. Overall reaction time (including both correct and incorrect trials) showed a significant effect of reward level (F (1.66, 139.50) = 23.90, $p < 0.001$), with No Gain exhibiting the slowest reaction times (mean = 324.94), Small Gain trials in the middle (mean = 309.48) and Large Gain trials exhibiting the fastest reaction times (mean = 304.54). Tukey's HSD post hoc analyses determined that the No Gain condition was significantly slower than both Small Gain ($t = -7.10$, $p < 0.05$), and Large Gain ($t = -9.37$, $p < 0.05$), but that reaction times for Small and Large Gain conditions were not significantly different from one another. In light of this lack of significant difference between small and Large Gain trials, we averaged the two gain conditions to get an overall “Gain Trial” Reaction time variable (see *Table 6*).

Accuracy for the different reward conditions was also statistically different ($F(1.79, 150.05) = 40.76$, $p < 0.001$), with best performance on Large Gain trials (mean = .82), Small Gain trials in the middle (mean = .788), and No Gain trials (mean = .730) showing the lowest accuracy (see *Table 6*). Tukey’s HSD post hoc analyses confirmed that not only was the No Gain condition significantly less accurate than from both the Small Gain ($t = 7.56$, $p < 0.05$), and the Large Gain ($t = 11.86$, $p < 0.05$) conditions, but the Small Gain and Large Gain conditions were also significantly different from one another ($t = 4.30$, $p < 0.05$) such that children were more accurate on Large Gain than Small Gain trials. To obtain an overall “Gain” condition accuracy variable, we averaged the accuracies for the Small and Large Gain conditions (see *Table 6*).

Effects of Age, Gender and IQ

Age. Age was significantly positively correlated with the number of adjusted pumps ($r= 0.242$, $p < 0.05$), the number of explosions ($r = 0.260$, $p< 0.01$) and the number of post-pop pumps ($r= 0.282$, $p < 0.01$) on the BART task indicating older children tended to be more risky. Age was also significantly correlated with level of discounting on the delayed discounting task ($r = .200$, $p < 0.05$) such that older children showed less discounting of a delayed reward. Furthermore, age was significantly negatively correlated with reaction times on each of the conditions in the Piñata task (No Gain: $r = -0.378$, $p < 0.01$; Small Gain: $r = -0.392$, $p < 0.01$; Large Gain: $r = -0.371$, $p < 0.01$) meaning that younger children were slower in each of the conditions of the Piñata task. However, age was not significantly correlated with accuracy on the Piñata task.

Age was controlled for in all subsequent analyses when appropriate as indicated by correlations with variables of interest. If age was not correlated with the variables of interest, it was not controlled for unless explicitly stated otherwise.

Gender. In the Piñata task, boys were significantly faster than girls on the gain ($t = -3.55$, $p < 0.01$, boys = 283.44, girls = 328.98) and no gain trials ($t = -3.55$, $p < 0.01$, boys = 283.44, girls = 328.98), indicating that boys overall showed faster reaction times than did girls. There were no other effects of gender in the reward tasks.

As with age, gender was controlled for only in subsequent analyses where variables of interest were found to significantly differ by gender. If variables did not show significant gender differences, we did not control for gender unless explicitly state otherwise.

IQ. IQ was not significantly related to performance measures on any of the reward tasks.

Task Relatedness

Reaction times for the no gain and all gain conditions on the Piñata task were negatively correlated with the number of adjusted pumps on the BART task ($r = -.265$, $p < 0.05$; $r = -.259$, $p < 0.05$). No other significant relationships were found among the reward task measures.

Reward Tasks and Questionnaire Measures

Number of pumps on the BART task, and level of discounting on the delayed discounting task were not significantly related to any of the CBCL, Conners', BRIEF, or SSSC subscales of interest. Additionally, reaction times for the all gain and no gain conditions on the Piñata task were not significantly related to the CBCL, Conners' or

SSSC subscales of interest when controlling for age and gender. However, accuracy for the all gain condition in the Piñata task was significantly related to a number of questionnaire measures (see *Table 8*). Specifically, all gain accuracy is positively correlated with CBCL externalizing problems ($r = 0.283$, $p < 0.01$), CBCL ADHD Problems ($r = 0.224$, $p < 0.05$), BRIEF Inhibit scores ($r = 0.225$, $p < 0.05$), and BRIEF Monitoring scores ($r = 0.223$, $p < 0.05$), indicating that higher levels of these types of behavioral problems are correlated with higher accuracy on the gain conditions in the Piñata task.

Data Reduction & Composites

In order to obtain a more holistic representation of overall executive function in this sample, we created composite variables of EF. Given the correlations between metrics of EF task performance as well as the correlations with some subscales on the BRIEF, we calculated alphas for groups of variables to find the best internal consistency. The initially hypothesized variables of interest for compositing were NoGo accuracy on the Go/NoGo task, Post-switch accuracy on the DCCS task, number of problems solved in the minimum number of moves on the Tower of London task, and the completion times in the inhibition and conflict conditions of the Stroop task. However, compositing these variables led to an alpha below 0.60, suggesting insufficient internal consistency to proceed. Specifically we found that NoGo accuracy and post-switch accuracy on the DCCS were the least cohesive of the task variables of interest. After further exploration of the task and BRIEF variables, we calculated an EF composite including the number of problems solved in the minimum number of moves on the Tower of London task, the completion time in the Inhibition condition of the Stroop task, the completion time in the

Conflict condition of the Stroop task, and five subscales from the BRIEF (Shift, Inhibit, Working Memory, Planning & Organization, and Initiate). The resulting alpha was .754 with these eight items. All measures were standardized, the five BRIEF subscales were reversed coded, and all variables were averaged and then subsequently standardized to provide a standardized metric of EF ability. We could not form a composite from the reward task variables because they were not cohesive enough to form a composite with acceptable internal consistency.

Goal 3: Intersection of EF Composite and Reward Processing Measures

The following results are split into three specific sections, each designed to examine the potential intersection of overall EF performance and performance on reward tasks. In the first section, four regressions are computed to examine whether the EF composite described above significantly predicts performance over and above age, gender and IQ on the three reward tasks. The four outcome variables of interest are: number of pumps on the BART, level of discounting on the delayed discounting task, reaction time on the all gain condition of the Piñata task, and the accuracy of the all gain condition of the Piñata task.

In the second section, we calculate the upper and lower quartiles of the EF composite and create High and Low EF groups to determine if there are any differences between extreme groups on these tasks. Four ANOVAs are computed with the same dependent variables listed above. As a follow-up, we are interested in determining whether any group effects on the Piñata task specifically might be a function of the level of reward. Therefore, conduct a repeated measures ANOVA between the Small and

Large Gain conditions to see if there are group differences on one reward level and not the other.

In the third section, we explore a priori hypotheses regarding the interaction of variables from specific EF tasks and specific reward task variables. Specifically we were interested in whether inhibitory control and cognitive conflict were related to risk taking in this sample. In the case of the BART task, we were interested in seeing whether NoGo accuracy from the Go/NoGo task or the completion time on the conflict condition on the Stroop task was predictive of the number of pumps. We hypothesized that planning and cognitive conflict might be processes involved with delaying gratification. For the level of discounting on the delayed discounting task, we were interested to see if the completion time of the conflict condition on the Stroop, or the number of problems solved in the minimum number of moves on the Tower of London task would be predictive of level of discounting. Lastly, we hypothesized that inhibitory control might be related to reward sensitivity. We were interested in whether NoGo accuracy on the Go/NoGo task and completion time on the Stroop inhibition condition were good predictors of both performance accuracy and reaction time on the Piñata task. For each of these questions, linear regressions were conducted, where age gender and IQ were controlled for in Step 1, and the specific task variable was added in Step 2.

EF Composite as a Predictor of Reward Task Performance

In order to examine the effect of the EF composite on reward task performance, four linear regressions were conducted. Age, gender and IQ were entered as control variables in Step 1, and the EF composite score was entered at Step 2 for all regressions. The dependent variables in each regression were: 1) number of pumps on the BART (risk taking), 2) reaction times for gain trials on the Piñata task (reward sensitivity), 3) accuracy for the gain trials on the Piñata task (reward sensitivity), and 4) degree of discounting on the delayed discounting task.

Age was a significant predictor of risk taking on the BART in Step 1, accounting for 9% of the variance (β = .261, $p < 0.05$). EF did not significantly predict risk taking on the BART in Step 2.

In predicting reward sensitivity through reaction time on the Piñata task, age, gender and IQ were all significant predictors at step 1 accounting for 27% of the variance (β = -.368, $p < 0.01$; β = .286, $p < 0.01$; and β = -.203, $p < 0.05$ respectively). EF was not a significant predictor of reward sensitivity through reaction time on the Piñata task in Step 2.

There were no significant effects in the regression examining the effect of EF on degree of discounting.

In the regression examining the effect of EF on accuracy on the Piñata reward sensitivity task, we found that age gender and IQ were not significantly predictive at Step 1, but that EF was moderately predictive at Step 2, accounting for an additional 5% of the variance (β = -.208, $p = 0.059$). However, this effect seems to be driven primarily by one individual who was not greater than 3 standard deviations above the mean on gain accuracy (and thus not originally excluded). Once this individual was removed, the effect was no longer sustained. The EF composite did not predict the reaction times for the gain conditions in the Piñata task over and above the effects of age, gender and IQ.

Group Extremes: High EF vs Low EF

To examine whether effects might be seen in the extremes of EF in the overall group, we calculated the upper and lower quartile cut-points for the standardized EF composite and created High and Low groups accordingly (High >= .756, Low <= -.557). When controlling for age, gender and IQ, there were no significant effects of group on the number of pumps on the BART task, on the degree of discounting on the delayed discounting task, or on the reaction times for the two gain conditions on the Piñata task. However, there was a marginal effect of group on accuracy for the two gain conditions in the Piñata task ($F(1,32) = 3.742$, $p = 0.062$) when controlling for age, gender, and IQ.

In follow-up analyses, we tested to see whether the groups performed differently from one another on the Large Gain trials, and on the small gain trials. We found that there was a significant difference between groups on the large ($F(1,32) = 4.199$, $p < 0.05$), but not the small condition when controlling for age and gender. The Low EF group performed better on the large trials than did the High EF group (mean = .860, mean = .806 respectively; see *Figure 1*).

Exploratory Analyses of Specific EF and Reward Task Interactions

None of the selected individual EF task variables were significant predictors of performance on the BART, the degree of discounting, or reward sensitivity on the Piñata task.

Discussion

Goal 1: Executive Function Task Performance and Parent Report

Overall, this sample of typically developing 9-11 year old children seem to show typical performance on these EF tasks (Anderson, 2002; Best, et al., 2009; Brocki & Bohlin, 2004; Davidson, et al., 2006; De Luca, et al., 2003; Luciana & Nelson, 2002; Luciana & Nelson, 2009; Zelazo, et al., 2008). The older children in this sample performed better on the Tower of London task, which has been previously documented in children in middle childhood (De Luca, et al., 2003; Luciana & Nelson, 2002; Luciana & Nelson, 2009). Furthermore, younger children tended to be slower on the reaction time measures on the DCCS task. Previous research has also found age related changes in task switching speed and ability (Anderson, 2002; Best, et al., 2009; Brocki & Bohlin, 2004). Similar to some previous research with EF tasks, we found gender differences with girls performing better on the pre-switch trial accuracy on the DCCS task and completion time in the conflict condition of the Stroop task (Zelazo, et al., 2008). However, much of the literature on EF has not documented gender differences in EF task performance, especially on more affective or “hot” EF tasks (Zelazo, et al., 2008). Clearly further research is needed in order to fully understand the complexities of gender differences on EF tasks.

Overall, these EF tasks seem to be good, cohesive metrics of cognitive performance in this sample of typically developing 9-11 year old children. Many of the task variables from these EF tasks were related to one another. Specifically, problems solved in the minimum number of moves on the Tower of London task was positively correlated with NoGo accuracy on the Go/NoGo task, as well as the accuracy and completion times on the Inhibtion and Conflict conditions of the Stroop task. Additionally, post-switch accuracy on the DCCS task was related to both NoGo accuracy and completion times for both the Inhibtion and Conflict conditions of the Stroop task. It is not uncommon to find correlations between these different measures of EF (Best, et al., 2009; Brocki & Bohlin, 2004; Luciana & Nelson, 2002; Zelazo, et al., 2008). In fact, some researchers would argue that this is evidence that EF is a unified yet diverse construct with many sub-processes that make up the overall construct of EF (Best, et al., 2009). Given the previous findings of these inter-task relationships, we were encouraged to see similar relationships found in our data. However, when attempting to form an EF task composite variable, we discovered that these variables did not have enough internal consistency to legitimately form a composite. Interestingly, it seemed to be the NoGo accuracy and post-switch accuracy that were most unrelated to other performance measures. This was initially surprising to us as we anticipated both NoGo accuracy and post-switch accuracy to be highly important factors in EF performance. However, given some of the developmental shifts in the relationships between task performance variables (Best, et al., 2009), perhaps these more basic measures of inhibition and task switching were less sensitive measures of EF than planning proficiency on the TOL task and cognitive conflict on the Stroop task.

When we examined relationships between task performance variables and the subscales of interest on the BRIEF questionnaire, we found significant relationships between task performance and parent-reports of behaviors. Specifically, children with higher numbers of reported problems on the BRIEF Inhibit, Working Memory, Planning and Organization, Organization of Materials, and Monitoring subscales showed lower performance on the TOL task. Additionally, children with better performance on the Stroop Inhibition and Conflict condition completion times showed lower levels of problems on the Working Memory, Planning and Organization, and Monitoring subscales. Furthermore, some of these BRIEF subscales, when added to the total EF composite showed high internal consistency especially with Tower of London and Stroop task variables. These findings fit generally with previous work regarding the concordance of questionnaire and task data (Valiente, Lemery-Chalfant, Swanson, & Reiser, 2008). Though some studies find modest to high correlations between parent-reports and task performance, others find small to no correlations between these measures of behavior. Researchers are continuing to examine how parent-report and task performance measures are related.

Within the BRIEF alone, the most notable was the finding that parent-reported difficulties in working memory and planning were positively correlated with age, such that older children tended to show more working memory and planning difficulties according to parents. It should be noted that the BRIEF accounts for age in the calculation of T-scores. Perhaps this difference was due to parents expecting more of their older children in terms of the behaviors associated with working memory skills. In other words, perhaps these parents' perceptions of what is acceptable for older children is different than what is accounted for on the BRIEF, and thus parents might be rating children as exhibiting more problems than would be expected. Alternatively, this finding could be related to the fact that the older children in our age range are approaching puberty and adolescence, a time in which we might expect to see changes in some EF-related behaviors (Steinberg, 2005). Perhaps parents are picking up the early manifestations of the changes in EF that accompany the beginnings of adolescence.

