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INHIBITORY CONTROL AND ITS RELATION TO PERSONALITY/TEMPERAMENT, EXECUTIVE FUNCTION, AND THE BRAIN

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EXECUTIVE FUNCTION, AND THE BRAIN

by

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A Dissertation
Submitted in Partial Fulfillment of the Requirements for the
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in the field of Clinical Psychology

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TITLE: INHIBITORY CONTROL AND ITS RELATION TO PERSONALITY/TEMPERAMENT, EXECUTIVE FUNCTION, AND THE BRAIN

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Inhibitory control, described as the ability to suppress one response in favor of a goal-directed response, is thought to play an important role in the development of emotional regulation as well as various forms of psychopathology, including ADHD. Up until very recently, inhibitory control has been researched within two completely separate fields of study: temperament and neuropsychology. In the temperament/personality literature, inhibitory control is a major component of the overarching temperament/personality factor of Effortful Control/Conscientiousness. In the field of neuropsychology, inhibitory control is considered one aspect of executive function. Further complicating the current understanding of inhibitory control is the complexity of the underlying neural networks implicated in inhibitory control. This study examined inhibitory control in temperament and executive function in children with and without ADHD, and it explored the relationship between inhibitory control and the superior frontal cortex (SFC) and orbital frontal cortex (OFC) volumes. In order to assess subareas of the OFC and SFC, an innovative parcellation method was used. Results suggested that the temperament and executive function measures of inhibitory control did form a single factor as long as they were measured within the same modality, parent-report. In contrast, the performance-based measure of inhibitory control was not correlated with any of the parent-report measures of inhibitory control and was, therefore, analyzed separately in relation to OFC and

SFC volumes. Parent-rated inhibitory control was predicted by ADHD status only, but exploratory analyses suggested that left anterior SFC, right and left anterior medial OFC, and gender were related to parent-rated inhibitory control. In contrast, performance-based inhibitory control was predicted by gender and left SFC, specifically posterior left SFC. Taken together, these findings suggest a conceptual overlap between temperament and executive function that brings together two areas of the literature and has implications for the understanding of various forms of psychopathology characterized by deficits in inhibitory control. This study provides evidence for the role of the SFC and the OFC in inhibitory control, depending upon the measurement method, and contributes to the broader understanding of the neural mechanisms of inhibitory control in children.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER I

INTRODUCTION

The purpose of this study was to examine inhibitory control and its relationship to temperament/personality, executive function, and specific areas of the prefrontal cortex. The first goal was to determine whether inhibitory control is best conceptualized as a singular factor spanning two separate areas of research or as two or more separate but related constructs. This study addressed the measurement issues present in previous studies by including both a lab-based and a parent-report measure of executive function along with a parent-report measure of temperament. The second goal was to relate inhibitory control differentially to superior frontal cortex (SFC) and orbitofrontal cortex (OFC) volume, each of which have been associated with inhibitory control in the literature. Finally, I divided the SFC and OFC into functional regions. Relating these smaller, parcellated regions of the SFC and OFC to inhibitory control makes this study a unique contribution to the current understanding of the neural mechanisms underlying this construct. These parcellations were based on connectivity and functional imaging research.

Inhibitory control is understood as both a temperament/personality trait and as an executive function. Traits are defined as consistent patterns of thoughts, behaviors, and emotions, whereas executive function is defined as a set of cognitive functions that regulate thoughts, behaviors, and emotion. Very little research has examined this construct across these domains in order to determine whether personality researchers and neuropsychologists are examining the same construct or two separate, but related, constructs when they study inhibitory control. Both areas define inhibitory control as a biologically based capacity to inhibit a behavior in favor of a goal-directed one. However, personality/temperament researchers view inhibitory control as a trait, whereas neuropsychologists view inhibitory control as a type of

neurocognitive function. Although some may argue that personality is a type of neurocognitive function, many researchers would agree that personality and neurocognitive functions are independent concepts; nevertheless, the construct of inhibitory control seems to be a single concept that is included in both temperament and neurocognitive function.

Personality and temperament are concepts that have been closely linked both theoretically and empirically, with temperament traits being identified as a subset of personality (Rothbart 2012; Shiner & Caspi, 2012). Overlapping models of temperament and personality include three to five factors that subsume the lower order traits, including inhibitory control (Rothbart, 2012; Shiner & Caspi, 2012; Watson, Kotov, & Gamez, 2006). The first two higher order factors are emotional or reactive (surgency/extraversion/positive affect and negative emotionality/neuroticism), whereas the third factor (effortful control/conscientiousness/ constraint) is regulative in nature and is thought to regulate emotions, behaviors, and thoughts. Inhibitory control is one facet of this third factor of temperament/personality (Hill et al., 2013; Jackson et al., 2009; Roberts et al., 2005).

The concept of inhibitory control has been included within the larger concept of executive function (EF) as well. Executive function has been defined as effortful neurocognitive processes that regulate emotions, thoughts, and behaviors (Hughes et al., 2010; Roth et al., 2006). Although theories of executive function vary, inhibitory control is often thought to be one of the three major factors of executive function, which include inhibition, shift, and updating (Jacques & Markovitch, 2010; Miyake & Friedman, 2012). Another conceptualization of executive function suggests that EF should be divided by whether or not the neurocognitive task occurs in an emotionally charged context (Zelazo & Carlson, 2012). This conceptualization suggests that different brain mechanisms underlie emotional (hot EF) and non-emotional (cool

EF) executive function and offers a possible understanding of the interaction between the regulative aspects of executive function and both the regulative and the emotional/reactive aspects of temperament/personality.

Studies of the development, genetic basis, neurochemistry, and neural mechanisms of inhibitory control in both domains of research suggest strong similarities in the construct of inhibitory control between the temperament/personality literature and the executive function literature (Gagne & Saudino, 2010; Jacques & Markovitch, 2010; Mervielde & De Pauw, 2012; Ordaz, Foran, Velanova, and Luna, 2013; Shiner & Caspi, 2012; Wiebe et al., 2014a). Of particular interest to this study are the similar underlying biological mechanisms involved in inhibitory control. Both research domains suggest the importance of the dorsolateral prefrontal cortex (DLFPC), ventrolateral prefrontal cortex (VLFPC), anterior cingulate cortex, and the orbital frontal cortex (OFC) in inhibitory control, although some of the conclusions made by the temperament researchers about these underlying mechanisms is actually based on the executive function literature (Ordaz et al., 2013; White et al., 2012). For example, making the assumption that inhibitory control is the same construct in both domains of research, some temperament researchers have used research conducted on the brain structures active during traditional executive function laboratory-based measures to provide evidence of the underlying neural mechanisms of inhibitory control in temperament (White et al., 2012). Research on executive function also has indicated that the superior frontal cortex (SFC), particularly the pre-supplementary motor area (preSMA) and the supplementary motor area (SMA), plays a role in inhibitory control (Hsu et al., 2011). In general, the bilateral lateral OFC has been associated with inhibitory control across both domains of research, and the bilateral posterior SFC have been associated with inhibitory control in the executive function research. This study used an

innovative method of parcellation to examine the relationship of different areas of the OFC and SFC to inhibitory control using quantitative magnetic resonance imaging (MRI).

Based on these similarities, some researchers have made the assumption that inhibitory control in temperament/personality and inhibitory control in executive function are the same construct (Rueda, Posner, & Rothbart, 2005); however, the empirical evidence that supports this connection directly is plagued by measurement issues (Hallquist, 2010). First, studies that purport to measure both constructs sometimes use measures designed to be temperament measures as measures of executive function and vice versa (Reck & Hund, 2011; Wolfe & Bell, 2003), so positive correlations between the two may indicate that they are both measuring temperament or executive function, not temperament and executive function. Second, the few studies that measure inhibitory control in both executive function and temperament tend to have problems with both constructs being measured cross-modality, with executive function being measured by laboratory-based measures and temperament being measured by questionnaires (Ellis, Rothbart, & Posner, 2004; Hallquist, 2010; Morasch & Bell, 2011). Weak or non-significant correlations between the constructs in this case may be due to cross-modality measurement issues and not actual differences in the constructs. One of the reasons for these problems in measurement is that temperament/personality is traditionally measured by parent-report or self-report measures, whereas executive function is traditionally measured by lab-based measures. This study addressed these measurement issues by including a parent-report measure of executive function, a parent-report measure of temperament, and a laboratory-based measure of executive function. Ideally, a laboratory-based measure of temperament would also have been included, but one was not available because of the archival nature of this study. Data were

collected as part of a larger, NIH funded study, but I did all of the measurement of the brain areas.

By combining the research base of these two areas, this study has contributed to the creation of a more comprehensive understanding of inhibitory control, which can offer insight into many forms of psychopathology, potentially leading to improved interventions and preventions for these disorders. The area of temperament/personality has accumulated decades of research on inhibitory control and its relationship with normative development and with various forms of psychopathology. The area of neuropsychology is newer but provides a complex understanding of the neural networks and cortical structures that underlie inhibitory control. By combining the strengths of these fields of research, a new understanding of inhibitory control has the potential to impact the treatment of many forms of psychopathology that have been associated with poor inhibitory control such as attention deficit/hyperactivity disorder (ADHD), conduct problems, aggressive behavior, borderline personality disorder, and depression (Nigg et al., 2004; Posner et al., 2002; Rudolph et al., 2013). This improved, joint understanding of inhibitory control is especially important in light of recent studies that have demonstrated promising results for interventions designed to improve executive function in children with ADHD, which may then have implications for treatment of other disorders associated with problems in inhibitory control.

CHAPTER II

LITERATURE REVIEW

This literature review discusses current conceptualizations of personality and temperament as they include the concept of inhibitory control, followed by a discussion of the neuropsychological literature that describes inhibitory control as an executive function, which is defined as a neurocognitive process that interacts with other neurocognitive functions to regulate cognition, emotion, and behavior. Each of these sections include the measurement, development, and biological bases of inhibitory control. In addition, individual differences and links to psychopathology are covered. The few studies that have examined the relationship between temperament/personality and executive function are then discussed.

The second part of this project looked at the relationship between inhibitory control, as a singular construct, and prefrontal cortex volumes, in particular the superior frontal and orbital frontal cortices. I manually traced these two structures on MRI scans as part of my research assistant assignment, and both structures are thought to play an important role in inhibitory control. Research on the functional anatomy of these structures, especially how they relate to self-control and executive function, is explained.

Inhibitory Control in Personality and Temperament

This project incorporates an understanding of both personality and temperament because both concepts are very closely related both theoretically and empirically. One of the most current conceptualizations of temperament and personality is that temperament is a subset of personality (Rothbart, 2012; Shiner & Caspi, 2012). Personality is a broader concept that incorporates a variety of individual differences in "thinking, feeling, and behaving" (Caspi, Roberts, & Shiner, 2005, p. 454). Temperament is the portion of personality that includes both

general reactivity and regulative capacities and is present early in life (Rothbart, 2012).