Overall, the findings reported here are consistent with previous work on the development of EF in middle childhood(Anderson, 2002; Best, et al., 2009; Brocki & Bohlin, 2004; Davidson, et al., 2006; De Luca, et al., 2003; Luciana & Nelson, 2002; Luciana & Nelson, 2009; Zelazo, et al., 2008; Zelazo, et al., 1996). Future research should more closely examine how these processes are inter-related across development. Furthermore, understanding the connections between separate tasks and constructs will be imperative in further developing a working model of EF across childhood.

Goal 2: Reward Tasks and Parent Reports

Unlike the EF literature, there were fewer examples of tasks that have been consistently used with children of this age group that measure the reward processing constructs of interest. However, these children completed the tasks successfully, and overall the data suggests that the tasks were effective in measuring our constructs of interest.

Within the BART task, the average number of pumps was 26.46, which is considerably lower than the average from a previous sample of 13- to 17-year-olds (33.0 pumps) (Lejuez, et al., 2003). However, the mean number of pumps for this sample was not that unlike the sample of young adults (18-25 year olds) from the original study (29.4 pumps) (Lejuez, et al., 2002). This finding may indicate that, similar to adults, these younger children are less likely to take risks than adolescents. This could be due to the increase in risk taking behaviors seen during adolescence (Steinberg, 2005). Very little research has been done using the BART task in children younger than adolescence, so it is unclear whether our data is representing a time prior to a developmental shift in risk taking, or whether our children in general are less likely to take risks compared to other children their age. Further work is needed to examine whether this type of risk taking task is really salient to children of this age or whether a different task would be more appropriate.

Though previous work had been done with a variant of the delayed discounting task with some success (Shiels, et al., 2009), we were concerned that our children did not always understand the task. Furthermore, we were worried that the children may have made very different decisions to true choices as opposed to the hypothetical choices. There were some cases in which it was unclear to the experimenter whether the child clearly understood the task. Sometimes children would provide seemingly odd answers (e.g. asking for $1 now instead of $100 tomorrow, and then subsequently requesting only $100 now instead of $100 in a week). In other words, they did not provide answers that would fit with the theoretical delayed discounting function. However, within the whole group the delayed discounting data appeared as expected, with higher levels of discounting the delayed reward in favor of the immediate one across the increasing delay lengths (Barkley, et al., 2001; Myerson, et al., 2001; Shiels, et al., 2009).

In order to address some of our initial methodological concerns, we attempted to increase the saliency of this task in a few ways. First, we used the incentive of earning tokens to increase the motivation to complete the task. However, given that there were no right or wrong answers, and there was no particular way in which to earn points, the use of tokens to motivate the children may not have been as effective as we had originally hoped. Additionally, we used pretend money when we were posing the questions in order for children to have a visual representation of the hypothetical question. Anecdotally, we observed many of the children looking carefully back and forth between the two quantities of money before making their decisions. In retrospect, we think using the pretend money was generally helpful to children. However there may be better ways to assess children's discounting of delay. For example, doing a more classic version of a delay of gratification task might be more useful. A version that involves children making a decision about real money would likely be more salient. For example, asking whether they'd rather receive the $5 bill today, or receive $10 in the mail in a week. Increasing the reality of the decision would likely lead to more generalizable and accurate results. It should be noted that though this task had some problems, there was a reasonably wide range of discounting in this sample, suggesting that it was a decent measure of hypothetical delayed discounting.

The Piñata task has not been used in this age group of typically developing children before, thus it is unclear whether our averages are appropriate for this group. However, it is worth noting that the accuracy increased and reaction time decreased across the no gain, Small gain, and Large Gain conditions, indicating that children were more sensitive to and motivated by the rewarding conditions. It is also interesting to note that the accuracy on the Piñata gain trials was significantly correlated with higher levels of problem behaviors such as externalizing behaviors, ADHD behaviors, inhibition difficulties, and behavior monitoring problems. These findings initially seem a bit striking because of the directionality of the effect. Generally we would expect higher accuracy to accompany lower levels of disruptive behaviors, especially given the findings in the ADHD literature which suggest that children with these types of problem behaviors have less sensitivity to reward magnitude and poorer accuracy in reward trials in general (Luman, et al., 2009b). The poorer accuracy is usually attributed to the poorer inhibitory control and higher levels of hyperactivity often found in children with ADHD (Barkley, 1997; Biederman, 2005; Gomez, 2003; Luman, et al., 2009b). We were surprised to find the opposite effect here. Other studies however, have suggested that adding a motivation component to a task can actually buffer task performance in children with ADHD and comorbid Oppositional Defiant Disorder (ODD; (Luman, et al., 2009a). Furthermore, one study found that children with ADHD tended to perform better during high reward versus low reward conditions, indicating a sensitivity to the magnitude of the reward (Huang-Pollock, et al., 2007). Thus, it is possible in this sample that some aspect of the reward component of the piñata task is especially motivational to the point of buffering and improving behavioral performance on the task for children who show higher levels of externalizing and ADHD types of problem behaviors.

All of these reward tasks were significantly related to age. Given the nature of the tasks, this isn’t particularly surprising. Reaction times on the Piñata task, level of discounting on the delayed discounting task and number of pumps on the BART task were all significantly related to age such that older children were faster, showed less discounting of a delayed reward, and showed higher numbers of pumps on the BART. It is possible that between 9-11 years of age, a developmental shift begins to occur. Eleven-year-old children are much closer to puberty and adolescence, thus the increase in the number of pumps, or riskiness, is not surprising (Lejuez, et al., 2003; Steinberg, 2005). It is also fairly well established that older children tend to have faster reaction times on cognitive and motor tasks (Best, et al., 2009; Brocki & Bohlin, 2004).

Overall, these reward tasks are not highly related to one another, though there were some correlations between task variables. Of particular interest was the relationship between Piñata reaction times and number of pumps on the BART. In both the no gain and all gain conditions, children who had faster reaction times tended to show higher numbers of pumps in the BART task. Given that the finding is not exclusive to the gain condition in the Piñata task, but instead includes both the gain and no gain conditions, it is difficult to say whether the increase in risk taking on the BART task is actually related to any type of sensitivity to rewarding situations. Instead it seems that children who are faster in the Piñata task are also more likely to press the button more often in the BART task. Future research is needed to elucidate the developmental course of these constructs more completely.

Goal 3: Intersection of EF Composite and Reward Processing Measures

Overall, our hypothesis of a connection between executive function behaviors and reward sensitivity and motivation behaviors was not supported in this sample. We examined the data in several different ways to fully address this question. In creating a composite variable of EF, we hoped to connect broad cognitive and behavioral manifestations of executive function to reward sensitivity and motivation behaviors. This exploration was generally unsuccessful as the EF did not predict level of discounting on the delayed discounting task, risk taking on the BART task, or reaction time on the Piñata task.

To examine the possible effect of the extremes of the sample, we examined the upper and lower quartiles of the sample on the EF composite metric to determine whether High EF performers differed from Low EF performers on the reward tasks. In general, we found that High and Low EF children did not differ in performance on the reward tasks. However, in the Piñata task, we did find a marginal effect between groups such that children in the Low EF group performed better than children in the High EF group in the gain condition overall. We also found that when we subdivided overall gain into small and Large Gain we found that children in the Low EF group performed significantly better than the High EF group in the Large Gain condition, whereas in the small gain condition this group differences was not apparent. This difference by gain magnitude is interesting given our previous finding demonstrating a link between increased levels of disruptive behaviors and better accuracy on the gain trials in general. Perhaps this finding again highlights the possibility that children with EF difficulties and more dysregulated behaviors, similar to those exhibited in ADHD, are particularly motivated by or sensitive to rewarding situations to the point where it buffers their performance (Huang-Pollock, et al., 2007). However, given other research with children with ADHD has found a lack of reward sensitivity and poorer performance on tasks with a reward component (Luman, et al., 2009b), clearly further research is needed in order to fully examine the situations in which reward contingencies are an effective buffer of performance, and when they are an ineffective motivational tool. However, the poorer performance in ADHD samples may be more driven by a decrement in inhibitory control (Barkley, 1997; Biederman, 2005; Gomez, 2003; Luman, et al., 2009b), whereas in this sample of Low EF children, the primary measures of EF were planning proficiency, cognitive conflict, and other parent-reported behavioral manifestations of disrupted EF. Thus, this sample of Low EF children does not necessarily have the same characteristics as a typical ADHD sample, and as a result may be exhibiting more subtleties of reward and motivational processes than are typically seen in children with ADHD.

The differences in executive functions typically seen in ADHD versus the Low EF group here may also explain the lack of findings between EF groups in the risk taking and delayed discounting tasks. Though previous research with the hypothetical delayed discounting paradigm has found higher levels of discounting a larger delayed reward in favor of a smaller immediate reward in adolescents with ADHD than typically developing children (Barkley, et al., 2001), we did not find a similar effect when comparing our Low and High EF groups. Perhaps this is due to the increased levels of hyperactivity and impaired inhibitory control often seen in children with ADHD (Barkley, 1997; Biederman, 2005), whereas the sample of Low EF children here showed more difficulty with more cognitively taxing tasks such as planning. However, it was surprising to us to find no relationships between individual task measure of inhibitory control or planning with the delayed discounting measure. This suggests that perhaps the hypothetical delayed discounting task may not be the most salient task for finding behavioral differences in this typically developing sample.

Furthermore, we did not find any differences between groups on the risk taking measure (average number of pump) on the BART. Again, due to the nature of the differences between this sample and a typical ADHD sample which would likely show increased levels of risk taking, it is not surprising that we did not find significant differences in risk taking. We were especially interested in examining the impact of inhibitory control difficulties on the number of pumps in the BART, but did not find any significant relationships between our inhibitory control measures and risk taking. As discussed previously, it is likely that the BART may not be sensitive enough to measure the construct of risk taking in middle childhood, though it has been found to be effective in adolescence and young adulthood (Lejuez, et al., 2003; Lejuez, et al., 2002).

Limitations and Future Directions.

It should be noted that this sample of children is generally from a moderate to high socio-economic status and does not display a wide range of economic or ethnic diversity. As such, this sample does not provide a wide range of cognitive functioning, meaning that they may be less representative of the average 9- throuh11-year-old child, and instead represent a highly regulated and atypical population of children. Despite our best efforts to try to diversify the sample by placing fliers in community centers, coffee shops, and libraries, we were unsuccessful in increasing our levels of diversity, perhaps because the success of the fliers was largely dependent on the involvement and interest of the parents. This is not an uncommon problem in research, but it should be noted that this sample may not be representative of typical development.

Unfortunately, due to computer difficulties at the outset of the study, we were unable to gather data in the Piñata task from the first 14 participants. Our findings regarding the Piñata task might be strengthened by the inclusion of the full 100 participant sample. However, our early exploration of potential imputation of the missing data seemed to suggest that no significant additional power would be gained from using an imputed dataset. Therefore, we did not statistically impute the missing data. However, future research should attempt this task with a larger sample to further explore the potential intricacies of the relationship between reward sensitivity and EF.

Due to the nature of the study and the scope of the work, it was impossible to recruit a sample of children diagnosed with ADHD. However, the inclusion of such a group would allow for the comparison of Low EF and ADHD children to determine whether children Low EF perform similarly or differently to children with ADHD on these reward tasks. We would expect that, similar to previous literature, children with ADHD might exhibit more difficulties with inhibition and hyperactivity that impact performance on reward tasks, whereas children with Low EF alone might exhibit different patterns that are less driven by inhibitory control and hyperactivity problems. Previous work by Biederman and colleagues (Biederman, et al., 2004) found that children with ADHD and EF deficits showed lower academic functioning as compared to children with ADHD alone. What is less understood is how patterns of behavior, especially with respect to reward processing, might be in children with an EF difficulty alone as compared to children with ADHD. Future research should more fully address these questions of the potential discrepancies in patterns of behavioral, cognitive and social functioning in children with EF difficulties as compared to children with ADHD diagnoses.

Chapter 3:

Study 2A – Impact of EF ability on neural processing of reward related information

Introduction

In this study, we examined the differences in brain activation patterns in response to rewarding stimuli for children who showed Low and High levels of EF ability. Participants completed the Monetary Incentive Delay task (MID) developed by Knutson and colleagues (2000). This task allowed us to examine changes in brain activity for reward (large and small) and non-reward conditions. Previously in this task, adolescents and adults have shown activation for rewarding conditions primarily in brain areas such as the nucleus accumbens, caudate nucleus, the anterior cingulate cortex, and orbitofrontal cortex (Bjork, et al., 2004; Bush, et al., 2002; Elliott, et al., 2000a; Knutson, et al., 2001a; Knutson, et al., 2001b; Knutson, et al., 2003; Knutson, et al., 2000). Previous research examining the developmental differences in reward processing found that adolescents showed activity in the nucleus accumbens that was more similar to adults, but activity in the orbitofrontal cortex was similar to that of younger children (Galvan, et al., 2006). Research on adolescents with ADHD on reward processing systems in the brain has found that children with ADHD tend to show blunted responses to reward magnitude when compared to their typically developing counterparts (Scheres, et al., 2007). Similar patterns have been found with adults as well (Ströhle, et al., 2008).

The current study is the first to our knowledge that has used the MID task with typically developing children of this age range exclusively. We were especially interested in examining the neural correlates of reward processing in children with lower EF ability as compared to children with higher EF ability to determine whether the effects observed in previous ADHD samples would also be apparent in a sample of children that exhibit EF difficulties. By examining the differences between High and Low EF groups on this task, we can more adeptly address the question of whether the underlying neural correlates of reward processing are in fact impacted by EF ability.

For the purposes of this paper, we limited our exploration to regions of the prefrontal cortex and the basal ganglia that have been previously documented to be involved in reward processing systems (Beck, et al., 2009; Bjork, et al., 2004; Delgado, Nystrom, Fissell, Noll, & Fiez, 2000; Galvan, et al., 2005; Knutson, et al., 2001a; Knutson, et al., 2001b; Knutson, et al., 2003; Knutson, et al., 2000; O'Doherty, et al., 2001; Thut, et al., 1997; Zink, Pagnoni, Martin-Skurski, Chappelow, & Berns, 2004). We hypothesized that children with Low EF ability would show significantly different patterns of activation for reward conditions than High EF children. Additionally, we expected to see either weaker, less focal activation in the expected regions, or more atypical patterns of activation for the different magnitudes of reward in the Low EF group.