Researchers have demonstrated a strong relationship between adult personality and adult temperament (Evans & Rothbart, 2007; Rothbart, Ahadi, & Evans, 2000), between childhood temperament and childhood personality (De Pauw & Mervielde, 2011; Dyer, 2000; Grist & McCord, 2010; Herzhoff & Tackett, 2012), and between childhood temperament and adult personality (Caspi & Silva, 1995; Deal, Halverson, Havill, & Martin, 2005; MacEvoy, et al., 1988; Steinberg, 1985). Inhibitory control is included among these traits that qualify as both a temperament and a personality characteristic. Therefore, both the temperament and personality literature can inform our understanding of inhibitory control as a trait.

Personality: Definition and Structure

The concept of personality has been around for centuries and is a rather broad concept that includes a range of individual differences in cognitions, emotion, and behavior (Shiner & Caspi, 2012). These individual differences are thought to demonstrate some consistency over situations and time, suggesting a biological basis, although the environment is also thought to have an impact on these individual differences (Rothbart, 2012). As a broad concept, personality includes traits as well as attitudes, adaptations, narratives, goals, values, self-concept, and interpretations (Rothbart, 2012; Shiner & Caspi, 2012; Zentner & Bates, 2008). A personality trait is defined as "a pattern of thoughts, emotions, and behavior that show consistency over situations and stability over time" (Rothbart, 2012, p. 3). Some of the most commonly studied personality traits include sociability, shyness/social inhibition, positive emotionality, aggressiveness, negative emotionality, attention, will to achieve, activity level, and inhibitory control (Shiner, 1998; Watson, Clark, & Harkness, 1994). In the personality/temperament literature, attention refers to the general ability to regulate attention, including shifting attention,

focusing attention, and maintaining attention (Caspi, Roberts, & Shiner, 2005). Today's personality theorists generally recognize that these personality traits fall into higher order factors, but the number of factors varies by study and theorist (Zentner & Bates, 2008). Since inhibitory control is considered a personality trait (Hill, Payne, Jackson, Stine-Morrow, & Roberts, 2013; Jackson et al., 2010; Roberts, Bogg, Walton, Chernyshenko, & Stark, 2004; Roberts, Chernyshenko, Stark, & Goldberg, 2005), the discussion of personality will be confined to the trait level and the factor level which subsumes these traits. The other concepts included in personality (attitudes, goals, values, etc.) are not considered traits and, thus, are not relevant to this project.

One of the best established higher-factor models of personality is the Big 5/Five-Factor Model (Digman, 1990; Shiner & Caspi, 2012). Various factor analytic studies of both single word descriptors and of existing personality inventories have yielded a five-factor structure made up of extraversion, neuroticism, conscientiousness, agreeableness, and openness to experience or intellect (Shiner, 1998; Watson, Clark, & Harkness, 1994: Watson, Kotov, & Gamez, 2006). Extraversion is the individual's tendency to be actively and positively engaged with the world, whereas neuroticism reflects the individual's tendency toward negative emotionality and distress. Conscientiousness is the tendency toward self-control, striving toward high standards, and inhibiting impulses. Agreeableness reflects individual differences in an individual's ability to self-regulate relationships with others. Openness to experience/intellect is the individual's tendency to be curious, clever, creative, and quick to learn (Shiner & Caspi, 2012). Although the names of the five factors vary from study to study, the general concept of each factor remains fairly consistent (Digman, 1990; Watson, Clark, & Harkness, 1994). For example,

conscientiousness is sometimes described as dependability or as will to achieve, but the general content of this factor remains the same despite the differences in nomenclature.

Other studies have supported two-, three, and four-factor alternatives to the five-factor model (Merenda, 2008; Olson, 2005; Watson, Clark, & Harkness, 1994). Watson, Kotov, & Gamez (2006) proposed that the variations in these alternative models are not contradictory but instead reflect the level at which the researchers were exploring personality, with the assumption that most three-factor models if broken down a little more would reveal four- or five-factor models. When these factors are broken down even further, they reveal the individual traits (e.g., inhibitory control). Perhaps the most popular of these alternative models is the three-factor model (Watson et al., 2006), which includes two of the same factors from the Big 5 models (extraversion/positive affect and neuroticism/negative affect) with the third factor, disinhibition vs. constraint, being a combination of agreeableness and conscientiousness from the Big 5 (Clark & Watson, 1999; Watson, Kotov, & Gamez, 2006). These three factors are found consistently across studies, and they are parallel to factors of temperament as will be discussed later (Rothbart, 2012). The other two of the five factors are not as clear, as the factor of openness/intellect is especially ambiguous and tends to be absent from four-factor models (Merenda, 2008; Watson et al., 1994). Despite these variations in the factors and despite the critique that the five-factor model may be preordained by the items selected for inclusion in each study (Block, 1995), the five-factor model has received tremendous support with over 3,000 articles published using the five-factor model between 1995 and 2009 alone (John & Naumann, 2010).

According to the few studies that have looked at the lower order traits of conscientiousness, inhibitory control or similar construct (like impulse control or self-control) is

identified as a subtrait of conscientiousness in the 5-factor models. The number of lower order traits identified in these studies varies from five to eleven, but inhibitory control, or similar construct, is always listed as one aspect of conscientiousness (Jackson et al., 2010; Roberts, Bogg, Walton, Chernyshenko, & Stark, 2004; Roberts, Chernyshenko, Stark, & Goldberg, 2005). Some of the adjectives included in the lower order trait of impulse control, which is conceptually similar to inhibitory control, were careful, rash (reversed), impulsive (reversed), careless (reversed), and cautious (Roberts et al., 2004). Other examples of the lower order traits identified in these studies of conscientiousness were reliability, orderliness, decisiveness, punctuality, formalness, conventionality, and industriousness. Inhibitory control loaded well on conscientiousness and demonstrated good discriminant validity with regard to the other four higher order personality factors. Hill, Payne, Jackson, Stine-Morrow, and Roberts (2013) assessed five aspects of conscientiousness in older adults and found that three of the aspects (order, self-control, and industriousness) improved with increased social support while the other two aspects (traditionalism and responsibility) did not. This study provides additional evidence that conscientiousness can be divided into meaningful components, including self-control/inhibitory control. No studies appear to identify inhibitory control as a subtrait of any of the other four factors. Correlational studies of self-control as a trait with the Big 5 demonstrate the strongest correlation with conscientiousness as expected, but moderate correlations also were found between self-control and agreeableness and between self-control and neuroticism as well (Tangney, Baumeister, & Boone, 2004). The reason for these additional correlations may be due to the broad definition of self-control used in this study.

Although the vast majority of the research on the five- and three-factor models of personality has been conducted with adult samples, a similar five-factor structure (Barbaranelli,

Caprara, Rabasca, & Pastorelli, 2003; Goldberg, 2001; Holgado-Tello, Carrasco-Ortiz, Gándara, & Moscoso, 2009; Tackett et al., 2012) and three-factor structure (Kokkinos Panayiotou, Charalambous, Antoniadou, & Davazoglou, 2010) have been extended downward into children as young as 2-years-old as well (Digman, 1990; Grist & McCord, 2010). De Pauw, Mervielde, and Van Leeuwen (2009) factor analyzed a mixture of three temperament measures and one personality measure, all completed by parents of preschool children, and found the same four factors as Watson's four-factor model with a fifth factor called Sensitivity, which shared some content with openness/intellect. This model also had a 6th factor, Activity, which usually is included in extraversion for most five-factor personality models. Although several adult studies have identified self-control (inhibitory control) as one of the lower order traits that make up conscientiousness in adults, no similar studies of the lower order traits of conscientiousness have been conducted with children.

Temperament: Definitions and Structure

Conceptualizations of temperament vary greatly across both researchers and time (Goldsmith et al., 1987; Shiner et al., 2012; Zentner & Bates, 2008). Early conceptualizations of temperament defined it as dispositions that affect the expression of emotion and behavior. These dispositions were thought to be relatively stable, to have a biological (genetic) basis, and to be most simple and easy to understand in infants (Goldsmith et al., 1987). This conceptualization of temperament being easiest to understand in infants implies that temperament is "pure" at birth but is influenced by the environment and personality as children develop. Newer research has challenged all aspects of this conceptualization of temperament. First, early conceptualizations did not include attention and self-regulation along with emotional and behavioral dispositions (Shiner et al., 2012). Second, although neurophysiological, neurochemical, and genetic research

has continued to demonstrate that temperament has both a biological and genetic basis, this is no longer considered a distinctive feature of temperament that distinguishes it from personality (Zentner & Bates, 2008). In traditional definitions temperament was biologically-based, whereas personality was the result of an interaction among temperament, intellect, and the environment. Current research has demonstrated that many personality traits also have a genetic basis, and temperament itself is now understood as a complex interaction between biological and environmental mechanisms (Shiner et al., 2012). Thus, the traditional distinctions between temperament and personality have been blurred. Third, the idea that temperament is easiest to study in infancy has been challenged with studies demonstrating that temperament is least stable in infancy and does not demonstrate moderate stability until the preschool years (Shiner et al., 2012; Zentner & Bates, 2008). Although some researchers maintain that temperament only describes traits in infancy, many studies have demonstrated the presence of temperament traits throughout childhood and into adulthood (McCrae et al., 2000).

Current definitions of temperament incorporate these newer findings. Zentner & Bates (2008) identified several inclusion criteria for child temperament. Temperament traits reflect patterns of individual differences in the areas of emotion, activity level, attention, and sensory sensitivity, and these characteristics can be expressed in terms of intensity (strength of the response), duration (the length of the response), threshold (the intensity of the stimulus required for a response), recovery times (speed of returning to baseline), or latency (time elapsed before responding to a stimulus). Temperament traits must appear early in life with full expression by preschool age. Sometimes indicated by traits that have counterparts in primates, temperament traits must be distinguished from more intellectual characteristics, and temperament traits must be linked to biological mechanisms. Finally, these traits should demonstrate relative stability

and be able to predict later outcomes. Although historically and currently temperament has been defined in many different ways both in terms of typologies (Kagan & Snidman, 2004) and dimensions (Rothbart, 2012), this paper will focus on Rothbart's three-factor theory of temperament. This three-factor model has four major advantages for this study. First, this model is consistent with the three- and five-factor models of personality discussed previously, which allows easier integration of the temperament and personality literature. Second, Rothbart's conceptualization of temperament incorporates a psychobiological understanding of temperament, making it compatible with theories of executive function. Third, inhibitory control is clearly included in this model as a subtrait of one of the three major factors. Fourth, Rothbart's model is one of the most widely accepted conceptualizations of temperament and has been extensively researched and confirmed across multiple ages and cultures (Mervielde & De Pauw, 2012; Putnam & Stifter, 2008).

As stated above, Rothbart's psychobiological theory of temperament has gained wide acceptance and much empirical support. Rothbart (2012) recently defined temperament as "constitutionally based individual differences in reactivity and self-regulation, influenced over time by genes, maturation, and experience." Reactivity refers to the excitability or arousability of neural systems involved in emotional, behavioral, and sensory responses, whereas self-regulation refers to the ability to modulate that reactivity according to environmental demands and personal goals (Mervielde & De Pauw, 2012; Rothbart, Ahadi, Hershey, & Fisher, 2001). Rothbart's measures of temperament, each of which is designed for a specific age group, all have three factors with the first two measuring different aspects of reactivity and the third measuring self-regulation (Rothbart et al., 2001). The first factor, Surgency, is analogous to the personality construct of extraversion and measures the tendency toward sociability and positive

13

emotionality. Negative Affect, the second factor, is analogous to neuroticism in personality and measures the tendency toward negative emotionality. Finally, Effortful Control is similar to the personality constructs of constraint or conscientiousness, depending on which model of personality is used, and measures the tendency/ability for self-regulation.

Inhibitory Control, which is defined as the ability to monitor, control, and inhibit inappropriate responses, is one facet of this third factor of Effortful Control, which also includes Low Intensity Pleasure, Attentional Focusing, Perceptual Sensitivity, and Activation Control (Rueda, 2012). Low Intensity Pleasure reflects the child's ability to enjoy situations involving low stimulation (e.g., reading or coloring). Attentional Focusing involves the ability to maintain focus during tasks. Perceptual Sensitivity is the ability to notice and respond to low level stimuli from the environment. Activation Control is the ability to focus one's efforts on a task when there is a strong tendency to avoid that task. Overall, this three-factor structure of temperament, with inhibitory control as part of the Effortful Control factor, has been well-established across cultures and multiple age groups from infancy through adulthood (Ahadi, Rothbart, and Ye, 1993; Evans & Rothbart, 2007; Putnam, Gartstein, & Rothbart, 2006; Rothbart et al., 2001).

The Relationship between Personality and Temperament

The theoretical understanding of the relationship between personality and temperament has shifted over the past 20 years. Historically, personality was almost exclusively studied in adults, whereas temperament was mostly studied in childhood, during which it was thought to be most "pure" and easiest to study (Shiner & Caspi, 2012). In this conceptualization, temperament was often conceptualized as a precursor to personality. Over the last twenty years, many studies have suggested that temperament and personality are very closely linked (De Pauw & Mervielde, 2011; Dyer, 2000; Herzhoff & Tackett, 2012; Schmidt, Fox, Perez-Edgar, & Hamer, 2009;

14

Shiner et al., 2012; Shiner & Caspi, 2012). Shiner and Caspi (2012) discussed four ways in

which research has linked temperament and personality: studies of genetic influences, animal

research on temperament and personality, longitudinal studies of trait stability, and studies of

structure and content. In terms of genetic influence, recent studies have demonstrated that both

temperament and personality are heritable and both are influenced by the environment (Caspi,

Roberts, & Shiner, 2005; Grist & McCord, 2010; Propper & Moore, 2006; Shiner & Caspi,

2012). Animal studies have demonstrated that both the Big 5 personality traits and the major

temperament traits are present in animals (with the possible exception of effortful

control/conscientiousness), contributing to the evidence that both temperament and personality

are biologically based (Shiner & Caspi, 2012). Longitudinal studies of both temperament and

personality have demonstrated that both can be stable and both can change over time (Caspi,

Roberts, & Shiner, 2005; Putnam, Rothbart, & Gartstein, 2008; Shiner & Caspi, 2012). Earlier

conceptualizations of personality stated that personality was stable, whereas temperament was

malleable. However, as both temperament and personality have been studied over the life

course, both appear to become more stable over time up through the preschool years at which

time the level of stability remains about the same until the 50's (Putnam, Rothbart, & Gartstein,

2008; Shiner & Caspi, 2012). It is not until these older years that personality appears to be more

stable than temperament. The fourth and final area of research that has suggested a strong link

between temperament and personality are studies of the structure and content of these two

constructs. Over the last 20 years, a great deal of research has demonstrated both conceptual and

structural similarities indicating either that temperament and personality have the same

biological underpinnings or that they are essentially the same thing (Grist & McCord, 2010;

Rothbart, 2012; Shiner et al., 2012; Shiner & Caspi, 2012).

Inhibitory Control in Personality and Temperament

Based on current understandings of the relationship between temperament and personality as described above, the concept of inhibitory control within personality and the concept of inhibitory control within temperament is treated as the same construct in this study, allowing for a richer understanding of this trait across the lifespan. For the purposes of this study, inhibitory control as a personality/temperament trait is defined as the "capacity to plan and to suppress inappropriate approach responses under instructions or in novel or uncertain situations" (Rothbart et al., 2001). In further clarifying this definition of inhibitory control, I first distinguish inhibitory control from other similar concepts, such as inhibition to novelty, behavioral disinhibition, and impulsivity. I then summarize how inhibitory control fits into the larger constructs of personality and temperament.

First, inhibitory control is distinguished from the construct of inhibition to novelty, which is an automatic response that is related to shyness or a fear response to novel stimuli (Eisenberg et al., 2013; Rueda, 2012). At the root of inhibition to novelty, also called reactive overcontrol, is an involuntary, fearful response to or withdrawal from a novel stimulus. In contrast, inhibitory control is thought to be effortful, not involuntary, and it involves the suppression of an approach response and is not related to a fear/withdrawal response. Supporting these conceptual differences, factor analyses have demonstrated that effortful control and inhibition to novelty in 2-year-old children are best described as separate constructs (Eisenberg et al., 2013). Inhibitory control is also separate from the concept of behavioral disinhibition, which is the tendency toward extreme approach in the face of novel situations (Hirshfeld-Becker et al., 2006). This extreme approach also can be thought of as behavioral undercontrol or sensation-seeking, which is associated with oppositional behavior, conduct problems, and substance use disorders

(Hirshfeld-Becker et al., 2006). In contrast, inhibitory control is not an approach process but a self-regulative process, which has the potential to suppress behavioral disinhibition, this tendency toward boldness or extreme approach.

Inhibitory control, although it is sometimes called impulse control in the literature, should not be confused with the broader concept of impulsivity, which includes both aspects of affective reactivity and constraint (Sharma, Markon, & Clark, 2014). Although inhibitory control is thought to contribute to impulsivity, impulsivity is broader and includes the tendency to respond quickly to novel stimuli, sensation seeking, and the ability (or lack thereof) to inhibit behavioral responses. These first two aspects of impulsivity, quick responses to novel stimuli and sensation seeking, are related to extreme approach, similar to the concept of behavioral disinhibition described previously. The third aspect of impulsivity is the self-regulative component, which is associated with inhibitory control. Contributing to the evidence that inhibitory control is a separate construct from impulsivity, inhibitory control tends to be exclusively associated with the constraint/effortful control factor of personality/temperament, whereas impulsivity and its components appear to correlate with all three major personality/temperament factors (McCrae & Lockenhoff, 2010; Sharma, Markon, & Clark, 2014; Whiteside & Lynam, 2001). In other studies, impulsivity is defined more narrowly, including only the sensation seeking and extreme approach aspects of impulsivity (Ahadi, Rothbart, & Ye, 1993; Eisenberg et al., 2013). When defined more narrowly, impulsivity is clearly a separate construct from inhibitory control. Eisenberg et al. (2013), in the same study that demonstrated that effortful control and inhibition to novelty were different factors, also found that impulsivity was best conceptualized as a factor separate from the other two constructs. In Rothbart's measures of temperament, impulsivity and inhibitory control are measured separately with impulsivity loading on Surgency and inhibitory

control loading on Effortful Control (Ahadi, Rothbart, & Ye, 1993; Dyer, 2000). Taken together, this research supports the idea that impulsivity and inhibitory control are not two ends of the same continuum, but instead, depending on the breadth of the definition used, they are either overlapping concepts, with impulsivity as the more encompassing concept, or are separate constructs.

In the temperament/personality literature, inhibitory control is a facet of the superordinate factor of conscientiousness/effortful control as noted above. Effortful control is a higher order factor that expresses "individual differences in self-regulation and the control of reactivity" (Rueda, 2012). Inhibitory control loads consistently and most highly on effortful control in the temperament literature. Although no child studies of personality incorporate inhibitory control, studies of adult personality support inhibitory control as a facet of the conscientiousness factor, which is analogous to effortful control in temperament.

A couple of findings, however, suggest that inhibitory control's role in temperament and personality may not be that simple. First, although inhibitory control is thought to be a facet of effortful control (EC), IC does not load exclusively on EC in low income populations, particularly African American children from low income families (Richard, Davis, & Burns, 2008). In this population, inhibitory control loaded significantly on all three factors (surgency, negative emotionality, and effortful control) with the highest loading being a negative loading on surgency. This difference in inhibitory control could be due to the way this specific American subculture interprets the wording on the questionnaire used, or this difference could represent a qualitative difference in inhibitory control due to the connection between self-regulatory skills and academic performance, which tends to be decreased in children in poverty (Richard et al., 2008).

Second, in very young children, the lines between surgency and effortful control are less clear, with surgency predicting later effortful control. Putnam, Rothbart & Gartstein (2008) found that high surgency in infants predicted high effortful control in those children as toddlers; however, high surgency in toddlers predicted low effortful control in those children as preschoolers. Putnam et al. (2008) cited the positive emotionality portion of surgency as the driving force behind the association between high infant surgency and high toddler effortful control. Given that high toddler activity level, which is part of surgency, predicted poor preschool effortful control, they concluded that this high activity level may be the reason for the connection between high toddler surgency and low preschool effortful control. In addition, high toddler negative affect was associated with poor preschool inhibitory control. Ideally, only effortful control would predict later effortful control, but these cross factor predictors may reflect the complex interaction between the development of the more reactive/affective systems and of the self-regulative systems (Putnam et al., 2008).

Third, there is some evidence that inhibitory control should be broken down further into behavioral and emotional self-control. When studying adult personality, King, Emmons, and Woodley (1992) explored the structure of inhibition itself, using multiple questionnaires of inhibition, and found that behavioral self-control and emotional self-control seemed to be the two separate factors within the larger concept of inhibition/constraint. This finding may imply that inhibitory control, as it is studied in the adult personality literature, tends to be a broader concept including both emotional control and behavioral control, with the latter being conceptually more similar to inhibitory control as it is studied in the child temperament literature. An alternative explanation is that inhibitory control in both personality and temperament can be further analyzed and separated into behavioral inhibitory control and emotional inhibitory control. In

my later discussion of executive function, underlying neurological mechanisms that may support this second explanation will be discussed.

In conclusion, inhibitory control in the temperament/personality literature is the effortful inhibition of an inappropriate response. Although similar to impulsivity and inhibition to novelty, inhibitory control differs from these two concepts which involve extreme approach or the reverse, extreme withdrawal, respectively. Inhibitory control is generally considered a lower order trait of the effortful control/conscientiousness factor. Although a few studies have demonstrated connections between inhibitory control and other higher order factors, these differences in findings are likely related to the sensitivity and conceptual content of the inhibitory control measures used.