Methods

Participants

Twenty-four children participated in the MRI follow-up portion of this study (male = 13, female = 11; mean age = 10.27). They were recruited from the initial sample of 100 children based on specific selection criteria. At the end of the behavioral research session described in Chapter 2, children were given an option to try out a mock MRI scanner, however some children chose not to try out the mock scanner. Those children were not recruited for this portion of the study. Additionally, children's scores on the EF tasks had to fall within predefined High EF or Low EF ranges. Specifically, if children had two scores below any of the following levels, they were eligible for the Low EF group: 80% accuracy on the post-switch condition of the DCCS, 80% accuracy on the NoGo trials of the Go/NoGo task, or a standard score of 8 on the Stroop Inhibition condition. If children had scores higher than at least two of the following levels, they were eligible for the High EF group: 95% accuracy on the DCCS, 90% accuracy on the NoGo trials of the Go/NoGo task, or above a standard score of 13 on the completion time of the inhibition condition. Not all eligible children were available for testing (e.g. some had changed their minds, were too busy, etc.). The MRI sample included 12 participants in the Low EF group and 12 in the High EF group.

Procedure and Task

Children were asked to lie with their head and shoulders inside the MRI tunnel while images were taken. During structural scanning, children watched a movie of their choice. Functional images were acquired while children played the Monetary Incentive Delay (MID) task (called “The Money Game” for participants). The scans lasted approximately 40-50 minutes in total. All children completed the entire scanning session.

The Monetary Incentive Delay (MID) task was a variant of the task developed by Knutson et al., (2000) and used previously with adolescents and adults (Knutson, et al., 2001a; Knutson, et al., 2001b; Knutson, et al., 2000). In our version, children were asked to press a button whenever they saw a solid white square come on the screen. The solid white square was preceded by another cue shape, which determined whether the trial was a “gain” or “loss” trial. Prior to the game beginning, children were told that if they saw a circle, they would have the chance to win points; if they saw a square, they would have a chance to lose points; and if they saw a triangle, they would not win or lose any points. Furthermore, small and large "gain" and "loss" conditions were added to determine if reward magnitude had any effect on brain activation patterns. If children saw a circle or square with one line drawn through it, they could win or lose 5 points, but if they saw a circle or square with three lines through it, they could win or lose 25 points respectively.

We adjusted the timing parameters slightly from the original paradigm to account for the fact that children tend to have slower reaction times than adolescents and adults (Best, et al., 2009). The cue stimulus (circle, triangle or square), which indicated whether the participant would be able to win, lose, or keep the same amount of money was presented for 350ms. Then, an anticipation window occurred after the cue and before the target stimulus, lasting between 2000-2500ms. The target stimulus (solid white square) was presented for 200-400ms depending on the child's own response times (see below). A second delay occurred after the target but prior to feedback, and varied between 1220-1820ms. Finally, children were given feedback, which indicated whether they had won or lost points. The feedback screen was presented for 1630ms, followed by a brief ISI of 100ms prior to the start of the next trial.

Children completed a practice round of the game prior to entering the scanning environment to get an accurate measure of each participant's reaction times. Following the practice round and each subsequent run, the subject's reaction times were rank ordered from fastest to slowest. The 66^{th} percentile point of the rank-ordered reaction times was determined, and the reaction time value at the 66^{th} percentile rank was used as the duration of the target stimulus in the next run. Each trial had a randomized duration for both the anticipation and post target delay periods. The anticipation duration was randomly selected from a range of 2000-2500ms. The post-target delay was simply 4000ms minus the sum of the anticipation duration and the target duration. Thus, the middle of each trial was equal to 4000ms, and the entire trial was 6080ms in length. Children completed a practice round and three runs of the MID task, with 44 trials per run (8 trials of each of the small and Large Gain and loss conditions, and 12 no incentive trials). Each run lasted approximately 4 minutes and 30 seconds.

Functional MRI Data Acquisition and Analysis

MRI and fMRI data were collected on a Siemen's Trio 3 Tesla whole-body scanner. For the structural analyses, high resolution T1-weighted magnetization prepared, rapid gradient echo (MPRAGE) images were collected (240 slices, thickness = 1mm, TR = 2530ms, TE = 3.65, FOV = 256, Flip Angle 7^{o}). T2*-weighted gradient echo, echo planar images were collected in three runs of 137 repititions. Blood oxygenation level dependent (BOLD) images were acquired over 35 slices aligned to the AC-PC plane (TR = 2050, TE = 28, FOV = 200, Flip Angle = 80, Matrix = 64x64, thickness = 3.1mm). Field Map data for the functional MRI were collected, but were not used in this analysis.

Functional MRI data were analyzed using Brain Voyager QX software [version 2.0] (Brain Innovation, Maastrict, The Netherlands) (Goebel, Esposito, & Formisano, 2006). All functional volumes were preprocessed using 3D motion-correction, temporal filtering and slice scan time correction. Volumes were interpolated to 1x1x1 mm isotropic voxels. Each individual volume of each run was aligned to the first volume to correct for small variations in head motion. Furthermore, the second and third runs were aligned to the first run. Any runs with mean motion greater than 3mm in any plane were excluded from further analyses. Three participants had motion greater than 3mm on two or more runs and were excluded from further analysis. The individual's functional datasets were then co-registered to the individual's T1-weighted structural scan. In order to allow for comparisons across individuals and groups, each function run was then spatially smoothed (6 mm Gaussian kernel) and transformed into standardized Talairach coordinates (Talairach & Tournoux, 1988).

Random effects general linear models were used to perform voxel-wise analyses across and between groups. Predictors for overall gain, small gain, Large Gain and no incentive trials were created from the behavioral data files using MATLAB software (The Mathworks Inc., Natick, MA). Because the questions in this paper center on reward processing specifically, we did not analyze the loss trials in the MID task. Motion parameters (x, y, z, pitch, roll, yaw) were included as nuisance predictors for all individuals for all runs. A significance threshold of $p < 0.05$ was used along with a minimum cluster size of 20 contiguous functional voxels. The analyses described here include group comparisons of BOLD signal for Gain > No Incentive, and Large Gain > Small Gain conditions within the anticipation (post-cue) and the post-target delay periods. In the post-cue analyses, we used all types of trials in a condition, regardless of behavioral accuracy (correct and incorrect). This period following the cue but prior to the presentation of the target has been shown to be sensitive to processing of the potential reward and its magnitude (Galvan, et al., 2005; Knutson, et al., 2001b; Knutson, et al., 2003; Knutson, et al., 2000). However, previous studies using the MID paradigm have limited the post-target analyses to correct trials only (Knutson, et al., 2001a). The rationale for this decision is based on the idea that the participant may be aware of whether she or he pressed correctly or incorrectly even before the presentation of feedback. Therefore, brain activity for correct and incorrect trials might be different. Though we do not have a good measure of whether or not participants were aware of their response accuracy before the presentation of the feedback, we wanted to have a more conservative estimate, and thus the incorrect trials were excluded from the post-target analysis. Examination of this period of the trial was based on previous literature that examined reward networks activated during the post-cue and post-target periods (Knutson, et al., 2003).

Results

Behavioral Findings

Accuracy and reaction times were calculated for all gain (average of large and small) and no incentive conditions. Reaction times for the all gain ($r = -0.524$, $p < 0.01$), No Incentive ($r = -0.555$, $p < 0.01$), Large Gain ($r = -.562$, $p<0.05$) and Small Gain ($r = -.466$, $p < 0.05$) conditions were all negatively correlated with IQ. There were no other significant effects of age, gender or IQ on any of the other performance variables. In the following analyses, IQ was controlled for when examining reaction time differences. The descriptives for the reaction time and accuracy data are presented in *Table 9*.

A repeated measures ANOVA revealed that there was a significant main effect of reward type accuracy (No Incentive vs all Gain trials) ($F(1,22) = 16.359$, $p < 0.05$), but no other main effects or interactions were found. However, there were no significant differences found when comparing accuracy on the Large Gain and Small Gain trials.

When examining reaction times for No Incentive vs Gain trials we found no significant effects of interest. Similarly, when comparing Small Gain versus Large Gain reaction times we found no significant effects of interest.

fMRI Results

Due to excessive motion artifact, three participants were excluded entirely from the fMRI analysis. In the final analysis, there were 10 children in the High EF group, and 11 children in the Low EF group.

Based on previous literature, we limited our analyses to fMRI data to a priori regions of interest, specifically, fronto-striatal circuits previously implicated in reward processing. There were often other areas of the brain that were also significantly active (e.g. occipital cortex, cerebellum), but these activations will not be discussed here. Tables are included listing all of the significant activations for each comparison within the a priori areas of interest, includeing prefrontal cortex and the basal ganglia.

Task Effects for the Post-Cue Period

Collapsing across the entire group of children, we found that many brain areas showed sensitivity to potential gain during the post-cue (anticipation) period. Specifically, large regions of the right and left putamen, right and left thalamus, and right and left anterior cingulate cortex showed significantly greater activation for Gain than No Incentive trials (see *Table 10* and *Figure 2*). Interestingly, areas of the right and left inferior frontal cortex showed the opposite effects with more activation for No Incentive versus Gain conditions ($t = -3.499$, $p < 0.01$; $t = -3.698$, $p < 0.01$). Only one region showed any significant differences based on the magnitude of the gain (Small Gain vs

Large Gain conditions). Portions of the left inferior frontal cortex showed greater activation for the Small Gain condition than for the Large Gain condition.

As a follow-up we examined these comparisons in each group separately for the Gain vs No Incentive, and the Large Gain versus Small Gain comparisons. These analyses were intended to qualitatively assess whether these effects represent areas of common signal change between groups, or whether the overall group effects are driven predominantly by one group or the other. On the whole, both groups showed activity in the regions identified in the overall analysis, suggesting that these regions are activated in common in both groups (see *Table 10*).

Group Differences for Post-Cue Period

A number of brain areas showed significant differences in activation between High and Low EF groups. Specifically, when comparing Gain versus No Incentive trials, we found that there were group differences in the right and left middle frontal ($t = 2.560$, $p < 0.05$; $t = 2.873$, $p < 0.05$) and the right medial frontal cortex ($t = -2.939$, $p < 0.05$; see *Table 11*). Interestingly, though there were few areas within the entire group that showed differences between the Large Gain and Small Gain conditions, there were many areas of the brain that exhibited group differences in this magnitude comparison. Of particular interest are the differences found in the right and left orbitofronal regions ($t = 3.046$, $p < 0.05$; $t=2.692$, $p < 0.05$; see *Figure 3*), as well as the right nucleus accumbens ($t = -2.588$, $p < 0.05$; see *Table 11*), regions that have been strongly linked to reward sensitivity in the adult literature.

We conducted follow-up analyses within each group to determine whether the High EF and Low EF groups individually showed significant differences between conditions, or only in the comparison between the groups. We found that the High EF group showed significantly more activation for the Gain than for No Incentive trials in the right middle frontal and left middle frontal cortices ($t = 2.776$, $p < 0.05$; $t = 3.217$, $p < 0.05$). Interestingly the Low EF group showed a significant effect in the opposite direction for the right middle frontal cortex ($t = -2.217$, $p = 0.05$) such that they showed greater activation for No Incentive over Gain trials (see *Table 12*).

When completing follow-up analyses on the magnitude effects (Large Gain vs Small Gain) we found that the High EF group tended to show greater activation for Large Gain over Small Gain trials (for example, in right orbitofrontal cortex ($t = 2.711$, $p < 0.05$), the left putamen ($t = 2.847$, $p < 0.05$) and the posterior caudate ($t = 2.431$, $p < 0.05$)). Interestingly, this same High EF group showed stronger activation for Small Gain compared to Large Gain trials in the nucleus accumbens ($t = -2.262$, $p = 0.05$). For the Low EF group, there were only two areas that showed significant differences in activation between Small Gain and Large Gain trials in the follow-up analyses. The left orbitofrontal cortex ($t = -3.499$, $p < 0.01$) and the left posterior caudate ($t = -3.199$, $p < 0.01$) showed significantly greater activation for Small Gain than Large Gain trials (see *Table 12*).

Task Effects for the Post Target Period

We also examined overall task activation patterns in frontal and basal ganglia regions during the post-target delay. Within the whole group, when examining the activation differences for Gain versus No Incentive trials, we found that left and right anterior cingulate ($t = 3.04$, $p < 0.01$; $t = 2.653$, $p < 0.05$), and the left hippocampus ($t = 5.811$, $p < 0.01$) were significantly more active for Gain trials than for No Incentive trials.

None of our a priori regions of interested showed differences between Large and Small Gain trials during the post-target delay period (see *Table 13*).

In a follow-up, we examined these comparisons of Gain vs No Incentive, and the Large Gain versus Small Gain in each group separately. These follow-up analyses were intended to qualitatively assess whether effects in the entire group represent areas of common signal change in both groups, or whether the overall group effects are driven predominantly by one group or the other. Within the High EF group alone, children showed greater activation for Gain over No Incentive trials in the left medial frontal cortex ($t = 3.066$, $p < 0.05$) and the right nucleus accumbens ($t = 4.299$, $p < 0.01$). Within the Low EF group alone, children showed significant activation in the right and left inferior frontal gyri for Gain over No Incentive trials ($t = 3.433$, $p < 0.01$; $t = 3.993$, $p < 0.01$; see *Table 16*).

We again completed these comparisons within each group to determine if the groups were utilizing different areas of the brain to process the reward magnitude information (Large Gain vs Small Gain trials). Children in the High EF group did not show any significant differences between Large and Small Gain trials overall (see *Table 16*). The Low EF group however did show differences between Large and Small Gain conditions in the left medial frontal gyrus ($t = -2.941$, $p<0.05$), the left middle frontal gyrus ($t = -3.419$, $p < 0.01$) and the right insula ($t = -3.379$, $p < 0.01$). All of these differences were in the direction of Small Gain greater than Large Gain (see *Table 16*).

Group Differences for the Post Target Period

We compared the High and Low EF groups to determine whether there were group differences in activation patterns for Gain over No Incentive conditions in the post-target period. We found significant group differences in the right recuts gyrus ($t = 3.076$, $p < 0.01$; see *Figure 4*), the left middle frontal gyrus ($t = -2.859$, $p < 0.05$), and the left inferior frontal gyrus ($t = -2.862$, $p < 0.05$; see *Table 14*). Several group differences in activation patterns emerged during the Large Gain versus Small Gain comparisons as well. Specifically, in the left medial frontal ($t = 2.739$, $p < 0.01$), two distinct areas of the left orbitofrontal cortex ($t = 2.866$, $p <0.05$; $t = 3.398$, $p < 0.01$; see *Figure 5*), and the right inferior frontal cortex ($t = 2.535$, $p < 0.05$) the groups showed opposite directions of effect (Large > Small vs Small > Large). In these areas, the Low EF group showed Small Gain > Large Gain activation patterns, and the High EF group showed Large Gain > Small Gain activation patterns. The right and left caudate nuclei also showed significant group differences in activation ($t = -2.85$, $p< 0.05$; $t=-3.142$, $p < 0.01$ respectively, see *Table 14* and *Figure 6*).

We completed follow up analyses of these areas to determine whether the effects were significant within each of the groups. We found a significant effect of No Incentive over Gain trials in the left middle frontal gyrus ($t = -2.589$, $p < 0.05$) in the High EF group, whereas the Low EF group showed a trend-level effect of more activation for Gain than No Incentive trials ($t = 2.005$, $p = 0.07$). Furthermore, the Low EF group showed a significant difference in the right rectus gyrus, with greater activation for Gain over No Incentive trials ($t = 2.692$, $p < 0.05$). The High EF group showed no significant effect in this region (see *Table 15*).

When examining the effect of Large versus Small Gain conditions separately in each group we found that children in the High EF group showed greater activation for Large Gain than Small Gain trials in the second left orbitofrontal cortex ($t = 2.903$, p <

0.05), and in the right inferior frontal cortex ($t = 2.554$, $p < 0.05$), but no significant effects of magnitude in the other areas identified in the comparison between groups (see *Table 15*). The Low EF group showed greater activation for Small Gain over Large Gain trials in the left medial frontal cortex ($t = -2.902$, $p < 0.05$), and marginal effects in the two areas of left orbitofrontal cortex ($t = -2.131$, $p = 0.06$; $t = -1.914$, $p = 0.08$) as well as the right inferior frontal cortex ($t = -2.151$, $p = 0.06$) in the same direction (see *Table 15*).

Discussion

For the purposes of this study, we examined two periods within the trials to attempt to assess differences in reward processing between the two EF groups. In the post-cue period, the participant has seen the cue that they know is related to a particular rewarding stimulus (in the case of the large and small reward conditions). Previous research has found that after the association between the cue and its subsequent reward has been learned, the nucleus accumbens activity shifts to respond after the cue is presented and not solely when the reward is provided (Galvan, et al., 2005; Schultz, 2001; Schultz, Dayan, & Montague, 1997; Schultz, et al., 1998; Schultz, et al., 2000). Thus, we were interested in assessing whether this sample of children showed similar patterns in reward system activity (specifically in the nucleus accumbens) as has been previously documented. However, we were also interested in investigating whether after the target stimulus, reward systems are activated to process the upcoming receipt of a reward. Previous studies have highlighted patterns in similar reward systems (e.g. nucleus accumbens, orbitofrontal cortex, caudate nucleus, etc) associated with the post-target period (Delgado, et al., 2000; Galvan, et al., 2005; Knutson, et al., 2001b). We expected that activation of reward systems would be more related to the behavioral response and the knowledge of the upcoming reward, as opposed to the post-cue patterns which would likely be more reflective of learning the association between the cue and the reward. Knutson and colleagues previously found that the post-cue activations were more represented in the ventral striatum (e.g. nucleus accumbens), whereas the post-target activations were more apparent in the ventromedial prefrontal cortex (Knutson, et al., 2001b). Here we wanted to determine whether children showed similar activation of reward networks as has been previously documented, and whether these patterns are disrupted in the presence of EF difficulty.

Post-Cue Anticipation of Upcoming Reward Trial

Similar to previous literature that has used this task with adolescents and adults, we found significant task related activations across the whole group in the putamen, thalamus, and anterior cingulate cortex (Bush, et al., 2002; Delgado, et al., 2000; Elliott, Friston, & Dolan, 2000b; Knutson, et al., 2000; Santesso, et al., 2008; Tricomi, Delgado, & Fiez, 2004; Zink, et al., 2004) in anticipation of the upcoming reward target. Interestingly, we did not find significant activation of the nucleus accumbens in the whole group as has been previously documented with the use of this task (Elliott, et al., 2000b; Galvan, et al., 2005; Knutson, et al., 2001a; Knutson, et al., 2001b; Knutson, et al., 2000). Galvan and colleagues (Galvan, et al., 2006) previously found that children showed more dispersion of activation in the nucleus accumbens than adolescents or adults, but that strength of activation in the nucleus accumbens was more similar to adults than to adolescents. It is unusual that we do not find significant change in signal for the nucleus accumbens in response to rewarding information given the extensive literature documenting the importance of that area in processing reward (Delgado, et al., 2000;

Knutson, et al., 2001a; Knutson, et al., 2000; Schultz, 2001; Schultz, et al., 1997; Zink, et al., 2004). We also found that areas of the right and left inferior frontal cortices were significantly more active for the No Incentive over the Gain conditions. The inferior frontal cortex has been previously associated with response inhibition (Durston, Thomas, Worden, Yang, & Casey, 2002). The inferior frontal cortex has also been found in previous studies of reward processing and has been associated with both rewarding and non-rewarding conditions (Ponchon, et al., 2002; Smith, et al., 2011; Zink, et al., 2004).

When examining the group differences between activation patterns within the post-cue anticipation of an upcoming reward target, in a number of key areas we found that the Low EF children tended to show atypical patterns of activation. Specifically, in areas of interest such as the right and left orbitofrontal cortex, the Low EF group showed more activation for Small Gain than for Large Gain trials, whereas the High EF group showed the opposite pattern. Furthermore, the Low EF group showed a greater activation for the No Incentive versus the Gain condition in the right middle frontal gyrus, whereas High EF children showed the opposite pattern. This region, the dorsolateral prefrontal cortex (DLPFC), is often associated with processing cognitive conflicts along with other executive functions (Zelazo, et al., 2008). It is interesting that we see patterns going in opposite directions in the DLPFC for this comparison, especially in light of the behavioral findings where children performed more poorly on the No Incentive condition than the Gain conditions overall. It is especially interesting that the Low EF group showed increased activation in the DLPFC in preparation for the upcoming No Incentive trials, but that the High EF group showed increased activation for the Gain trials. This may be indicative of differences in processing in this region of the DLPFC for the children with lower EF ability.

From these findings, it seems that the High EF group on the whole is utilizing many of the hypothesized brain areas in expected ways for the post-cue condition (Knutson, et al., 2001a; Knutson, et al., 2001b; Knutson, et al., 2000), whereas the Low EF group is showing an atypical pattern of activation for rewarding conditions (Galvan, et al., 2006; Scheres, et al., 2007; Ströhle, et al., 2008). Previous work examining the reward processing systems in children with ADHD has found that children with ADHD tended to show less activation for reward conditions than typically developing children in the nucleus accumbens (Scheres, et al., 2007). Furthermore, a study in adults with ADHD found no significant activations in areas typically associated with reward processing such as the thalamus and orbitofrontal cortex (Ströhle, et al., 2008). It is possible that our Low EF group is showing a type of altered activation similar to individuals with ADHD. Given that ADHD is often associated with a decrement in EF performance, it is interesting that our Low EF group might show similar patterns of this atypical activation to children with ADHD.

One of the most intriguing findings was that when comparing the groups on activation for large versus small reward trials in the post-cue period, the High EF group showed significantly greater activation for the small over the large reward trials in the nucleus accumbens. This finding was not expected from previous literature with this task which has consistently found the opposite effect (Galvan, et al., 2005; Knutson, et al., 2001a). Previous work in both animal and human literature has found that during learning of a rewarding task that nucleus accumbens activity shifts from later in the trial to earlier in the trial, coding for the upcoming reward (Galvan, et al., 2005; Schultz, 2001; Schultz, et al., 1997). Perhaps these patterns are an artifact of this shift, however it is strange that there would be a significantly greater activation for the Small Gain over the Large Gain condition. We are cautious in interpreting this effect, especially when we did not find effects in the nucleus accumbens of Gain greater than No Incentive. Further research on the development of the brain's response to rewarding information in this age range is needed to address these findings.

We also found a significant group difference in activation of the caudate between groups for the large versus small reward trials. The High EF group showed significantly greater activation for the large over the small condition, similar to previous work by Knutson and colleagues (2001a) whereas the Low EF group showed the opposite effect. The caudate has been previously found to be activated in both rewarding tasks, as well as cognitive and motor tasks (Delgado, et al., 2000; Tricomi, et al., 2004). The High EF group showed a graded effect of reward as has been previously found (Delgado, et al., 2000). The Low EF group showed patterns in the caudate that are indicative of differences in processing magnitude of rewards. Though the effect of small greater than large reward has not been previously documented, the atypical pattern for reward magnitude is somewhat similar to the disruptions in fronto-striatal circuits reported in samples of individuals with ADHD (Scheres, et al., 2007; Ströhle, et al., 2008)

Overall, children in the Low EF group showed atypical findings in response to the cue of an upcoming reward trial. Unlike previous literature, children with low EF ability showed stronger activation for non-rewarding and small rewarding situations than large rewards (Knutson, et al., 2001a; Knutson, et al., 2000). Perhaps this is indicative of atypical patterns of reward processing in the brain similar to those found in children with ADHD (Scheres, et al., 2007; Ströhle, et al., 2008). It is possible that these children show similar patterns of reward processing to those of ADHD children, especially given that these Low EF children tend to show more difficulties with inhibitory control and task switching processes, which are often found to be impaired in children with ADHD.

Post-Target Anticipation of Reward Outcome

When examining the task related activation in the post-target delay period, we found that, similarly to previous literature, the anterior cingulate cortex was active in anticipation of receiving a reward (Bush, et al., 2002; Elliott, et al., 2000b; Santesso, et al., 2008). We also found significantly greater activation in the left hippocampus across the whole group for the Gain over the No Incentive conditions. This may be a response to remembering the number of points associated with the gain conditions as opposed to the No Incentive condition, but previous research has found similar activation patterns to rewarding stimuli (Delgado, et al., 2000). Interestingly, in this post-target delay period, there were no significant differences between the Large Gain and Small Gain conditions across the whole group.

Within the follow-up of the overall task effects within each group, we found increased activation for gain over no incentive trials in the High EF group in the nucleus accumbens as has been previously found with this task (Knutson, et al., 2001a; Knutson, et al., 2001b; Knutson, et al., 2000). However, the Low EF group did not show that pattern, highlighting a potentially atypical pattern of processing rewarding information, similar to patterns observed in children and adults with ADHD (Scheres, et al., 2007; Ströhle, et al., 2008). Additionally, when examining task effects within the Low EF group alone, we found increased activation for Small Gain greater than the Large Gain trials in the left medial frontal, left middle frontal, and right insula. It is striking that these areas would show more activation for processing the anticipation of receiving a small reward. The regions of the left medial and left middle frontal cortex areas are both part of the DLPFC, which is important in processing cognitively taxing information (Zelazo, et al., 2008). Engagement of these areas suggests that children with lower EF ability show disrupted processing of reward magnitude.

When we examined group differences in the post-target period of anticipating an upcoming reward, we found some interesting differences between the patterns of activation in the two groups. Specifically, we found that the Low EF group showed significantly greater activation in the right rectus gyrus, an area bordering the orbitofrontal cortex, for the gain over the no incentive trials. This is especially intriguing given the previous finding that in the post-cue period, children in the Low EF group showed greater activation for small than large reward trials in the orbitofrontal cortex. One previous study found that activation in the medial portions of the orbitofrontal cortex was positively correlated with higher levels of reward magnitude (O'Doherty, et al., 2001). Another study found that adults with ADHD showed increased orbitofrontal activations in response to reward outcomes compared to the control group which did not show increased orbitofrontal activations (Ströhle, et al., 2008). The Low EF group is again exhibiting atypical pattern of response similar to individuals with ADHD. It should be noted however, that many studies have found increased orbitofrontal activation for reward outcomes (Elliott, et al., 2000a; Knutson, et al., 2003; Thut, et al., 1997). As such, it is unclear to what degree these findings are indicative of overall disrupted reward processing in the Low EF group.

To further complicate matters, we found activation differences between High and Low EF groups between the Small Gain and Large Gain trials, in two areas of the left orbitofrontal cortex. In these areas, we found that the High EF group showed greater activation for large over small rewards, whereas the Low EF group showed greater activation for small over large rewards (see *Table 15*). This again is evidence for an atypical pattern of reward processing within the Low EF group, and may be further evidence for an insensitivity to reward magnitude within this Low EF group.

Overall, the findings from the post-target condition suggest that children with poorer EF skills are showing differential recruitment of brain systems in anticipation of reward outcomes. Specifically it seems that children within the Low EF group are showing patterns that resemble those of individuals with ADHD (Scheres, et al., 2007; Ströhle, et al., 2008). Overall this research highlights that children with relative EF deficits do in fact process reward information differently in the brain than children with strong EF skills. Further research is needed to fully understand the neural correlates of reward processing in this developmental period, as well as how processing might be impacted by impairment in other areas of cognitive function.

Limitations & Future Directions

This study had a number of limitations, most notably the small sample size. Unfortunately, due to the cost of MRI research, this could not have been avoided in this dissertation research study. Future research should endeavor to fund and recruit a higher number of participants in the MRI portion to increase confidence in the overall findings.

Furthermore, the children were recruited for the MRI study before the behavioral portion of the study was complete and analyses were conducted. Thus, the children in the Low and High EF groups were recruited based on three task variables that we hypothesized would be a part of a larger EF composite variable, but in fact neither the NoGo Accuracy in the Go/NoGo task nor the post-switch dimension accuracy on the DCCS task proved to have enough internal reliability with the other EF measures to be included in the overall composite. Thus, there are some children who were recruited for these samples that were not in the High and Low groups specified in the previous section. Because the same definitions were not used to define executive function ability in this section as in previous sections, the children recruited for this portion of the study were not selected using the same definition as the High and Low EF groups specified in Chapter 2. There were even a few cases in which children in the Low EF group in this study were not defined as Low EF in the previous study because their scores on measures used in the EF composite from Chapter 2 were considerably higher than their scores on the measures used to recruit for the MRI portion. Generally however, children who were recruited for the Low EF group for the MRI study were within the Low EF group for the behavioral portion as well.

To our knowledge, this was the first study to use the MID task in children of this age range. We altered the task slightly from the adult and adolescent version to make it suitable for this age range. It is unclear whether this significantly altered the nature of the task overall, however, we are generally confident that this is not the case. Children were challenged by this task, as is evident in their behavioral performance. Children also seemed motivated by the chance to win additional money depending on how they did on the game. However, future research should explore whether the MID task is the best metric of reward processing in this age group.

It should also be noted that this was a sample of typically developing children, and that the incidence of EF difficulties was not high. These were not children who were exhibiting excessive difficulty with EF tasks. Thus, in order to more adeptly address the question of the overlap between EF and reward processing, it would be beneficial to recruit a sample of children who show more extreme, or even clinical levels of EF problems. Furthermore, in order to get the most extreme ranges of function, we recruited a High EF group instead of a "typical" EF group. The High EF group might not be the best comparison group for a Low EF sample. In the future, research should explore whether there are brain differences between High and Moderate EF groups as well. Additionally, examining correlates between behavior and brain function would be insightful in exploring individual differences in function.