Measurement of Inhibitory Control as a Personality/Temperament Trait

Report measures, including self-report, peer-report, and spouse-report, are a common way of measuring inhibitory control as a temperament or personality trait. In particular, personality is most commonly measured by self-report since it has been most commonly measured in adults. The range of adult personality measures is vast, based on many different definitions and theories of personality; however, the most commonly used personality measure based on the five-factor model in adults is the NEO Personality Inventory-Revised (NEO PI-R). In adults, the NEO PI-R has demonstrated good reliability and validity (Gartstein, Bridgett, & Low, 2012; Mullins-Sweatt & Widiger, 2006); however, this measure also has demonstrated reliability and validity in youth ages 12-17 (Costa & McCrae, 1992). One measure that was designed for use with school-aged children is the Big 5 (Barbaranelli, Caprara, Rabasca, & Pastorelli, 2003), which has the confirmed five-factor structure, demonstrates evidence of reliability, and has been cross-validated against the NEO PI-R. The Big 5 measures

Conscientiousness, but it does not specifically measure inhibitory control even though several items within the Conscientiousness factor clearly measure this concept.

In terms of report measures, temperament has been measured using parent-report, caregiver/teacher-report, and self-report measures in children and adults. Several of the childhood measures of temperament were based on the New York Longitudinal Study (NYLS), which included 9 dimensions of temperament (e.g., activity level, rhythmicity, and approach/withdrawal). Although these measures are commonly used in research settings, several of these measures have shown poor internal consistency and unstable factor structure (Gartstein, Bridgett, & Low, 2012). In contrast, Rothbart's theoretically-based measures of temperament have demonstrated reasonable internal consistency, ranging from .62-.91 within each of the various age groups, as well as a stable three-factor structure (Gartstein, Bridgett, & Low, 2012; Neppl et al., 2010). In addition, Rothbart's measures have demonstrated convergent validity with lab-based measures of temperament, other parent-report measures of behavior, and report measures of personality (Dyer, 2000; Evans & Rothbart, 2007; Gartstein, Bridgett, & Low, 2012; Rothbart, 2012; Zentner & Bates, 2008). Generally, Rothbart's measures have demonstrated good reliability and validity across cultures and measures, which are available for infancy through adulthood (Ahadi, Rothbart, & Ye, 1993; Putnam, Rothbart, & Gartstein, 2008; Rothbart, Ahadi, Hershey, & Fisher, 2001).

In general, the use of self- and other-report measures to capture temperament and personality has its strengths and weaknesses. In terms of strengths, these measures offer the opportunity to capture temperament over time (not just in a brief observation or laboratory situation) and across settings, as parents and other caregivers or teachers presumably have many opportunities to observe the child and to rate the child's temperament accurately. These

measures are also easy to administer, inexpensive, and quick for the researcher although some of the questionnaires are quite lengthy for the individuals completing them. On the downside, these report measures generally show low inter-rater correspondence (Gartstein, Bridgett, & Low, 2012), which brings up questions of rater bias, the validity of the measures, and reliability across settings. For example, Putnam, Gartstein, and Rothbart (2006) found gender differences in temperament ratings varied by rater. In rating toddlers, primary caregivers (mostly mothers) rated girls higher in fear and lower in high intensity pleasure, whereas secondary caregivers (mostly fathers) rated girls higher in several aspects of effortful control. Other gender differences were consistent across raters, with inhibitory control being rated as higher in females than in males in this toddler population across raters. It is unclear if this gender difference reflects rater bias or actual gender differences. In addition to rater bias, there is some question as to the ecological validity of the constructs purported to be measured by self-report, parent-report, and other-report questionnaires. Generally, low, but appropriate, correlations have been found between report measures and laboratory observed behaviors, suggesting some concurrent validity. One reason for these low correlations may be the global nature of the questionnaires as opposed to the specific behaviors measured in the laboratory settings. Although report measures have their weaknesses, this type of measure remains the most commonly used way of assessing temperament and personality in both children and adults (Goldsmith & Gagne, 2012).

In addition to report measures, many different types of behavioral assessment have been used to measure temperament in young children, especially infants, toddlers, and preschoolers, although few behavioral measures have been used to look at temperament in older children and adults. For the purposes of this paper, I will focus the discussion of behavioral measures of temperament on behavioral measures of effortful control and inhibitory control. Behavioral

assessments in general fall into two larger categories: those that are observations (ratings and counts) of naturalistic behavior and those that are elicited behavioral responses to a specific situation, generally in a laboratory setting (Goldsmith & Gagne, 2012). The measurement of inhibitory control is by nature more easily measured in this second type of assessment since, as Rothbart (2012) stated, inhibitory control is the ability to plan and to inhibit behavior in the face of an instruction or novel task. Without instructions or novel tasks, both of which are commonly present in laboratory tasks, the child may not have the opportunity to exhibit inhibitory control.

Kochanska and colleagues created a series of laboratory tasks to measure the five aspects of effortful control: delaying gratification, slowing motor activity, suppressing or initiating a response to a signal, lowering vocal volume, and paying attention (Goldsmith & Gagne, 2012; Kochanska et al., 1997, 2000). Tasks used to measure each aspect of effortful control varied by the whether the child was a toddler, preschooler, or early grade school child. Generally, delaying gratification was measured by five tasks: snack delay, wrapped gift, gift-in-bag, tongue, and dinky toys. In each of these situations, the child is asked to wait for the reward, and ratings of the child's ability to wait during the task are made. Slowing motor activity is measured by having the child walk a line slowly and by requiring the child to draw at normal, fast, and slow speeds. Suppressing a response to a signal would be the task that best measures the inhibitory control aspect of effortful control. One task that was designed to measure this was tower, which required the child to take turns adding blocks to a tower. The examiner waits to place their block until the child indicates that it is the examiner's turn. The child has to inhibit the desire to continue building and wait for the examiner first. Another measure used was the Simon Says Game, which requires the child to follow directions, but only when preceded by the words "Simon says" (Kochanska et al., 1997). Lowering vocal volume was measured by whisper,

which required the child to whisper the names of well-known cartoon characters on flashcards.

Effortful attention was measured using the shapes task, which required the child to point to a

smaller, less salient picture imbedded within a larger, more salient picture. Generally,

Kochanska's lab-based composite of effortful control demonstrated longitudinal stability,

reliability, and convergent validity with parent ratings (Goldsmith & Gagne, 2012).

In addition to laboratory-based behavioral tasks used with children, Goldsmith and Gagne

(2012) listed several computer-based tasks that measure the attentional and impulsive aspects of

temperament. However, upon further examination, these tasks were really intended to measure

executive function, not temperament. The tasks cited by Goldsmith and Gagne included the

continuous performance task (CPT), the Attention Network Task (ANT), the stop-signal task,

and the go/no-go tasks. The studies cited for the CPT (Dougherty, Marsh, & Mathias, 2002) and

the ANT (Fan, McCandliss, Sommer, Raz, & Posner, 2002) focus on these measures as assessing

attention and impulsivity in the context of executive function, not temperament. The study cited

by Goldsmith and Gagne for the stop-signal task does correlate with a personality measure of

impulsivity, which interestingly is part of the Extraversion factor on Eysenck's personality

measure (Logan, Schacher, & Tannock, 1997), but generally in the literature this measure is used

as a measure of executive function, not temperament. For the go/no-go task, Barkley (1991)

used this as a part of a battery designed to examine attention, impulsivity, and hyperactivity in

children with ADHD. Although the go/no-go task is frequently used as a measure of inhibitory

control, it is generally used as a measure of executive function, not temperament. Goldsmith and

Gagne argue that Inhibitory Control should be considered both a personality/temperament trait

and an executive function, thus making these executive function measures relevant to the

measurement of temperament. For my purposes, these computer-based "temperament" tasks, as

they are relevant to inhibitory control, are discussed in more detail in the section on measurement

of executive function where they are most commonly used.

In conclusion, lab-based behavioral measures of inhibitory control have been used to

examine temperament in infants through early grade school children. However, no lab-based

measures of inhibitory control in personality or temperament are available for older children or

adults, with the exception of the computer-based tasks which are really designed as measures of

executive function, not temperament or personality per se. Parent-report and self-report remain

the preferred methods of measuring inhibitory control in temperament and personality

(Goldsmith & Gagne, 2012).

Development of Inhibitory Control in Temperament/Personality

In general, both temperament and personality are thought to remain relatively stable over

time overall (McCrae et al., 2000); however, the different temperament and personality traits

demonstrate varying degrees of stability across development. The higher order factor of interest

in this study, Effortful Control, is thought to emerge in infancy, with some aspects of

conscientiousness (orderliness, dependability, and striving for high standards) not developing

fully until the preschool period. Effortful control is thought to be stable starting in the preschool

years through middle childhood (Shiner & Caspi, 2012). In order to address the changing

expression of Effortful Control over the course of infancy and childhood, Rothbart has developed

measures of Effortful Control specific to different periods of development. The infant version

includes Low-intensity Pleasure, Duration of Orienting, Cuddliness, and Soothability, whereas

the adult version includes Attentional Control, Inhibitory Control, and Activation Control. More

specifically, Inhibitory Control is first included in the Early Childhood Behavior Questionnaire

(ECBQ), which measures Effortful Control in children 18-36 months of age. This suggests that

inhibitory control is either not measureable or not present as part of effortful control in children below this age. All of Rothbart's measures of Effortful Control from age 18 months through adulthood include Inhibitory Control (Rueda, 2012). In comparison with the other two temperament personality factors (Surgency and Negative Emotionality), Effortful Control is slightly less stable in the early years, demonstrating stability from infancy to toddlerhood and from toddlerhood to preschool-aged, but not from infancy to preschool-aged (Putnam, Rothbart, & Gartstein, 2008).

Biological Mechanisms Underlying Inhibitory Control in Temperament/Personality

A variety of theories and empirical evidence support a link between biological mechanisms, social experiences, and the development of temperament/personality. Several theorists have proposed that temperament and personality have similar underlying biological mechanisms (Ahadi & Rothbart, 1994; Shiner & Caspi, 2012; Tellegen, 1985). One theory of these possible underlying biological mechanisms has grown out of Gray's Behavioral Activation System (BAS) and Behavioral Inhibition System (BIS) (Rothbart, Ahadi, & Evans, 2000). In this theory, the BAS is the reward or approach system that underlies the temperament/personality factor of surgency/extraversion and is responsible for individual differences in response to reward. The BIS system is related to passive avoidance, fear, and sensitivity to punishment. This system is thought to underlie the temperament/personality factor of Negative emotionality/neuroticism. Although in name the Behavioral *Inhibition* System would appear to be relevant to inhibitory control or effortful control, it is related not to inhibitory control but rather to inhibition to novelty, which as discussed previously, is motivated out of fear or shyness.