Lastly, the MID task was designed to enable researchers to examine brain activation patterns for both gain and loss trials. In this study, we merely examined the brains responses to gain trials. In the future, we plan to examine the effects of loss on brain activation patterns as well to explore whether children who lower EF skills also show differences in processing potential losses when compared to the High EF group.

Overall this study provides some support for the hypothesis that EF and reward processing are functionally overlapping in the brain. Though it is not entirely clear what the differences in brain activation patterns between groups might mean, it is intriguing that even though these children do not show excessive difficulties with EF tasks, that they do still show significant differences in brain activation patterns when compared with

High EF children. Further research is needed to expand our knowledge of how behavior and the brain are intertwined in this context.

Chapter 4:

Study 2B – Relationship between EF ability, reward sensitivity, and structural brain volumes

Introduction

As established in Chapter 3, there are a number of brain areas that are involved in reward processing (Bjork, et al., 2004; Bush, et al., 2002; Delgado, et al., 2000; Elliott, et al., 2000a; Elliott, et al., 2000b; Galvan, et al., 2005; Knutson, et al., 2001a; Knutson, et al., 2001b; Knutson, et al., 2003; Knutson, et al., 2000; O'Doherty, et al., 2001; Scheres, et al., 2007; Thut, et al., 1997; Tobler, Christopoulos, O'Doherty, Dolan, & Schultz, 2009; Tricomi, et al., 2004; Zink, et al., 2004). Many of these areas are thought to be involved in executive function abilities as well (Casey, et al., 1997; Duncan & Owen, 2000; Durston, et al., 2003a; Inoue, Inagaki, Gunji, Furushima, & Kaga, 2008; MacDonald, Cohen, Stenger, & Carter, 2000; Miller & Cohen, 2001; Tamm, Menon, & Reiss, 2002). Previous work has found that areas such as the caudate nucleus, anterior cingulate cortex, and dorsolateral prefrontal cortex (DLPFC) are especially involved during executive function tasks (Casey, et al., 1997; Duncan & Owen, 2000; MacDonald, et al., 2000; Miller & Cohen, 2001). Both executive function and reward processing seem to rely on similar dopamine rich fronto-striatal circuits in the brain (Sagvolden, et al., 2005; Sonuga-Barke, 2005). It is unknown however, to what degree the size of the structures in these fronto-striatal circuits might be related to either EF or reward processing behaviors.

Here we examine whether executive function and reward processing performance are related to the volume of specific structures of the brain thought to underlie these processes. For this purpose, we computed composites of behavioral tasks described in chapters 2 and 3 to capture EF and reward sensitivity more broadly, and to relate those processes to the volume of specific structures in the brain. We had a priori interests in areas previously identified in reward processing include: the orbitofrontal cortex, the nucleus accumbens, the caudate nucleus, the thalamus, the amygdala, and the anterior cingulate cortex (Bush, et al., 2002; Delgado, et al., 2000; Elliott, et al., 2000b; Knutson, et al., 2001a; Knutson, et al., 2001b; Knutson, et al., 2003; Knutson, et al., 2000; Santesso, et al., 2008; Taylor, et al., 2004; Tricomi, et al., 2004; Zink, et al., 2004). When examining the executive function composite, we identified the following areas of interest based on previous work: anterior cingulate cortex, caudate nucleus, middle frontal gyrus, and superior frontal gyrus (Casey, et al., 1997; Duncan & Owen, 2000; MacDonald, et al., 2000; Miller & Cohen, 2001). Previous studies of individuals with ADHD, who often exhibit EF difficulties, has often found smaller volumes in structures such as the caudate nucleus, and parts of the prefrontal cortex (F. X. Castellanos, et al., 2002; Durston, 2003b). Though there has been minimal literature regarding the links between behavioral performance measures and structural brain volumes in typical development, a few studies have found smaller volumes associated with better behavioral performance on some cognitive tasks (Toga, et al., 2006).

Method

Participants

Twenty-four children participated in the MRI follow-up portion of this study (male = 13, female = 11; mean age = 10.27). See Chapter 3 for complete details on recruitment of these participants and details on the scanning session.

Structural MRI Data collection and analysis

High resolution MPRAGE data were collected on a Siemen's Trio 3 Tesla scanner (240 1 millimeter slices, TR = 2530ms, TE = 3.65, FOV = 256, Flip Angle 7). Structural data were analyzed using Freesurfer image analysis suite (http://surfer.nmr.mgh.harvard.edu/). Automated cortical reconstruction and volumetric segmentation were performed. The technical details for these procedures have been documented in previous publications, but briefly, the process includes motion correction and averaging, removal of non-brain tissue, automated Talairach transformation, segmentation of cortical and subcortical structures, intensity normalization, and specification of white and grey matter boundaries(Dale, Fischl, & Sereno, 1999; Dale & Sereno, 1993; Fischl & Dale, 2000; Fischl, Liu, & Dale, 2001; Fischl, et al., 2002; Fischl, et al., 2004a; Fischl, Sereno, & Dale, 1999a; Fischl, Sereno, Tootell, & Dale, 1999b; Fischl, et al., 2004b; Han, et al., 2006; Jovicich, et al., 2006; Reuter, Rosas, & Fischl, 2010; Segonne, et al., 2004; Segonne, Pacheco, & Fischl, 2007). Volume is calculated as the surface area multiplied by cortical thickness.

Data Reduction

Areas of interest were pre-specified based on previous literature identifying specific brain areas involved in EF and reward processing. Specifically we focused primarily on the fronto-striatal circuits. The areas of interest with relation to reward include: medial and lateral orbitofrontal cortex, caudate nucleus, anterior cingulate cortex, thalamus, amygdala, and nucleus accumbens. The areas of interest that are classically related to EF that we examine here included: anterior cingulate cortex, caudate nucleus, middle frontal gyrus, and superior frontal gyrus.

The executive function composite described in chapter 2 was used as a continuous measure of EF ability in this subsample of children. We also used the High and Low EF groups as defined in chapter 3 to address whether there were group differences in the volume of EF-related areas. Additionally, we created a reward processing composite, which included tasks from the behavioral session as well as the MID task to provide a metric of overall reward sensitivity and motivation. Six items were combined in the composite including: degree of discounting from the delayed discounting task, number of pumps on the BART task, reaction times for large and small rewards on the piñata task, and reaction times for large and small on the MID task (alpha = .826 for 6 items). Though the Piñata task and MID task are almost identical in design, we included both in the composite because some of the children who returned for the scanning session were in the initial 14 participants who did not complete the piñata task. Thus, for those five children the reward composite does not include the piñata data.

All volumetric data were corrected for total intra-cranial volume (ICV) using the proportional method (O'Brien, et al., 2006) in which each volume was divided by the total ICV in order to account for the total brain size as a potential factor that would affect the volumes of different areas of interest. There was one subject who was excluded from analysis after correcting for ICV because the volumes on multiple structures were consistently between 1.5 and 3 standard deviations below the mean. We decided to exclude this subject from further analyses because this subject was an outlier in multiple volumes.

Results

Effects of Age, Gender, and IQ

Age was significantly correlated with both right and left lateral orbitofrontal cortical volumes ($r = -.505$, $p < 0.05$; $r = -.735$, $p < 0.01$ respectively). Age was also significantly correlated with right medial orbitofrontal cortical volume ($r = -.604$, $p < 0.05$), and with the left superior frontal cortical volume ($r = -.505$, $p = 0.05$). IQ was not significantly related to any of the brain regions of interest. However, IQ was strongly correlated with the reward sensitivity and motivation composite ($r = .650$, $p < 0.01$). There were a few areas in which males and females showed significant differences in volume. These areas included: right thalamus ($t = -2.125$, $p < 0.05$), the right nucleus accumbens ($t = -2.831$, $p < 0.05$), the left lateral orbitofrontal cortex ($t = -2.682$, $p < 0.05$), left superior frontal gyrus ($t = -2.911$, $p < 0.01$), the right lateral orbitofrontal cortex ($t = -2.239$, $p < 0.05$), the right superior frontal cortex ($t = -3.617$, $p < 0.01$), and the left anterior cingulate cortex ($t = - 2.446$, $p < 0.05$). In all of these areas, girls show slightly larger ICV corrected volumes than boys. Furthermore, girls show significantly lower scores on the reward sensitivity and motivation composite than boys ($t = 2.292$, $p < 0.05$). Age, gender and IQ were controlled for in all subsequent analyses.

Executive function and brain volume

Several marginally significantly effects were found between the EF composite variable and regional brain volume. The right superior frontal cortex ($r = -.442$, $p = 0.051$), the left middle frontal gyrus ($r = -.392$, $p = 0.088$), and the left anterior cingulate cortex ($r = -.419$, $p = 0.066$) all showed that smaller brain volume was associated with higher scores on the EF composite (see *Table 15*).

There were no significant differences found in hypothesized brain areas when comparing the pre-specified High and Low EF groups, although some marginal effects were observed. There was one marginal effect in the left middle frontal gyrus, such that children with low EF showed larger volumes ($t = 1.837$, $p = 0.08$) that those with High EF.

Reward sensitivity/motivation and brain volume

We found significant correlations between the reward sensitivity and motivation composite and two regions of interest, the right medial orbitofrontal cortex ($r = -.481$, $p < 0.05$), and the left anterior cingulate cortex ($r = -.542$, $p < 0.05$), such that smaller volumes were associated with higher degrees of reward sensitivity and motivation. The left lateral orbitofronal cortex ($r = -3.93$, $p = 0.087$) showed a marginal effects in the same direction as well (see *Table 15*).

Discussion

In this section, we explored whether executive function and reward processing might be broadly related to the size of different structures in the brain thought to support these cognitive processes. We found some compelling relationships in this sample of typically developing 9-11 year olds. First, we found age and gender were associated with volumes in some brain regions, most notably in parts of the orbitofrontal cortex. Older children tended to show smaller volumes overall, and female children showed larger regional volumes than males after correcting for overall differences in total brain volume (ICV). In past research, it has been found that males tend to have somewhat larger brains overall, as well as larger volumes of specific structures (Wilke, Kraegeloh-Mann, & Holland, 2007). This was the case in the current sample as well. Boys showed significantly larger intracranial volume, so we accounted for the intracranial volume differences by dividing the volume of each structure by the ICV for that subject. Thus, these differences between boys and girls are not due to overall brain size, but actually reflect differences in the structure itself, controlling for overall intracranial volume. It is interesting that though boys show bigger intracranial volumes overall, girls show larger structures when accounting for overall ICV. The girls in this sample are slightly younger than the boys (girls mean age = 10.03, boys mean age = 10.48), but these differences are not statistically significant. Furthermore, because we used the proportional method to account for overall ICV, there are other regions where the gender difference would show the opposite pattern. It is likely that these differences between girls and boys are due primarily to the use of this method to correct for overall brain volume.

It is also intriguing that older children are showing smaller volumes in areas of the orbitofrontal cortex and the superior frontal cortex. This is not inconsistent with previous research on brain morphology changes across development (Toga, et al., 2006; Wilke, et al., 2007). Previous research has found that generally cortical gray matter decreases with age, while white matter increases with age (Toga, et al., 2006; Wilke, et al., 2007). However, more recent research suggests that the global decrease in gray matter does not begin in the frontal cortex, especially the orbitofrontal cortex, until adolescence (Giedd, et al., 1999; Gogtay, et al., 2004). The findings from this study would suggest that that decrease in frontal lobe gray matter may be already beginning in middle to late childhood.

We found marginal relationships between executive function ability and structural volume such that children with smaller volumes in the right superior frontal cortex, the left anterior cingulate cortex, and the bilateral middle frontal cortex showed higher levels of EF as defined by the EF composite described in Chapter 2. These findings address questions about whether there may be a consolidation effect occurring during development, such that smaller gray matter volume may indicate more concise connections and efficient processing in the brain (Giedd, et al., 1999; Gogtay, et al., 2004; Toga, et al., 2006; Wilke, et al., 2007). This interpretation would fit from a neural pruning perspective, that the more practiced or efficient you become at a task, the more concentrated and focused the neural connections related to that task become and other less used or important connections are pruned away (Toga, et al., 2006). Smaller brain volumes have also been associated with disruptions in early brain development due to toxic stress, adverse environmental effects, or extreme prematurity (Lodygensky, Vasung, Sizonenko, & Hueppi, 2010; Lupien, McEwen, Gunnar, & Heim, 2009). Because the sample of children in this study are typically developing, it is not likely that the reduced cortical volumes related to task performance observed here are due to any disruption in early brain development.

Interestingly, we also found similar effects between reward sensitivity/motivation and structural volume in the right medial orbitofrontal cortex, and the left anterior cingulate cortex. Again, this may be reflecting a consolidation or specification of those regions as they relate to reward sensitivity and motivation. That is, the higher the level of sensitivity to reward, the more consolidated and precise the neural connections within the structures in question. Both of these areas have been previously related to reward processing in animals (Schultz, et al., 1998; Schultz, et al., 2000) and humans (Bush, et al., 2002; Elliott, et al., 2000a). We are not aware of any studies that have examined the effects of structural volume as they relate to behavioral performance on reward sensitivity or motivation tasks.

It should be noted however, that size of structure of the brain is not always related to speed of processing, or strength of neural connectivity. That is, it would be most informative to collect diffusion tensor imaging (DTI) data to determine the structure of white matter pathways to address questions of how EF might be related to the connectivity of different areas of the brain. DTI allows researchers to draw more nuanced conclusions about how efficiently different parts of the brain connect to one another, and allow for a more holistic interpretation about the structure and function of different neural circuits in the brain.

Overall, these findings suggest that some consolidation of function may be reflected in the structural volumes in the brain during this age period. Given the nature of the data however, it is difficult to draw any conclusions about the actual speed, or complexity of processing. Those questions can only be addressed by utilizing other, more complex methods of neuroimaging. Future research involving executive function training studies might provide an avenue for further research into understanding how improvement of executive function might change the structure of the brain. Overall, further research is needed to further substantiate these effects with larger sample sizes, and more nuanced questions related to the role of these brain regions in executive functioning and reward processing.

Chapter 5: General Discussion

This dissertation work provides some compelling evidence for the possible overlap in both behavioral manifestations and in neurological correlates of executive function and reward processes. In the behavioral study we found that children who had lower EF ability were significantly more accurate on the Large Gain trials in the Piñata reward sensitivity task than children with higher EF ability. This finding aligns with previous work revealing that children with ADHD were more accurate on trials that had a higher reward associated with them (Huang-Pollock, et al., 2007; Luman, et al., 2009a). Furthermore, difficulties with executive function may be especially linked to the motivational or affective aspects of rewarding stimuli. Some previous work has postulated that the more affective processes such as emotion and reward processing may overcome top-down cognitive processing, especially during adolescence, leading to more difficulties with cognitive tasks (Best, et al., 2009; Steinberg, 2005). However, this interpretation would suggest that performance would be negatively impacted in the children with lower EF ability and this was not the case. Instead, the addition of a motivational component seems to buffer performance on a cognitive task for children with lower EF ability. Perhaps this is evidence for the value of incentives in buffering the cognitive performance of children with EF difficulties (Luman, et al., 2010).