Derryberry and Rothbart (1997) developed this theory of the underlying mechanisms of temperament/personality even further, both in order to provide an explanation of the effortful

control/conscientiousness/constraint factor and in order to incorporate the expanding field of neuropsychology (Mervielde & De Pauw, 2012). Derryberry and Rothbart described Gray's BAS and BIS as being just a portion of the underlying biological mechanisms involved in temperament. The BIS and BAS are just two of four motivational systems, which work in conjunction with three attentional systems. The third motivational system is the aggressive behavior system that is connected to Gray's fight/flight system. The fourth motivational system is an affiliative system which serves the need for nurturing. The four motivational systems are related to the emotional or reactive temperament constructs of surgency and negative emotionality. The three attentional systems are the vigilance system which is related to alertness, the posterior attentional system which helps with attentional shift, and the anterior attentional system which is thought to underlie Effortful Control which then regulates the other systems (Derryberry & Rothbart, 1997; Mervielde & De Pauw, 2012; Rothbart, Ahadi, & Evans, 2000). According to Rothbart (2012), these biological mechanisms of temperament interact in a bidirectional manner with cognitions and one's social environment.

Recent studies have provided specific evidence of this link between personality/temperament and neurobiological and neurochemical mechanisms. The reactivity part of temperament (Surgency and Negative Emotionality) has been connected with the arousability of the limbic system (particularly the amygdala), striatum functioning, dopaminergic functioning of the ventral tegmental area which projects to the striatum, heart rate, levels of cortisol and norepinephrine, variability in right frontal EEG activations, and changes in right frontal ERP response (White, Lamm, Helfinstein, & Fox, 2012). My focus is on the regulation part of temperament, which has its own neurobiology and neurochemistry. In general, temperamental regulation is strongly connected with the anterior cingulate cortex and the lateral

prefrontal cortex (Luna, Padmanabhan, & O'Hearn, 2010; Fan & Posner, 2004; Posner & Rothbart, 2009; White et al., 2012); however, much of the understanding of these underlying neurological processes is based on research on executive function and not on temperament per se.

White et al. (2012) described several functional imaging studies as support of the underlying mechanisms involved in the regulation/effortful control portion of temperament; however, these studies are all based on inhibitory control rooted in cognitive neuroscience and executive function, not rooted in temperament. These findings do not directly link temperament traits with neural mechanisms. Instead, these findings link brain mechanisms and temperament traits through the assumed connections between temperament and executive function. The neural mechanisms involved in inhibitory control in the neuropsychological literature are discussed in greater detail in the executive function section of this paper. The following is a summary of the particular mechanisms that White et al. highlighted as playing a role in the regulative portion of temperament. The anterior cingulate cortex (ACC) is thought to monitor attention, emotion, and behavior based mostly on adult studies demonstrating higher activation when regulating stronger emotional experiences (White et al., 2012), and similar processes are suggested for children as well (Rubia et al., 2009). The lateral prefrontal cortex (PFC) is thought to be involved in the actual modulation of attention, emotion, and behavior (White et al., 2012). More specifically, during cognitive control or inhibitory control tasks, adults and children showed activation in the bilateral ventrolateral and bilateral dorsolateral regions of prefrontal cortex as well as the anterior and posterior cingulate cortex.

Evidence of the maturation of the ability to self-regulate behavior and emotions across development suggests that temperamental regulation and the underlying brain networks are

28

maturing up through middle childhood and even adolescence (White et al., 2012). In comparing

children and adults, Bunge, Dudokovic, Thomason, Vaidya, and Gabrieli (2002) found that

children (ages 8-12) showed significantly less activation in many of these areas than adults and

showed very little activation in the right ventrolateral prefrontal cortex. However, the go/no-go

task used in this study had an even ratio of go to no-go trials, which may change the nature of the

task. Go/no-go tasks measure inhibitory control when there are more go trials than no-go trials

creating a prepotent tendency to respond to trials. When the number of go and no-go trials is

even, there is no prepotent response to inhibit, and the task may measure decision accuracy, as

opposed to inhibitory control accuracy. The ventrolateral PFC appears to modulate emotion by

connecting back to the emotional reactivity systems in the brain, such as the limbic system and

amygdala (White et al., 2012). Neuroimaging studies implicate the importance of the

connectivity between the reactive (surgency and negative emotionality) and the regulative

(effortful control) neural systems in controlling emotional reactivity (Smith et al., 2012).

Because the two systems mature at different rates, the connectivity between them also varies

through development (Smith et al., 2012).

Based upon their review, White et al. concluded that functional neuroimaging studies

indicate that the ventrolateral PFC, dorsolateral PFC, and cingulate play a part in the inhibitory

control portion of temperament. Zhang (2010) made similar conclusions, describing two systems

of temperament: one is regulative (analogous to effortful control) including the DLFPC, OFC,

and ACC, and the other is an evaluative, including amygdala, hippocampus, insula, superior

temporal sulcus, ventral tegmental area (VTA), and nucleus accumbens. However, these studies

did not directly correlate temperament with brain functionality, perhaps because the preferred

method of measuring effortful control in temperament is not lab-based and, therefore, does not

lend itself well to most functional imaging studies, which measure brain activity during a task, not responses to a questionnaire.

A few structural imaging studies have examined connections between specific cortical volumes and questionnaires measuring effortful control in temperament. In a sample of 11- to 13-year-old children, Whittle (2008) found that higher effortful control was correlated with larger volume of the left orbital frontal cortex and that exploratory analyses showed a link between effortful control and larger volume of the left hippocampus. Vijayakumar, Whittle, Dennison, Yucel, Simmons, and Allen (2013) studied the connection among effortful control, psychopathology, and the prefrontal cortex in adolescents. Between the ages of 12 and 16, the adolescents' prefrontal cortices (anterior cingulate cortex, dorsolateral prefrontal cortex, and ventrolateral cortex) showed cortical thinning during this time of development. Also during this time in development, overall levels of effortful control tended to decrease, perhaps in connection with the increasing independence of adolescents who may exhibit less effortful control as part of this maturation process, which involves less rule following and more risk taking in connection with individuation from parental control (Kloep, Guney, Cok, & Simsek, 2009). In terms of the connection between effortful control and cortical thickness, greater reduction in effortful control during this period of development was associated with less thinning of the left anterior cingulate. These changes in effortful control mediated the relationship between anterior cingulate thinning and psychopathology. In addition to these studies which connect brain volumes with measures of the superordinate effortful control factor, Schilling et al. (2011) found that the lower order trait of impulsiveness, which includes inhibitory control, in adolescents was inversely associated with volume in the left orbital frontal cortex, which is consistent with previous studies linking OFC to inhibitory control.

In summary, an anterior attentional system is thought to underlie effortful control in temperament. The specific brain structures implicated in inhibitory control are the anterior cingulate cortex, dorsolateral and ventrolateral prefrontal cortex, and the orbitofrontal cortex. Specific to the 8- to 12-year-old age group, children tend to show activation in these same areas, but they show less activation than adults in these areas, especially in the right ventrolateral prefrontal cortex. In the early adolescents (12-year-olds), evidence indicates a normal period of cortical thinning in these areas and an accompanying reduction in effortful control. Because of these age-related differences, controlling for age and/or watching for nonlinear relationships between age and cortical volumes will be important in studying this age group. Despite the emphasis on underlying mechanisms in the definitions and theories of temperament, relatively few studies have directly linked neural structures and functions with inhibitory control in temperament or personality specifically.

Genetic and Neurochemical Contributions to Inhibitory Control as a Temperament/Personality Trait

Another key assumption in the definition of temperament is that it is genetically based. Research in this field does support the assumption that temperament and personality have an underlying genetic and biological basis. At a broad level, temperament is considered heritable, with estimated heritability ranging from 35% to 50% for extraversion (Braungart, Plomin, DeFries, & Fulker, 1992; Keller, Coventry, Heath, & Martin, 2005), around 50% for negative emotionality/neuroticism (Keller et al., 2005), and 49% to 79% for parent-rated effortful control (Lemery-Chalfant, Doelger, & Goldsmith, 2008; Yamagata, et al., 2005). Generally, effortful control has been related genetically to the dopamine and serotonin systems (Nederhof et al., 2010; Sheese, Rothbart, Voelker, & Posner, 2012; Smith, et al., 2012).

Looking more specifically at the genetic research of inhibitory control, a study of 24-month-old twins found that parent-rated inhibitory control was 58% heritable and lab-measured inhibitory control was 38% heritable (Gagne & Saudino, 2010). The relationship between the lab-measured and parent-rated inhibitory control was largely explained by common genetic factors. In another study, parent-rated inhibitory control demonstrated a genetic basis, whereas lab-based measures of inhibitory control did not demonstrate a genetic basis (Gagne & Goldsmith, 2011). It is possible that the lack of heritability for the lab-based inhibitory control is due to measurement issues, differences in the constructs measured, or the more global nature of parent-ratings as opposed to a specific lab-based task. In a study of Japanese adult twins (ages 17-32 years old), Effortful Control was 49% heritable; however, when broken into its subscales, Inhibitory Control had the lowest heritability (32%) compared to the other subscales, Attentional Control (45%) and Activation Control (39%) (Yamagata et al., 2005).

In adults, all five personality factors have heritability estimates between 40% and 60% across studies (Caspi, Roberts, & Shiner, 2005). In line with the genetic studies of temperament, dopamine and dopaminergic genes have been implicated in the regulative processes of personality (Posner, Rothbart, Sheese, & Voelker, 2007; Smith et al., 2012; White et al., 2012). The gradual development of these regulative processes is parallel with dopaminergic activity reaching maturity in late adolescence as well (Smith et al., 2012). Genes related to serotonin are also thought to play a part in emotional regulation (Nederhof, 2010; Smith et al., 2012). These findings implicating the involvement of dopamine, which is active in the prefrontal cortex (Kolb & Wishaw, 2009), and serotonin, which is active in both the prefrontal and cingulate cortices (Kolb & Wishaw, 2009), in personality's conscientiousness are consistent with the research linking the prefrontal cortex and cingulate cortex with inhibitory control in temperament.

Psychopathology and Inhibitory Control as a Temperament/Personality Trait

In general terms, effortful control/conscientiousness/constraint has been associated with many adaptive behaviors as well as many different forms of both internalizing and externalizing psychopathology. In terms of adaptive behavior, effortful control has been connected with social competence, theory of mind, empathy, compliance, and conscience development (Rothbart, Sheese, & Posner, 2007). The impulse control/inhibitory control aspect of conscientiousness has been linked with several maladaptive behaviors including avoiding work, impulsivity, antisocial behavior, laziness, lack of punctuality, and lack of attention to self-appearance (Jackson et al., 2010).

In addition to evidence linking effortful control/conscientiousness to various behavioral outcomes, effortful control also has been associated with both internalizing and externalizing forms of psychopathology (Runions & Keating, 2010; Vijayakumar et al., 2013). For example, Rudolph, Troop-Gordon, and Llewellyn (2013) found that parent-rated, temperament-based inhibitory control problems in third graders predicted both aggression and depressive symptoms one year later. Parent-reported effortful control was the strongest predictor of unintentional self-injury in 6-year-old children (Schwebel, 2004). In addition to internalizing and externalizing disorders, personality disorders also are associated with conscientiousness/effortful control. More specifically, problems with behavioral self-regulation and emotional-regulation have been shown to mediate the development of borderline personality symptoms in children (Gratz, et al., 2009). Poor effortful control and attention have been associated with borderline personality disorder in adults as well (Posner, et al., 2002). In young adults, effortful control was modestly related to measures of personality dysfunction, such as aggression, manipulativeness, and entitlement (Hallquist, 2010).