When examining the neural correlates of reward processing in children with High and Low EF ability, we found a number of differences between groups. In the functional neuroimaging task, we found that overall children within this age range showed to activation patterns similar to those observed previously in adolescents and adults during the MID other reward processing tasks (Bjork, et al., 2004; Elliott, et al., 2000b; Knutson, et al., 2001a; Knutson, et al., 2001b; Knutson, et al., 2003; Knutson, et al., 2000; Thut, et al., 1997). However, we found a number of differences between the High and Low EF groups. The Low EF children tended to show atypical patterns of activation for reward information. Specifically they tended to exhibit greater activation for Small over Large reward trials in the orbitofrontal cortex, which has been previously linked to with reward processing (Elliott, et al., 2000a; O'Doherty, et al., 2001). These patterns were similar to findings reported in a study with adults with ADHD (Ströhle, et al., 2008). It is intriguing that children with poorer EF functioning showed these atypical patterns of processing reward information, whereas the High EF group showed more of the typical graded response with more activation for Large over Small rewards. These differences may reflect a similarity in reward processing between the children with Low EF and individuals with ADHD. Previous research on reward processing in children with ADHD has found that children with ADHD tend to show lower levels of activity in the ventral striatum during reward conditions than shown by controls (Scheres, et al., 2007; Ströhle, et al., 2008), but greater, yet less focal, activation in areas of the orbitofrontal cortex for reward conditions (Ströhle, et al., 2008). Though we did not replicate the findings in the ventral striatum, the fact that children in the Low EF group tended to show less activation for the large reward condition than the small reward condition suggests that they are processing reward information differently compared to their High EF counterparts.

One goal of this project was to explore to what degree behavioral performance was related to brain structure. We found that children with higher behavioral EF performance showed marginally smaller volumes in the right superior frontal, left middle frontal, and left anterior cingulate cortex regions. Furthermore, children who showed higher levels of reward sensitivity on the reward tasks also had smaller volumes in reward-related regions including right medial (OFC), left anterior cingulate cortex, and left lateral OFC. These smaller volumes may be due to increased pruning and specialization of these areas of the brain that are important for processing reward or cognitive information (Giedd, et al., 1999; Gogtay, et al., 2004; Toga, et al., 2006; Wilke, et al., 2007). Future research should employ other methods such as Diffusion Tensor Imaging (DTI) to examine the relationships between structural connectivity in the brain and the potential relationships with behavioral functions.

Taken together, these findings suggest that children with lower levels of EF ability do show atypical patterns of brain activation especially for the small reward condition, coupled with a higher level of behavioral performance on highly rewarded trials of a task. Furthermore, it seems that higher EF ability and higher sensitivity to reward magnitude are related to small structural volumes in regions thought to underlie those processes, potentially suggesting stronger more coherent connections within those regions of the brain. Taken together, these findings suggest that children with higher EF ability have more finely honed and specialized EF-related brain systems that support successful EF performance. Contrarily, the children with lower EF performed better on large reward trials in the Piñata task, but showed atypical brain activation patterns for reward information, similar to children with ADHD (Huang-Pollock, et al., 2007; Luman, et al., 2009a; Scheres, et al., 2007; Ströhle, et al., 2008). These findings indicate that children with lower EF ability show behavioral and neural patterns similar to children with ADHD, and as such, EF ability may intertwine intricately with how children understand and process rewarding information.

Limitations and Future Directions

One of the main limitations of this study is the lack of diversity in the sample. Primarily our participants were Caucasian children from relatively affluent backgrounds. We attempted to recruit a more variable sample by placing fliers around the Twin Cities and surrounding communities, but these were not as effective as we hoped in garnering a more diverse sample. The EF ability in this sample of children is not as variable as we would have liked, and consequently, we are measuring a smaller window of the entire range of EF skills. However, the fact that we found significant results with this sample is interesting given the limited range of diversity in the sample. Further research is needed using data from a wider range of EF ability to determine if the effects found here are enhanced or exaggerated in a sample with more dispersed EF ability.

Unfortunately, due to limited previous research on the topic, much of the selection of appropriate reward tasks for this age range was exploratory in nature. Many of the tasks had not yet been used in this age range to our knowledge, and thus it was unclear whether we would get data that were representative of our constructs of interest. Though we did not find significant relations between the BART or delayed discounting tasks, and the EF measures, the two tasks did provide interesting information about the sample as a whole. For example, the average number of pumps calculated on the BART task was lower than previous studies have reported in adolescents and adults (Lejuez, et al., 2003; Lejuez, et al., 2002). The delayed discounting task did not show effects related to EF ability, but did show similar linear pattern of discounting across time as has been previously found in adults and adolescents (Barkley, et al., 2001; Myerson, et al., 2001; Shiels, et al., 2009). Future research could include efforts to hone these and other reward tasks to maximize the age appropriateness, while still measuring the constructs of interest. Continued explorations to improve these tasks will provide a more comprehensive understanding of the development of reward sensitivity and motivation across development.

Unfortunately, due to funding limitations, we were not able to complete the follow-up MRI portion with the full sample of 100 children. This portion of the project would undoubtedly have been strengthened by the inclusion of more children from the sample, although past fMRI research has suggested that large samples are not always crucial for reliable patterns of activation. Many past neuroimaging studies have had sample sizes smaller than the one reported here, and functional neuroimaging data are thought to be quite robust and generally involve group comparisons, therefore not requiring the large samples sometimes needed in behavioral or correlational research (Desmond & Glover, 2002). However, with a larger sample, we could potentially look more coherently at questions regarding the relationships between individual difference measures and functional and structural neuroimaging data. Future studies should incorporate the follow-up method used here, and attempt to fund more extensive and in-depth analysis of these questions.

Overall, this study is a first step in understanding the intersection of executive function and reward processing on both a behavioral and neural level in typical development during middle childhood. Future research should address how these questions translate to other more diverse populations of children, as well as expand the age range in both directions to obtain a more cohesive picture of the development of executive function and reward processing throughout childhood and adolescence. Additionally, future research should examine how this intersection of EF and reward processing might be related to the development of ADHD in childhood. Data on normative samples can provide a more complete view of how behavior and brain function may be atypical in children with ADHD (Luman, et al., 2010). This research adds to the growing support for the use of motivational and incentivized tools in the classroom in order to scaffold academic success, especially for children who have difficulties with executive function. As middle childhood period marks the beginning of the transition into puberty and adolescence, when risk-taking and impulsive behaviors become significantly more prominent (Steinberg, 2005), it is crucial to understand how these processes develop and interact during this period. Additionally, middle childhood is a period when the cognitive, social, and emotional demands are higher, so understanding how these processes interact is an important factor in understanding the developmental puzzle of middle childhood (Best, et al., 2009). The current research provides a window into this complex and tumultuous period of development, expanding our understanding of the interactions between executive development and reward processing. However, further work is clearly needed to better and more fully understand how these cognitive and affective processes interact and impact the development of children.

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Appendix: Figures and Tables

Tables

Table 1: Executive Function Task Descriptives

Task	Variable	N	Mean	Standard Deviation	Min/Max
Go NoGo	Go Accuracy	98	0.9969	0.007	.96-1.00
	NoGo Accuracy	98	0.852	0.116	.38-1.00
	Go Reaction Time	98	505.265	72.024	364.70-273.25
	NoGo Reaction Time	93	390.662	75.128	273.25-634.33
Tower of London	Probs Solved in Min Moves	98	9.918	2.039	5.0-14.0
Stroop					
Completion Time	Color Naming Standard Score	96	10.458	2.977	1.0-15.0
	Word Reading Standard Score	98	10.878	2.087	1.0-14.0
	Inhibition Standard Score	97	11.454	2.541	4.0-16.0
	Conflict Standard Score	97	10.732	2.252	2.0-15.0
Number of Errors	Color Naming Standard Score	96	58.969	37.664	2.0-100.0
	Word Reading Standard Score	98	49.082	40.334	1.0-100.0
	Inhibition Standard Score	95	9.653	3.192	1.0-14.0
	Conflict Standard Score	96	9.094	3.241	1.0-14.0
Dimensional Change Card Sort	Pre-switch Accuracy	100	0.956	0.046	.78-1.0
	Post-switch Accuracy	100	0.838	0.157	.50-1.0
	Pre-switch Reaction Time	99	835.158	214.774	397.22-1619.19
	Post-switch Reaction Time	99	889.32	216.899	453.38-1500.88

Table 2: Questionnaire Descriptives

Questionnaire	Scale	N	Mean	Standard Deviation	Min/Max
CBCL	Attention Problems	99	53.88	5.711	50-71
	Externalizing	99	46.23	10.755	33-73
	ADHD Problems	93	52.49	4.476	50-66
Conner's	Cognitive Problems/Inattention	94	50.57	9.166	40-80
	Hyperactivity	94	52.76	12.007	43-90
	ADHD	94	49.56	9.263	40-80
BRIEF	Inhibit	100	48.72	10.717	37-84
	Shift	100	46.2	9.554	36-81
	Emotional Control	100	46.38	11.043	36-80
	Initiate	100	48.08	9.104	35-75
	Working Memory	100	48.31	10.395	36-79
	Planning & Organization	100	47.08	10.175	33-80
	Organization of Materials	100	49.85	10.075	34-71
	Monitoring	100	46.93	10.673	28-79
SSSC	Thrill & Adventure Seeking	94	7.298	3.232	0-12
	Social Disinhibition	94	2.915	1.764	0-7

Table 3: Executive Function Task Correlations

Task	**Variables**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**
TOL	*1. Probs Solved in Min Moves*	1												
Go/NoGo	*2. Go Accuracy*	0.079	1											
	3. NoGo Accuracy	0.267*	0.330**	1										
	4. Go Reaction Time	-0.038	-0.283*	0.240*	1									
	5. NoGo Reaction Time	0.068	-0.244*	0.113	0.514**	1								
Stroop	*6. Inhibition Standard Score - Time*	0.371**	0.212*	0.217*	-0.426**	-0.308**	1							
	7. Conflict Standard Score - Time	0.311**	0.102	0.346**	-0.088	-0.111	0.594**	1						
	8. Inhibition Standard Score- Error	0.333**	-0.005	0.094	-0.035	-0.074	0.219*	0.259*	1					
	9. Conflict Standard Score- Error	0.264**	0.145	0.201	0.098	0.009	0.08	0.350**	0.465**	1				
DCCS	*10. Pre-switch Accuracy*	0.189	0.026	0.077	-0.41	-0.058	0.055	0.027	0.204	0.135	1			
	11. Post-switch Accuracy	0.14	0.223*	0.386**	0.028	-0.033	0.118	0.093	0.14	0.154	0.024	1		
	12. Pre-switch Reaction Time	-0.2	-0.011	-0.07	0.282*	0.188	-0.394**	-0.355**	-0.054	-0.011	0.064	0.1	1	
	13. Post-switch Reaction Time	-0.104	-0.058	-0.033	0.316**	0.2	-0.301**	-0.330**	-0.036	-0.005	0.017	0.197	0.786**	1

Note: All correlations reflect controlling for any effects of age, gender, and non-normal distributions where appropriate.

* = *p* < 0.05

** = *p* < 0.01

Table 4: Questionnaire Correlations

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
1. CBCL Attention Problems[+]	1															
2. CBCL Externalizing[+]	0.492**	1														
3. CBCL ADHD Problems[+]	0.845**	0.483**	1													
4. Conner's Cognitive Probs/Inattention	0.762**	0.439**	0.575**	1												
5. Conner's Hyperactivity[+]	0.55**	0.507**	0.563**	0.605**	1											
6. Conner's ADHD[+]	0.811**	0.57**	0.718**	0.902**	0.687**	1										
7. BRIEF Inhibit	0.628**	0.595**	0.555**	0.591**	0.694**	0.671**	1									
8. BRIEF Shift	0.509**	0.501**	0.397**	0.437**	0.468**	0.614**	0.546**	1								
9. BRIEF Emotional Control[+]	0.393**	0.68**	0.336**	0.375**	0.414**	0.484**	0.568**	0.623**	1							
10. BRIEF Initiate	0.712**	0.434**	0.556**	0.664**	0.452**	0.713**	0.601**	0.622**	0.498**	1						
11. BRIEF Working Memory[+]	0.776**	0.439**	0.624**	0.810**	0.436**	0.826**	0.575**	0.516**	0.440**	0.733**	1					
12. BRIEF Planning & Organization	0.711**	0.382**	0.548**	0.838**	0.427**	0.721**	0.634**	0.603**	0.413**	0.761**	0.819**	1				
13. BRIEF Organization of Materials	0.504**	0.425**	0.418**	0.592**	0.397**	0.548**	0.545**	0.403**	0.433**	0.582**	0.569**	0.647**	1			
14. BRIEF Monitoring	0.714**	0.511**	0.582**	0.731**	0.580**	0.775**	0.751**	0.566**	0.479**	0.758**	0.705**	0.831**	0.692**	1		
15. SSSC Thrill & Adventure Seeking	0.086	-0.028	0.132	0.071	0.269*	0.079	0.103	-0.052	-0.088	-0.027	0.085	0.02	0.126	0.068	1	
16. SSSC Social Disinhibition	0.134	0.322**	0.260*	0.15	0.263*	0.197	0.173	0.105	0.16	0.238*	0.174	0.149	0.273**	0.138	0.462**	1

[+] *Using Spearman non-parametric correlations*

Note: All correlations reflect controlling for any effects of age, and gender where appropriate.

** = $p < 0.05$*

*** = $p < 0.01$*

Table 5: Correlations between BRIEF Questionnaire Subscales and EF Tasks

	Inhibit	*Shift*	*Emotional Control*	*Initiate*	*Working Memory*	*Planning & Organization*	*Organization of Materials*	*Monitoring*
TOL - Probs Solved in Min Moves	-.267**	-0.135	-0.17	-0.116	-.310**	-.354**	-.296**	-.341**
Go/NoGo - Go Accuracy	0.105	0.063	0.141	0	0.056	0.04	0.002	0.116
Go/NoGo - NoGo Accuracy	-0.039	-0.054	-0.019	0.012	-0.155	-0.11	-0.112	-0.123
Stroop - Inhibition Standard Score - Time	-0.076	-0.176	-0.124	-0.097	-.266*	-.309**	-0.12	-.213*
Stroop - Conflict Standard Score - Time	-0.057	-0.109	-0.114	-0.081	-.265*	-.278**	-0.023	-.211*
DCCS - Pre-switch Accuracy	-0.074	0.019	-0.046	-0.064	-0.125	-0.122	-.199*	-0.129
DCCS - Post-switch Accuracy	-0.104	-0.044	-0.057	-0.084	-0.113	-0.108	-0.095	-0.189
DCCS - Pre-switch Reaction Time	0.084	0.127	0.092	0.095	0.114	0.095	-0.127	0.143
DCCS - Post-switch Reaction Time	0.037	0.231*	0.122	0.168	0.043	0.085	-0.049	0.132

Note: All correlations reflect controlling for any effects of age, and gender where appropriate.