As noted, problems in inhibitory control or effortful control have been associated with internalizing, externalizing, and personality disorders, but the form of psychopathology that is most commonly associated with inhibitory control/effortful control is attention deficit/hyperactivity disorder (ADHD). When examining ADHD, children with ADHD demonstrate higher temperamental levels of anger and activity and lower levels of attentional shift, attentional control, and inhibitory control than controls (Auerbach et al., 2008). Foley, McClowry, and Castellanos (2008) found that children with ADHD had lower inhibitory control, task persistence, and attentional focusing and higher impulsivity, negative reactivity, and activity level. Interestingly, when children with ADHD rated themselves, they actually indicated elevated levels of conscientiousness, suggesting that children with ADHD are not aware of their difficulties in this area and actually overestimate their abilities instead (Bouvard, Sigel, & Laurent, 2012). The ADHD symptom of inattention has been associated with low conscientiousness from the Big 5 in adults as well (Avisar & Shalev, 2011). The comorbidity of ADHD and conduct disorder is associated with low constraint as well as with high negative emotionality in children and adolescents (Cukrowicz, Taylor, Schatschneider, & Iacono, 2006). Clearly, many studies indicate that children with ADHD have problems in conscientiousness/effortful control or, more specifically, inhibitory control. In fact, a few of the possible impulsive symptoms listed in the diagnostic criteria for ADHD are nearly identical to items on Rothbart's measures of inhibitory control (American Psychiatric Association, 2013; Rothbart, 2012). For example, an item on the Rothbart inhibitory control measure is "has a hard time waiting his/her turn to talk when excited." The similar diagnostic symptom is "often interrupts or intrudes on others...butts into conversations." Another example is "has difficulty

waiting in line for something" (Rothbart) and "often has difficulty waiting his or her turn (e.g., while waiting in line)" (APA).

Beyond these face valid similarities between inhibitory control and ADHD symptomology, Nigg, Goldsmith, and Sachek (2004) developed a theory of ADHD incorporating research in child temperament and adult personality traits. Their model posits that problems in effortful control and executive functioning are at the core of ADHD, with problems of negative emotionality being more related to the comorbidity between ADHD and conduct problems. They also describe two different pathways to the development of ADHD-Combined Type (ADHD-C), which includes symptoms of both inattention and hyperactivity/impulsivity. The first pathway is marked by extreme positive approach and leads to ADHD-C with no comorbidity. The second pathway is more governed by weak regulatory control, similar to inhibitory control, and is associated with ADHD-C with comorbidities, such as different types of conduct problems and anxiety problems. This conceptualization of ADHD is consistent with the previously discussed nature of impulsivity, which is a key feature of ADHD-C. Impulsivity includes both a thrill-seeking component, analogous to the extreme positive approach in the first pathway, and an inhibitory control component, analogous to the weak regulatory control associated with the second pathway. The impulsive behavior in ADHD-C may develop out of either or both of these weaknesses. This model offers a possible explanation of how behavioral disinhibition (extreme approach) and poor inhibitory control (weakness in inhibiting inappropriate behavior) may each contribute to the development of impulsive symptoms in ADHD.

Inhibitory Control as an Executive Function in the Neuropsychological Literature

Executive Function: Definition and Structure

Executive function as a broad concept is hard to define (Miyake & Friedman, 2012). Conceptualization of executive function developed out of both the clinical literature based on brain damage to the prefrontal cortex (PFC) and the cognitive literature based on effortful goal-directed processes as opposed to more automatic cognitive processes (Hughes, Ensor, Wilson, & Graham, 2010). Roth, Randolph, Koven, and Isquith (2006) define executive functions as a "set of interrelated cognitive processes that are essential for regulation of cognition, behavior, and emotion" (p. 2). Given this definition of executive function and its emphasis on regulation, it is not surprising that inhibitory control has been viewed as the core of executive function (Miyake & Friedman, 2012; Roth et al., 2006). The definition of inhibitory control as an executive function has two major components. The first is that inhibitory control is effortful or voluntary, and the second is that it involves the suppression of a prepotent response in favor of a goal-directed response (Greene, Braet, Johnson, & Bellgrove, 2007; Ordaz, Foran, Velanova, & Luna, 2013). Hughes et al. (2010) would add to this definition that executive function is inextricably linked to the prefrontal cortex. The executive function of inhibitory control, which is also sometimes referred to as response inhibition in the literature (Greene et al., 2007), has been studied extensively in the neuropsychology literature. My review of this literature will describe theories of executive function as they relate to inhibitory control, various methods used to measure inhibitory control, the developmental course of inhibitory control, the underlying mechanisms of inhibitory control, the current genetic and neurochemical understanding of inhibitory control, and the links between inhibitory control and various forms of psychopathology.

In contrast to the personality/temperament literature which includes a balance of models that are theoretically-driven and empirically-driven, the neuropsychological literature tends to be more empirically focused. Two types of theories have been used to explain executive function (EF): representational models which conceptualize EF in terms of representations that people can hold in mind and componential models which state that EF is comprised of several different types of cognitive functions. Within these componential models, there are unified and diverse models which either suggest that EF is a single unified EF factor that controls the cognitive factors (Bodnar, Prahme, Cutting, Denckla, & Mahone, 2007) or that EF is made up of several separate but related cognitive processes (Jacques & Marcovitch, 2010). Some studies have derived higher order executive function factors, but there is less consensus concerning what these factors are due to the variety of EF measures included in each study, the definitions of EF used, and the relative newness of this area of research.

Miyake and Friedman (2012), based on their own research, presented a theory of executive function, which by their own admission is not comprehensive. They present three latent variables (higher order factors) of EF: updating, shifting, and inhibition. In examining these three executive functions, they make four conclusions. Updating is related to working memory and refers to the ability to monitor and update representations held in working memory. Shifting refers to the ability to switch between tasks, rules, or mental sets (Miyake & Friedman, 2012). Inhibition refers to inhibitory control, the ability to inhibit prepotent responses when necessary. First, these EF's show both unity and diversity, meaning that they are closely related but separable constructs. The unity is thought to be a result of common underlying biological and cognitive mechanisms, and it is more evident in younger children for whom executive function seems to be a single factor which separates into subfactors as children mature (Hughes

et al., 2010). The factor structure of executive function will be discussed in greater detail below.

The second conclusion about executive function made by Miyake and Friedman (2012) was that

executive function at the latent variable/factor level is highly heritable, with heritability estimates

over .75. Additional evidence of heritability of executive function and inhibitory control more

specifically will be presented later. The third conclusion is that executive function is related to

clinically relevant adaptive behavior and psychopathology. The fourth and final conclusion is

that executive function remains relatively stable over time. For example, children who have

difficulty inhibiting responses as toddlers are likely to have that same difficulty at age three and

at age seventeen (Miyake & Friedman, 2012).

Several studies have provided support for three EF factors demonstrating both unity and

diversity. McAuley and White (2011) studied a three-factor model of executive function, but the

components were slightly different (inhibition, working memory, and processing speed). They

found that these components were separate constructs in a group of 6-year-old to 24-year-old

individuals. However, the separate constructs were more distinct in the older children and young

adults than in the younger children. In older children and adults, a three-factor model (updating,

shifting, and inhibition) described executive function fairly well with significant correlations

amongst these factors (Jacques & Markovitch, 2010). Miyake and Friedman proposed an

improvement to this model that takes into consideration the unifying factors among these three

factors of executive function. A superfactor of executive function explains a large portion of the

variability in all of the updating, shifting, and inhibition tasks. The updating and shifting factors

remain in the model to explain some of the additional shared variance in these tasks that is not

explained by the superfactor of executive function; however, once this superfactor is inserted

into the model, the common variability in the inhibition tasks is completely explained. A

separate inhibition factor is no longer needed. This is consistent with other literature which cites inhibition as the "core" of executive function (Miyake & Friedman, 2012; Roth et al., 2006). Friedman et al. (2006) studied the factor structure of executive function in adolescents and found the same three factors (inhibition, shifting, and updating) were separate and moderately correlated. The fact that updating, but not shifting and inhibition, strongly predicted intelligence in this study provided further evidence that these are separate constructs, not a single factor, in this age group. This multi-component nature of EF is supported by neural evidence of various frontal and posterior cortical networks involved in these functions (Wiebe et al., 2014a). The neural involvement in inhibitory control, more specifically, is described in greater detail below.

In contrast to the work of Jacques and Markovitch (2010) and Friedman et al. (2006), some studies do indicate that a single factor of executive function is a better conceptualization than these separate factors. For example, Wiebe, Espy, and Charak (2008) conducted the first confirmatory factor analysis study of EF in preschoolers and found that tasks measuring various executive skills, like working memory and inhibitory control, were best conceptualized as a single cognitive ability in preschool children. This finding held regardless of socioeconomic status or sex. In another study, Bodnar et al. (2007) found that a frequently used a questionnaire measure of executive function, the BRIEF which will be discussed in greater detail later, had all 8 scales loading on a single factor of EF in children 6- to 18-years-old. This study pointed to the unity of executive function, whereas other studies of the same measure have found three separate factors, pointing again to the diversity of executive function (Gioia, Isquith, Retzlaff, & Espy, 2002). The degree of diversity is likely related to the variability in measures used across studies and to developmental differences. Most studies of children under the age of 6 seem to indicate a

single factor of executive function, whereas most studies of older children and adults seem to indicate multiple factors describe executive function better.

Wiebe et al. (2014b) outlined several challenges to developing a unified theory of the development of executive function. First, each component of EF must be understood within the context of development. Second, these processes must be understood in terms of how they relate to changes in other processes over time. Third, theories must describe the relationship between neural and behavioral systems. Fourth, theories of EF should integrate how these separate processes relate to one another in the moment, across learning, and across development. Finally, theories of EF must address how this system of executive control can change itself over time. Most theories of the development of executive function only address one or two of these challenges (Wiebe et al., 2014a). The theories that integrate both behavioral and neural systems provide some of the most promising understandings of executive function (Wiebe et al., 2014a). Unfortunately, the more integrative and comprehensive models of executive function are generally based on the systems involved in a single executive task.

Another way of conceptualizing executive function divides executive function, not by the specific neurocognitive processes involved with a task (inhibition, working memory, etc.), but by whether these processes are functioning in emotionally charged contexts, "hot EF," or emotionally neutral contexts, "cool EF" (Zelazo & Carlson, 2012). Traditionally, cognition and emotion have been studied as completely separate entities, but this model suggests that these are dimensions of the same thing, "the human psychological experience" (Zelazo, Qu, & Kesek, 2010, p. 99). Implications for how this integration of emotional and neurocognitive functioning may influence our understanding of the relationship between executive function and personality/temperament, which generally is thought to include trait affect, will be discussed

40

later. This distinction between hot and cool EF has demonstrated utility in explaining

differences in behavioral response and has suggested that different neural networks are involved

to different degrees in hot EF versus cool EF. Especially in younger children, a "hot" context

can interfere with children's ability to complete EF tasks (Zelazo et al., 2010). Other research

has demonstrated that positive stimuli may increase dopamine levels and improve performance

on EF tasks when the approach-avoidance response is less salient (Zelazo et al., 2010).