* = $p < 0.05$

** = $p < 0.01$

Table 6: Reward Task Descriptives

Task	Variable	N	Mean	Standard Deviation	Min/Max
BART	Adjusted Number of Pumps	100	26.455	11.678	6.17-58.41
	Number of Explosions	100	7.01	3.295	0.0-18.0
	Post-Pop Pumps (>=5 pops)	99	24.142	11.371	5.50-51.46
Delayed Discounting	Degree of Discounting	98	0.467	0.324	.013-.997
	Day	98	71.571	38.623	0-100
	Week	98	65.449	35.857	0-100
	Month	98	56.388	36.553	0-100
	6 Months	98	43.98	37.412	0-100
	Year	98	38.878	34.372	0-100
Piñata Task					
Reaction Time	No Gain	85	324.936	67.165	180.83-489.48
	Small Gain	84	310.084	64.397	176.07-519.64
	Large Gain	85	304.538	63.502	158.14-475.86
	All Gain	85	307.011	62.99	167.11-491.11
Accuracy	No Gain	85	0.73	0.091	.52-.95
	Small Gain	85	0.788	0.078	.55-.95
	Large Gain	85	0.821	0.076	.57-.98
	All Gain	85	0.805	0.067	.56-.97

Table 7: Tukey HSD Post-hoc comparisons for Delayed Discounting (t-values)

	Day	*Week*	*Month*	*6 months*
Day				
Week	-2.07			
Month	-5.15*	-3.07		
6 months	-9.35*	-7.28*	-4.20*	
Year	-11.08*	-9.00*	-5.93*	-1.73

*= *alpha < 0.05*

Table 8: Piñata Task Accuracy & Questionnaire Measures

	Piñata No Gain Accuracy	Piñata All Gain Accuracy
1. CBCL Attention Problems+	0.12	0.198
2. CBCL Externalizing+	0.129	0.283**
3. CBCL ADHD Problems+	0.182	0.224*
4. Conner's Cognitive Probs/Inattention	0.081	0.126
5. Conner's Hyperactivity+	0.161	0.162
6. Conner's ADHD+	0.111	0.113
7. BRIEF Inhibit	0.065	0.225*
8. BRIEF Shift	0.04	0.158
9. BRIEF Emotional Control+	0.123	0.17
10. BRIEF Initiate	0.035	0.112
11. BRIEF Working Memory+	0.112	0.207
12. BRIEF Planning & Organization	0.044	0.115
13. BRIEF Organization of Materials	-0.051	0.155
14. BRIEF Monitoring	0.034	0.223*
15. SSSC Thrill & Adventure Seeking	-0.02	0.168
16. SSSC Social Disinhibition	-0.012	-0.001

+ *Using Spearman non-parametric correlations*

Note: All correlations reflect controlling for any effects of age, and gender where appropriate.

* = $p < 0.05$

** = $p < 0.01$

Table 9: Descriptives for MID Task (N=24)

Measure	Variable	Mean	Standard Deviation	Min/Max
Accuracy	No Incentive	0.626	0.113	.36-.83
	Small Gain	0.694	0.101	.42-.96
	Large Gain	0.737	0.122	.46-.88
	All Gain	0.715	0.092	.44-.86
Reaction Time	No Incentive	234.278	48.59	147.97 - 356.81
	Small Gain	222.994	60.082	142.96 - 398.13
	Large Gain	232.426	61.832	149.88 - 379.25
	All Gain	227.71	59.9	149.88 - 388.69

Table 10: Task Effects in the Post-Cue delay

Gain vs No Incentive				
Area	*Talaraich*	*t*	*p*	*Voxels*
Right Inferior Frontal	45,34,3	-3.499	0.002	1206
Left Inferior Frontal	-53,23,13	-3.698	0.001	1863
Right Putamen	21,5,8	3.457	0.002	10127
Left Putamen	-20,4,8	3.463	0.002	12290
Right Thalamus	10,-14,8	3.877	0.001	3933
Left Thalamus	-12,-14,8	3.879	0.001	2896
Left Anterior Cingulate	-12,-3,40	4.631	0.0002	3277
Right Anterior Cingulate	10,9,39	3.899	0.001	1545
Large Gain vs Small Gain				
Area	*Talaraich*	*t*	*p*	*Voxels*
Left Inferior Frontal	-48,30,7	-2.735	0.01	1088

Table 11: Group Differences in the Post Cue Delay

Gain vs No Incentive				
Area	*Talaraich*	*t*	*p*	*Voxels*
Right Middle Frontal	32,50,-10	2.56	0.02	2456
Left Middle Frontal	-30,58,-2	2.873	0.01	2055
Right Medial Frontal	10,55,12	-2.939	0.01	528
Large Gain vs Small Gain				
Area	*Talaraich*	*t*	*p*	*Voxels*
Right Orbitofrontal	10,48,-12	3.046	0.01	1186
Left Middle Frontal	-23,47,0	-2.789	0.01	399
Left Orbitofrontal	-30,26,-15	2.692	0.01	605
Left Putamen	-14,5,10	2.77	0.01	903
Right Nucleus Accumbens	7,2,-3	-2.588	0.02	380
Posterior Caudate	-8,-10,20	2.795	0.01	925

Table 12: Followup Analyses on Post Cue Delay Differences Between Groups

HIGH EF				**LOW EF**			
Gain vs No Incentive				***Gain vs No Incentive***			
Area	*Talaraich*	*t*	*p*	*Area*	*Talaraich*	*t*	*p*
Right Middle Frontal	32,50,-10	2.776	0.02*	Right Middle Frontal	32,50,-10	-2.217	0.05*
Left Middle Frontal	-30,58,-2	3.217	0.01*	Left Middle Frontal	-30,58,-2	-1.081	0.31
Right Medial Frontal	10,55,12	-2.168	0.06	Right Medial Frontal	10,55,12	1.612	0.14
Large Gain vs Small Gain				***Large Gain vs Small Gain***			
Area	*Talaraich*	*t*	*p*	*Area*	*Talaraich*	*t*	*p*
Right Orbitofrontal	10,48,-12	2.711	0.02*	Right Orbitofrontal	10,48,-12	-2.555	0.03*
Left Middle Frontal	-23,47,0	-1.897	0.09	Left Middle Frontal	-23,47,0	1.724	0.12
Left Orbitofrontal	-30,26,-15	1.981	0.08	Left Orbitofrontal	-30,26,-15	-3.499	0.006**
Left Putamen	-14,5,10	2.847	0.02*	Left Putamen	-14,5,10	-1.624	0.14
Right Nucleus Accumbens	7,2,-3	-2.262	0.05*	Right Nucleus Accumbens	7,2,-3	1.114	0.29
Left Posterior Caudate	-8,-10,20	2.431	0.04*	Left Posterior Caudate	-8,-10,20	-3.199	0.01*

* = $p < 0.05$
** = $p < 0.01$

Table 13: Task Effects in the Post Target Delay

Gain vs No Incentive				
Area	*Talaraich*	*t*	*p*	*Voxels*
Left Anterior Cingulate	-15, 41,7	3.04	0.006	2281
Right Anterior Cingulate	7,24,25	2.653	0.02	700
Right Putamen	24,8,9	-2.798	0.01	749
Left Putamen	-19,1,11	-2.876	0.009	1032
Left Hippocampus	-23,-15,-11	5.811	0.00001	1892
Large Gain vs Small Gain				
Area	*Talaraich*	*t*	*p*	*Voxels*
None				

Table 14: Group Differences in the Post Target Delay

Gain vs No Incentive				
Area	*Talairach*	*t*	*p*	*Voxels*
Right Gyrus Rectus	6,43,-11	3.076	0.004	330
Left Middle Frontal	-30,31,27	-2.859	0.01	753
Left Inferior Frontal	-17,20,-7	-2.862	0.01	517
Large Gain vs Small Gain				
Area	*Talairach*	*t*	*p*	*Voxels*
Left Medial Frontal	-14, 61, 6	2.739	0.01	330
Left Orbitofrontal	-6,45,-6	2.866	0.01	164
Left Oribitofrontal 2	-2,37, -12	3.398	0.003	344
Right Inferior Frontal	45,27,16	2.535	0.02	595
Right Caudate	7,3,10	-2.85	0.01	539
Left Caudate	-5,0,11	-3.142	0.005	389

Table 15: Followup Analyses on Post Target Delay Differences Between Groups

HIGH EF				**LOW EF**			
Gain vs No Incentive				***Gain vs No Incentive***			
Area	*Talairach*	*t*	*p*	*Area*	*Talairach*	*t*	*p*
Right Gyrus Rectus	6,43,-11	-1.787	0.1	Right Gyrus Rectus	6,43,-11	2.692	0.02*
Left Middle Frontal	-30,31,27	-2.589	0.03*	Left Middle Frontal	-30,31,27	2.005	0.07
Left Inferior Frontal	-17,20,-7	-1.984	0.08	Left Inferior Frontal	-17,20,-7	2.079	0.06
Large vs Small Gain				***Large vs Small Gain***			
Area	*Talaraich*	*t*	*p*	*Area*	*Talaraich*	*t*	*p*
Left Medial Frontal	-14, 61, 6	1.707	0.12	Left Medial Frontal	-14, 61, 6	-2.902	0.02*
Left Orbitofrontal	-6,45,-6	1.738	0.12	Left Orbitofrontal	-6,45,-6	-2.131	0.06
Left Oribitofrontal 2	-2,37, -12	2.903	0.02*	Left Oribitofrontal 2	-2,37, -12	-1.914	0.08
Right Inferior Frontal	45,27,16	2.554	0.03*	Right Inferior Frontal	45,27,16	-2.151	0.06
Right Caudate	7,3,10	-2.47	0.04*	Right Caudate	7,3,10	2.229	0.05*
Left Caudate	-5,0,11	-2.53	0.03*	Left Caudate	-5,0,11	1.773	0.12

* = $p < 0.05$
** = $p < 0.01$

Table 16: Within Groups Post Target Delay Differences

HIGH EF					**LOW EF**				
Gain vs No Incentive					***Gain vs No Incentive***				
Area	*Talaraich*	*t*	*p*	*Voxels*	*Area*	*Talaraich*	*t*	*p*	*Voxels*
Left Medial Frontal	-17,45,8	3.066	0.01	536	Left Anterior Cingulate	-2,28,15	3.993	0.003	1041
Right Nucleus Accumbens	15,1,-11	4.299	0.002	692	Right Inferior Gyrus	46,31,6	3.433	0.006	1205
Left Hippocampus	-15,-22,-8	4.035	0.003	1171	Left Inferior Gyrus	-28,22,-13	3.622	0.005	1775
					Right Putamen	25,7,7	-3.416	0.007	1294
					Left Putamen	-22,2,1	-3.851	0.003	1244
					Left Hippocampus	-24,-18,-12	3.548	0.005	1421
Large Gain vs Small Gain					***Large Gain vs Small Gain***				
Area	*Talaraich*	*t*	*p*	*Voxels*	*Area*	*Talaraich*	*t*	*p*	*Voxels*
None					Left Medial Frontal	-14,55,7	-2.941	0.01	879
					Left Middle Frontal	-32,31,24	-3.419	0.007	751
					Right Insula	34,11,13	-3.379	0.007	668

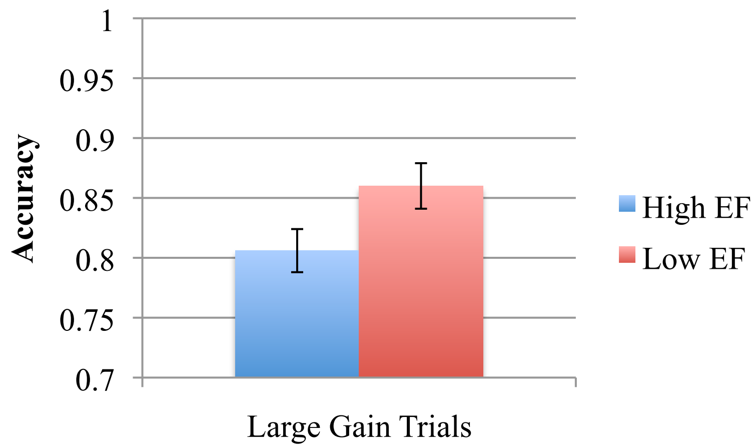
Table 17: Correlations of Behavior and Brain Volume

Executive Function and Brain Volumes of Interest		**Reward Sensitivity and Brain Volumes of Interest**	
Structure	*EF Composite*	*Structure*	*Reward Composite*
Left Caudate	-0.252	Left Thalamus	-0.336
Right Caudate	-0.236	Right Thalamus	-0.059
Left Anterior Cingulate	-0.419+	Left Caudate	-0.338
Right Anterior Cingulate	-0.189	Right Caudate	-0.098
Left Middle Frontal	-0.392+	Left Amygdala	-0.295
Right Middle Frontal	-0.179	Right Amygdala	-0.342
Left Superior Frontal	-0.33	Left Accumbens	-0.091
Right Superior Frontal	-0.442+	Right Accumbens	-0.211
		Left Lateral Orbitofrontal	-0.393+
		Right Lateral Orbitofrontal	-0.333
		Left Medial Orbitofrontal	-0.047
		Right Medial Orbitofrontal	-0.481*
		Left Anterior Cingulate	-0.542*
		Right Anterior Cingulate	-0.273

All correlations control for age, gender and IQ
** = $p < 0.05$*
+ = marginal effect

Figures

Figure 1. *High and Low EF group differences on Large Gain Piñata task trials.*



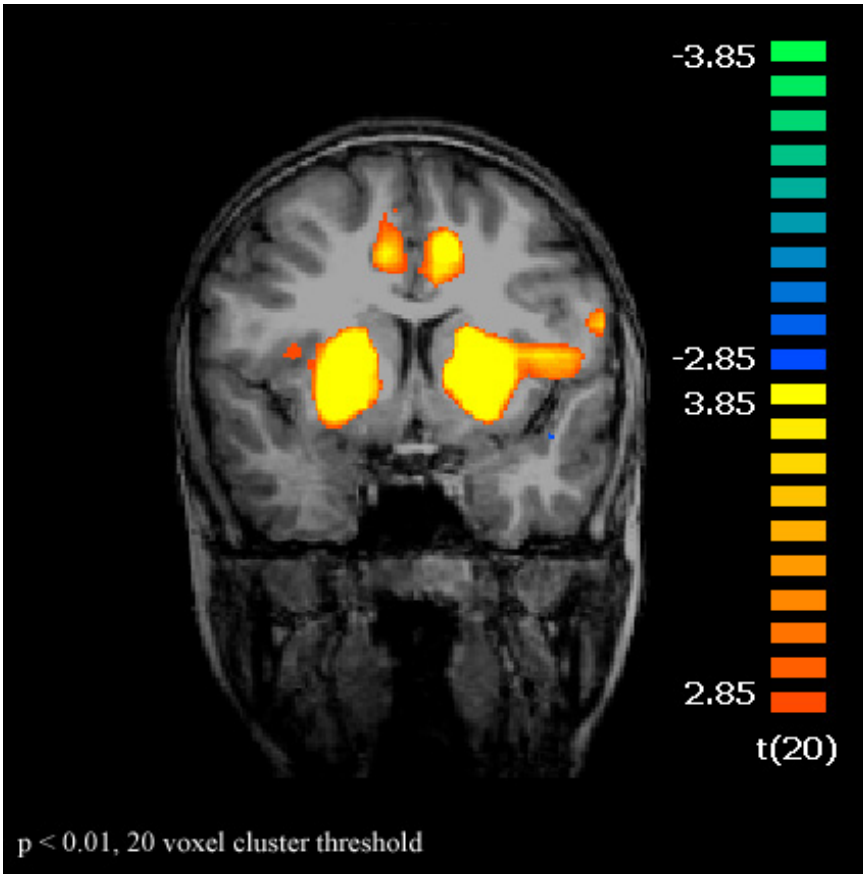


Figure 2. *Task-related activation patterns for Gain vs No Incentive trials in the post-cue period in bilateral putamen and bilateral anterior cingulate cortex.*

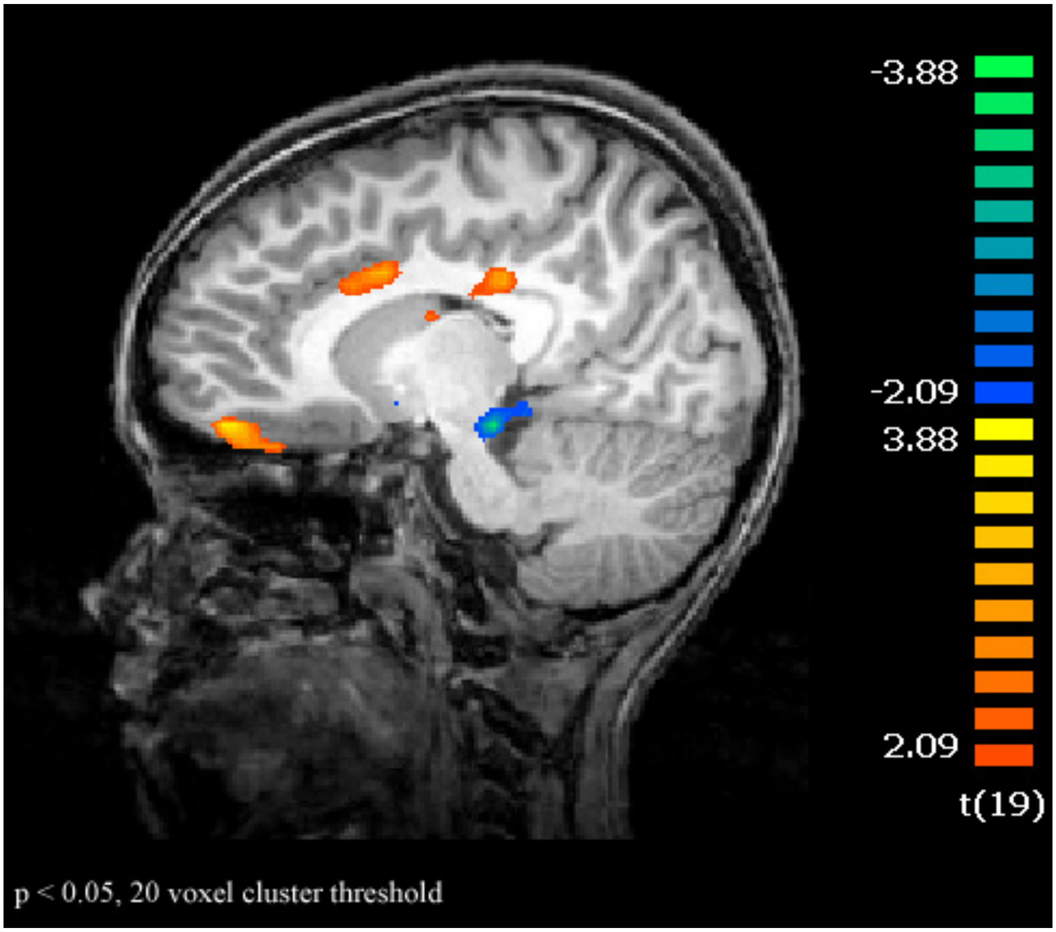


Figure 3. *Group differences in activation patterns in the Large Gain vs Small Gain comparison during the post-cue period in the left orbitofrontal cortex.*

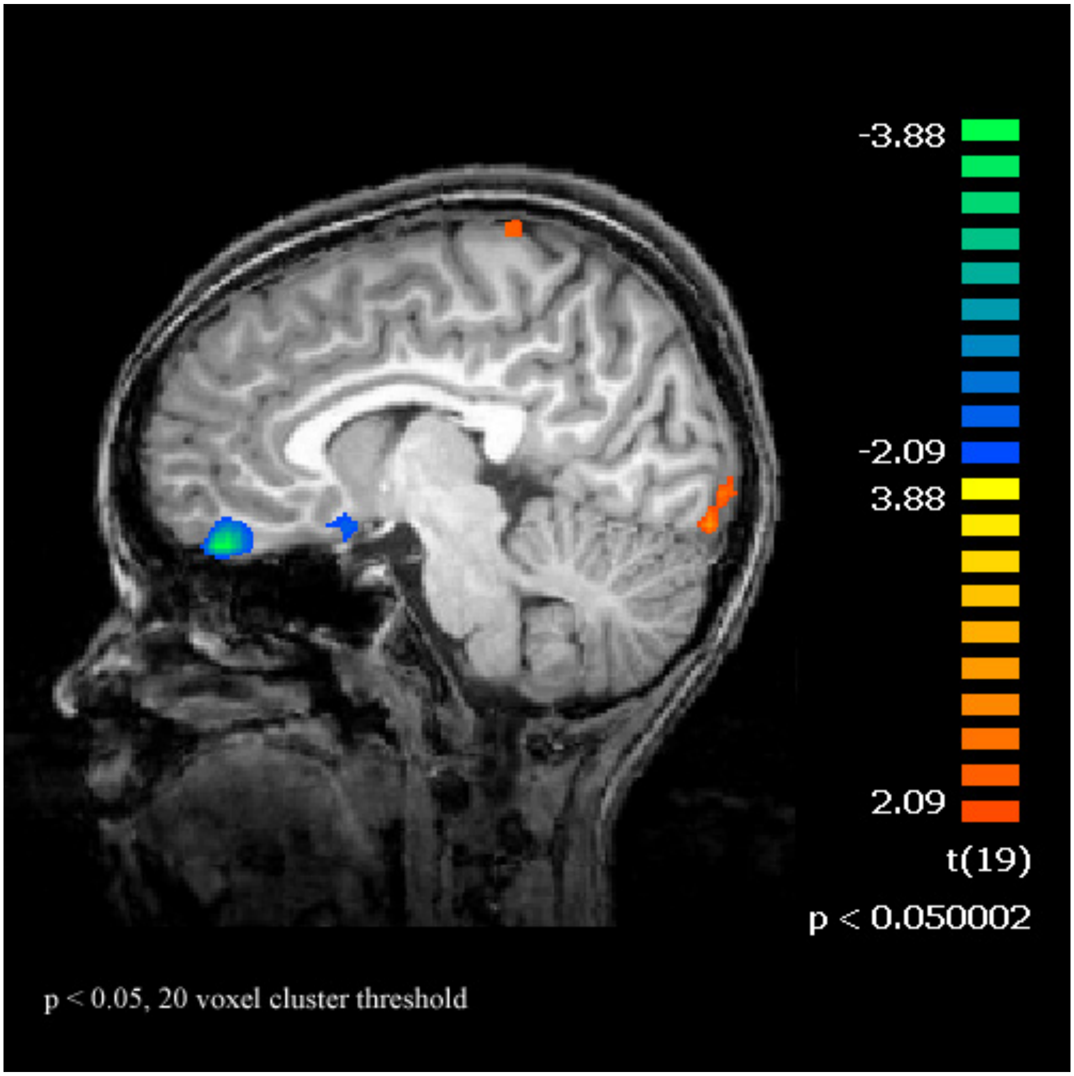


Figure 4. *Group Differences in the Gain vs No Incentive condition in the right rectus gyrus in the post-target period.*

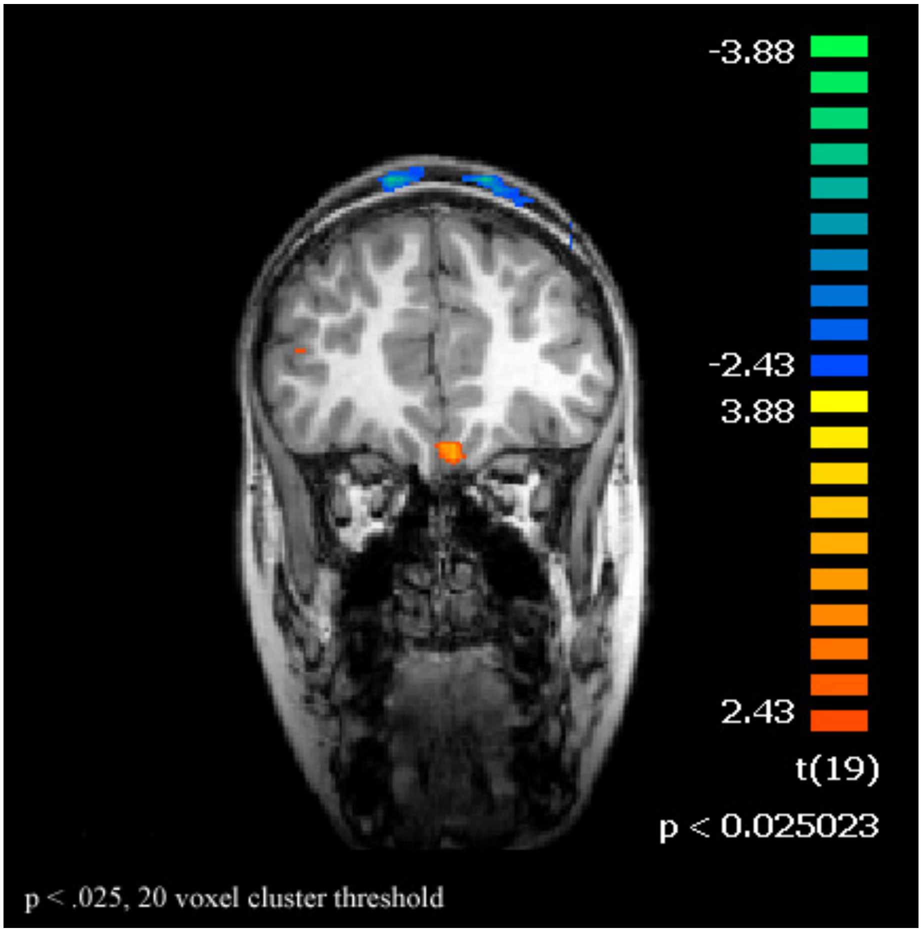


Figure 5. *Group Differences in the Large Gain vs Small Gain comparison in the post-target period in the left orbitofrontal cortex.*

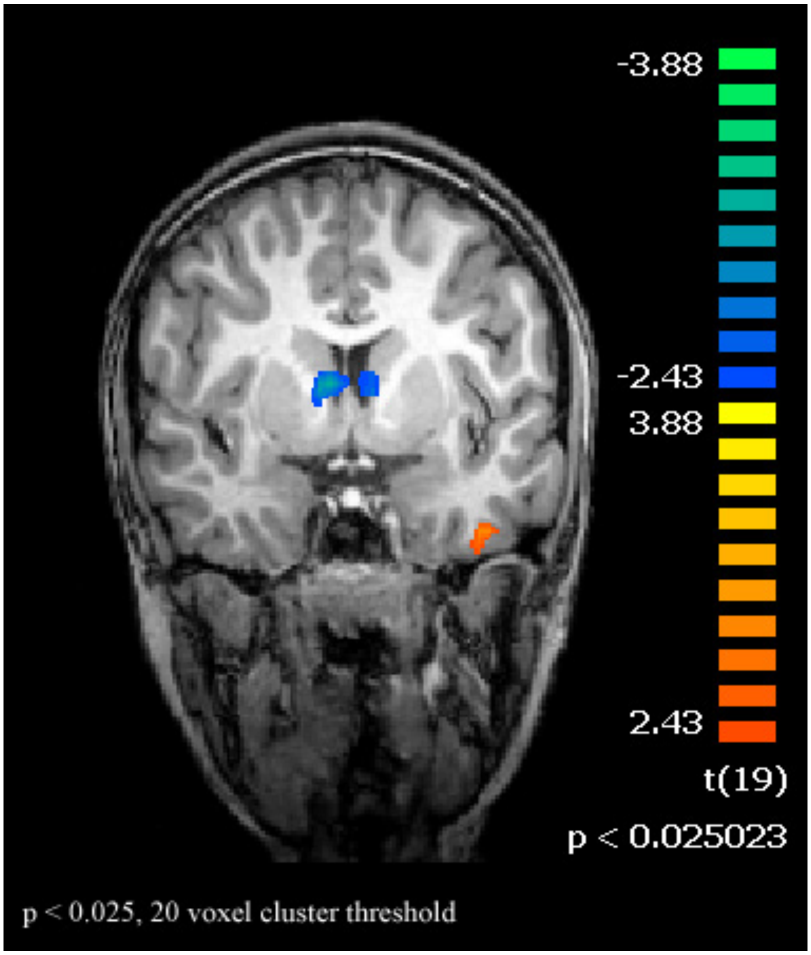


Figure 6. *Group differences in activation patterns for the Large Gain vs Small Gain condition in the post-target period in bilateral caudate.*