According to this theory, EF begins with an emotional response processed in the thalamus and

amygdala. This information is then sent to the orbitofrontal cortex (OFC), which is involved in

simple approach-avoidance decision making. If this level of processing is not sufficient, the

anterior cingulate cortex (ACC) then monitors performance and determines if there is a need for

higher processing. This higher processing occurs in the lateral prefrontal cortex, including the

OFC, ventrolateral PFC, dorsolateral PFC, and the rostrolateral PFC (which helps with task

selection). Different levels of task complexity determine how many of these areas, and which

areas, are involved in the decision making process. Since hot and cool EF are considered to be

on a continuum, the degree to which the amygdala, thalamus, and OFC are involved in the

decision making process varies by the emotional context of the task. Interestingly, inhibitory

control, which would be more closely related to cool EF, and emotional regulation, which would

be more closely related to hot EF, are highly correlated in preschool-aged children (Carlson &

Wang, 2007), perhaps indicating either that these networks work very closely together in

younger children or that they begin as a unified system and develop separate networks over the

course of development.

Although no one theory has been generally accepted as the dominant theory of executive

function, several conclusions can be made based on the theories described here. First, the

different aspects of executive function are unified but separate, with inhibitory control as the

core of executive function. Second, a comprehensive theory of executive function should be

capable of explaining performance on multiple tasks of EF. Third, the different aspects of EF

must have evidence of underlying neural mechanisms. Fourth, the emotional or motivational

context of executive function tasks should be considered since these "hot" or "cool" contexts

may involve different neural mechanisms. Finally, the developmental context also must be

considered since EF appears to be more unified in younger children and more separable in adults.

In light of these conclusions, I am conceptualizing EF as a three-factor construct (updating,

shifting, and inhibition) that must also be considered in the context of "hot" or "cool" contexts.

Measurement of Inhibitory Control as an Executive Function

Inhibitory control as an executive function can be measured by questionnaire measures or

behavioral lab-based measures. Although laboratory-based measures are most commonly used

to measure inhibitory control as an executive function, parent- and teacher-report questionnaires

have been used to measure executive function in daily life as rated by those who are with the

child on a daily basis. The most frequently used questionnaire of executive function is the

Behavior Rating Inventory of Executive Function (BRIEF; Gioia, Isquith, Guy, & Kenworthy,

2000). This measure was empirically constructed through the collaboration of four

neuropsychologists. Principal components analysis found eight subdomains of executive

function, and these eight subdomains comprise two domains. Inhibit, Shift, and Emotional

Control all are included within the Behavior Regulation Index (BRI), and Initiate, Working

Memory, Plan/Organize, Organization of Materials, and Monitor make up the Metacognition

Index (MI). Combining the BRI and MI creates the Global Executive Composite (GEC), which

is an overall measure of executive function. A later study (Gioia et al., 2002) used confirmatory

factor analysis to examine several different competing models of executive function using the

BRIEF. The model that fit the data best was a three-factor model of Behavioral Regulation

(Self-Monitor and Inhibit), Emotional Regulation (Shift and Emotional Control), and

Metacognition (Initiate, Working Memory, Plan/Organize, Organization of Materials, and Task-

Monitor). The Monitor scale from the original measure was divided into self-monitoring and

task-monitoring, with self-monitoring loading on Behavioral Regulation and task monitoring

loading on Metacognition. This model is consistent with Barkley's model of the executive

function deficits in ADHD (Gioia, et al., 2002). The reliability and validity of this measure will

be discussed in greater detail in the Methods section of this paper.

The primary method for measuring inhibitory control as an executive function is using

lab-based measures, most of which are computer tasks. These tasks require an individual to

inhibit a prepotent behavioral response and, in some cases, complete a different behavior instead.

The measure of inhibition is generally either the accuracy of being able to inhibit behavior when

needed or the extra time delay required to inhibit one behavior and select a different one. One of

the most simplistic tests of inhibitory control is the A-not-B task, which teaches the child the

habit of reaching toward one location, A, and then cues them to reach toward a new location, B

(Wiebe et al., 2014a). This task has been used to measure inhibition in infants as young as 10

months of age. Prior to 10 months, infants continue to reach to A and cannot inhibit this

prepotent response even when encouraged to reach to B.

The most common, and perhaps the most pure, measures of inhibition are known as

response inhibition tasks. One of the most common response inhibition tasks is the go/no-go

task, which has several variations using auditory or visual stimuli. Generally, the go/no-go task

asks individuals to respond to one type of stimulus but not to another type of stimulus. Some of

these go/no-go tasks are designed and commercially distributed to measure problems in attention and inhibition in children with suspected ADHD or attention problems more generally. Examples of these commercial go/no-go measures are the Connors Continuous Performance Test (CPT-II) and the Test of Variables of Attention (TOVA) (Bodnar et al., 2007). Other versions of the go/no-go task are used purely in research settings. The version used in this project is an auditory go/no-go task, which requires the child to respond to one tone but not to another tone. In order for a go/no-go task to measure inhibition, it must have set up a prepotent response, either through practice of go-trials first or through a higher percentage of go trials than no-go trials during the task. If the concept of the go trial is not taught or if the number of go and no-go trials is even, then the go/no-go task becomes a measure of decision making, rather than inhibitory control. The experimenter must set up a "prepotent" or dominant response to inhibit under the no-go trials (Wiebe et al., 2014a).

The stop-signal task is similar to the go/no-go task, but it is slightly more complicated (Huizinga, Dolan, & van der Molen, 2006; van Boxtel, van der Molen, & Jennings, 2005; van Boxtel, van der Molen, Jennings, & Brunia, 2001). In one version, a green arrow that points either right or left indicates that the individual should press the corresponding right or left button. On a portion of the trials, the arrow starts green but quickly becomes red. When it turns red, it indicates that the person should inhibit the prepotent response and not press any button. The timing of the arrow changing color is varied so that each individual correctly inhibits on about 50% of the color change trials and accidentally responds on about 50% of the color change trials. The reaction time, referred to as the stop-signal reaction time (SSRT), on the accidental responses to the stop signal is the measure of inhibition. Van Boxtel et al. (2001) found similar

physiological responses in young adults for both the no-go trials (using a red arrow) and the stop (color change) trials, indicating that they were likely measuring similar processes.

The Eriksen flankers task is similar to the stop-signal task described above in that either right or left facing arrows are presented, and the participant is asked to press the corresponding right or left buttons (Huizinga et al., 2006). However, this task is made more difficult with additional "flanker" arrows that are presented to the right and left of the target arrow. These arrows are congruent (facing the same way as the target arrow) in some trials and incongruent (facing the opposite way as the target arrow) in other trials. Inhibition on this task is measured by the response latencies on the incongruent versus the congruent trials. Similar to the distractors in the flankers task, distractors have been used in a negative priming task to measure inhibitory control. These negative priming tasks present visual distractors, which can be ignored but which either slow or reduce accuracy in performance on a subsequent task when the new stimulus is similar to the previously ignored stimulus (Pritchard & Neumann, 2009). The ability to inhibit the influence of the primed distractors is measured by the response reaction time for this task.

The traditional Stroop task (Stroop, 1935) requires individuals to name the ink colors of color words that are incongruent with the ink color (i.e., name the ink color green of the word "red" printed in green ink). Reading the word is the prepotent or automatic response that must be inhibited in order to give the color of the ink. Many similar Stroop tasks have since been created that work on the same basic concept of needing to inhibit a prepotent response in order to give a different one. The Stroop task used by Huizinga et al. (2006) had smiley faces of two different colors, each requiring a different response. In addition, the smileys were given two different orientations (normal and upside down), which each required a different response. In the

inhibition task, one color indicated one response, but only when the smiley was in one orientation. The other color indicated a different response, but only when the smiley was in the opposite orientation. Another variation on the Stroop task is the Simon task. In the Simon task participants are asked to press the button corresponding to the direction of an arrow (right or left) regardless of its location on the screen (which could also be on the right or on the left) (Jacques & Marcovitch, 2010). Another Stroop-like task is the Real Animal Size Task (RAST). This inhibitory control task requires children to decide which animal is larger in each condition. In the first condition, the child must decide which animal is larger in real life and which animal is larger on screen in the second condition. In the third and fourth conditions, the child must decide the real size of the animals with the on screen size either being congruent or incongruent with real size. This is similar to the Stroop test but made simpler as not to require reading skills (Catale & Meulemans, 2009).

Generally, executive function is difficult to measure (Miyake & Friedman, 2012), and weak correlations among these measures of inhibitory control may indicate several problems with these measures. Bodnar et al. (2007) found weak correlations between parent-report measures and computerized measures of inhibitory control, as measured by the BRIEF, CPT (Conners et al., 2000), and the TOVA (Leark, Greenberg, Kindschi, Dupuy, & Hughes, 2007). Even relationships among different lab-based measures of inhibitory control have been found to be weak. Huizinga et al. (2006) found that a factor analysis of three inhibitory control tasks (stop-signal, Eriksen flankers, and Stroop) did not load together as a single factor. Some of the reasons for this weak relationship among measures of inhibitory control are rater-bias, measurement modality differences, task impurity, multiple weaknesses contributing to the same scores, and developmental issues.

As with questionnaire measures of temperament and personality, questionnaire measures of executive function are susceptible to the same forms of rater-bias. The weak correlations between questionnaire and lab-based measures may be due to this rater bias or differences in measurement modality. Questionnaire measures are more global and indicate behavior in "real life," whereas laboratory-based behavioral measures are more specific and indicate behavior only in the laboratory setting. Of course, it is possible that the weak correlations are due to these measures capturing different aspects of inhibitory control, which would be better described as separate pieces than as a single process.

Another reason the lab-based measures of inhibitory control may not work well as a single factor is the "task-impurity" problem (Miyake & Friedman, 2012). The task-impurity problem is rooted in the idea that every executive function task involves multiple processes. For example, the go/no-go task, which is often considered the purest measure of inhibitory control, requires the individual to attend to the stimuli (attention control), to keep the rules of go or no-go in mind (working memory), to switch rules sets if the stimulus indicates a shift (shift or cognitive flexibility), to inhibit the prepotent response if appropriate (inhibitory control), and to monitor for errors in performance (error monitoring). Weaknesses in any of these areas may contribute to poor performance in this inhibitory control task. Without understanding why the person made the error, the experimenter cannot know if the individual had difficulty with inhibition or conflict-monitoring (Botvinick, Braver, Barch, Carter, & Cohen, 2001) or working memory (Marcovitch & Zelazo, 2009). One way to address this issue is to use latent variables so that the shared variance of similar tasks could help remove some of the variance due to other processes; however, Huizinga et al.'s (2006) finding that their cognitive measures of inhibitory control did not hold together to form a single latent variable indicates that this way of handling the issue

may not always be adequate. The overlap of underlying processes across tasks, along with the diversity of processes involved in a single task, may contribute to the varying degrees of unity and diversity found in executive function as a whole.

Another source of problems in measurement of inhibitory control in executive function is how the stage of development affects measurement. First, different tasks are used to measure inhibitory control in different age groups (Jacques & Marcovitch, 2010). The A not B task is often used with infants and toddlers, whereas go/no-go is the preferred method of measurement in older children and adults. These tasks vary in complexity and may or may not be measuring the same underlying construct. In addition, the same task given at different ages may measure different underlying processes. For example, a younger child may have difficulty understanding and holding the rules of the go/no-go task in memory, making errors in go/no-go task performance reflective of learning or working memory problems. In contrast, an older child or adult would have no difficulty with understanding or remembering the rules so that errors on this task are more likely to measure inhibitory control. Different strategies or capabilities may influence which process are used in performing a task as well.

Although every task of inhibitory control has its strengths and weaknesses, the go/no-go task is the most commonly used and can be considered the "purest" measure of inhibitory control in the executive function literature. This study used the go/no-go task along with the behavioral regulation scales from the BRIEF, which is the most commonly used executive function questionnaire. By using more than one measure of inhibitory control, I was able to reduce the impact of the weaknesses of these measures and to increase confidence that I am actually measuring the intended construct.

The Development of Inhibitory Control as an Executive Function

As various definitions and models of executive function emphasize the importance of cognitive self-regulation (Miyake & Friedman, 2012), inhibitory control may be critical to the development of executive function as a whole. In this section, first the development of executive function from a single factor in younger children to separate constructs in older children and adults is discussed. Second, the development of inhibitory control performance, as tested by different measures, is discussed. Third, brain development as it relates to the development of executive function and inhibitory control is discussed.

As described previously, several studies indicate that the three-factor structure of inhibitory control does not fully emerge until early grade school. Several explanations have been proposed for this developmental difference. One possible explanation for why EF presents as a single factor in younger children is that the EF tasks for younger children are limited by one aspect of executive function that is not fully developed yet (Zelazo et al., 2003). For example, one explanation is that a limited capacity for working memory in young children limits the child's ability to inhibit behaviors or switch tasks since the child must be able to hold the "rules" for these other EF tasks in mind in order to complete them. However, research has demonstrated that working memory demands only partially explain children's performance on executive function tasks (Zelazo et al., 2003). Another limiting factor could be inhibitory control (Zelazo et al., 2003), which would fit with Miyake and Friedman's model (2012), which places inhibitory control hierarchically above the other aspects of executive function. Even though this theory explains some of the variability in children's executive function performance, it does not explain the variability in preschoolers' ability to complete different types of inhibitory tasks or the decision making necessary prior to inhibiting behaviors in these tasks (Zelazo et al., 2003).

Another explanation, the inability to see objects in different ways, also does not explain executive function in preschoolers well since they are able to make these different descriptions even though switching is difficult (Zelazo et al., 2003). These various findings suggest that there may be multiple limiting factors in preschoolers or that the simplified measures of EF used with younger children are not sensitive enough to demonstrate the diversity of executive function in this age group.

In addition to developmental differences in the structure of executive function, children's performance on specific inhibitory control measures changes over the course of development. The earliest, simplest form of inhibitory control can be measured as early as 10-12 months of age using the A-not-B task (Wiebe et al., 2014a). Before 10 months, infants cannot inhibit the tendency to reach for A and continue to reach for A even when cued to reach for the new location B. By three years, most children are able to complete more complex inhibitory control tasks, which are slightly simplified versions of the adult inhibitory control tasks. These tasks, including a child version of the go-no-go, Stroop, Simon, and flanker tasks, elicit a response from the child that is either compatible or incompatible with the task demands. The ability to inhibit the compatible (or prepotent) response and complete the incompatible response instead is present at age 3 and continues to improve through age 5. In contrast, the other aspects of executive function demonstrate different developmental trajectories (Wiebe et al., 2014a). Working memory capacity (controlling for chunking, rehearsal, and other strategies) is 1-2 items up through age 3 years and increases to 3 items by 5 years and 4-5 items by ten years. Another executive function, cognitive shift or task switching, does not emerge until 2 years of age. The ability to shift rule sets is present beginning at about 3 years of age although it is not seen consistently until 5 years of age.

Although all three aspects of executive function demonstrate different developmental trajectories, all three demonstrate significant development during the 3-5 year old time period. The complexity of how the development of these three aspects of EF are related is not well understood, and how these trajectories relate to executive function as a single cognitive ability in this 3-5 year old period of development is not known. Even though factor analytic studies of EF in younger children support the unity of executive function early in development, the separate developmental trajectories provide evidence that these functions should be considered separately even in young children.

After this early period of rapid development in executive function, changes in EF performance are mostly due to improvements in efficiency, not in whether or not the child is able to complete the task (Jacques & Marcovitch, 2010). Overall, EF in infants, toddlers, and preschoolers tends to be measured in terms of accuracy, addressing how often the child is able to do the task correctly, but by school-age most typically developing children are able to do most EF tests accurately most of the time, making efficiency (often response time), rather than simple accuracy, the preferred measure of performance. This suggests that the basic mechanisms necessary to complete most EF tasks are developed by the time the child reaches grade school, but that their performance continues to become more efficient over time (Jacques & Marcovitch, 2010). This continuing development may be due to improvements in the efficiency of brain mechanisms themselves (through increased connectivity and/or pruning of inefficient networks) or may be due to improvements in strategy, which may then involve different brain mechanisms. These improvements in efficiency also may be related to other mechanisms such as improved processing speed or better sustained attention. The change in measurement from accuracy to

efficiency can make studying a single component of EF over development difficult since the way in which it is measured may change across age ranges.

The studies that have looked specifically at the development of inhibitory control within executive function have suggested that the maturation of inhibitory control may vary by task, possibly based on task complexity. Studies of go/no-go task performance demonstrated improvements in both accuracy and reaction time from 5 to 7 years old (Torpey, Hajcak, Kim, Kujawa, & Klein, 2012) and from 18 to 19 years old (Eigsti et al., 2006). Huizinga et al., examined performance on three tasks of inhibition in four different age groups (7, 11, 15, and 21 years old). On the stop-signal task there was more variability in response time in the 7-year-olds than the 11-year-olds, and there was more variability in the 11-year-olds than the 15-year-olds. There was no difference between the 15- and 21-year-olds. Similar results were found on the Eriksen flankers task, with continued improvements in performance with age until age 15, but no difference between the 15- and 21-year-old groups. For the Stroop task, development of inhibition did not stop at 15 years old but continued until 21 years old, with higher reaction times in the interference trials for 7-year-olds than 11-year-olds, for 11-year-olds than 15-year-olds, and for 15-year-olds than 21-year-olds. Although all of the measures in the Huizinga et al. study are somewhat dependent on reaction time (processing speed), information processing speed is not likely to have a large impact on overall performance since both the flankers and Stroop tasks measure reaction time differences between congruent and incongruent trials. Overall, these results seem to suggest that maturation from childhood through young adulthood yields improvements in performance on inhibition tasks with reduced performance in older adults (Jacques & Marcovitch, 2010).

In contrast to the above findings that indicate continued improvement in both accuracy and reaction time on inhibitory control trials through adolescence or even young adulthood, several studies have suggested that improvements in inhibitory control after the age of 5 are largely due to maturational improvements in other skills like sustained attention or processing speed. Pritchard and Neumann (2009) found that inhibitory control, as measured by performance in a negative priming task, remained consistent from age 5 through 25 years of age after controlling for processing speed. They suggested that IC itself remains stable after early childhood but that improvements in other skills, such as general processing speed, can contribute to continuing improved performance on inhibitory control tasks over the course of development through adolescence or adulthood (Pritchard and Neumann, 2009). Catale and Meulemans (2009) looked at inhibitory control, as measured by the real animal size test, in 6- and 9-year-old children. They found that reaction time improved with age; however, there was no age effect for the difference between congruent and incongruent items. This is consistent with the idea that inhibitory control is fully formed in early childhood but that inhibitory control performance continues to improve with age because of the development and improvement of information processing speed with age. Reck and Hund (2011) demonstrated sustained attention, as measured by parent-report and by laboratory measures, and age predicted inhibitory control performance in 3- to 6-year-old children. Although some of the improvement in performance between ages 3 and 6 may have been due to development of inhibitory control, other processes, such as attention, may largely explain these improvements.

During this same time period of development of executive function, the brain, especially the prefrontal cortex and connections to it, demonstrates rapid development (Blair, Zelazo, & Greenberg, 2005). As these abilities continue to improve and develop into the adolescent years,

developmental changes in the brain mirror these behavioral changes. For example, increased connectivity between the frontal and parietal areas, along with decreased connectivity within the parietal area, mirrors improvement in executive function in a study of development in 8- to 27-year-olds (Hwang, Velanova, & Luna, 2010). Changes in cortical volume and neural activation, as demonstrated in imaging studies, also are closely associated with the development of executive function as measured behaviorally.

Over the course of development, different cortical areas have been associated with inhibitory control, working memory, and cognitive shift. Research has demonstrated that the lateral prefrontal cortex is one of the slowest developing brain regions and that impairment in this area produces executive function performance, including inhibitory control specifically, that mimics the performance of younger children (Wiebe et al., 2014a). These cortical areas as they relate to inhibitory control are discussed in detail in the next section in terms of the underlying neural mechanisms of inhibitory control (Klimkeit, Mattingley, Sheppard, Farrow, & Bradshaw, 2004; Ordaz et al., 2013; Wiebe et al., 2014a).

Biological Mechanisms Underlying Inhibitory Control as an Executive Function

Generally, functional magnetic resonance imaging (fMRI), functional Near-Infrared Spectroscopy (fNIRS), and Evoked Response Potential (ERP) have shown activation of the prefrontal cortex during inhibitory control tasks in studies of executive function. In examining the underlying neural mechanisms of executive function, fMRI is most commonly used in older children, adolescents, and adults; however, this form of imaging is difficult to use in infants and younger children because it is very sensitive to movement. Another form of imaging, fNIRS is sometimes used with younger children since it is less sensitive to movement and allows the children to be more active during the imaging process. The fNIRS method utilizes near infrared

light to detect changes in blood oxygenation levels due to brain activity during cognitive processes. Like ERP, it should be noted that fNIRS is not useful for detecting more medial cortical activity because it is only accurate to 4 cm deep. In neural studies of emerging inhibitory control, infants perform the A-not-B task while neural activation is measured using fNIRS. In infants, Baird et al. (2002) found activation in the frontal cortex during this simple task of inhibition. In fNIRS studies, 4- to 6-year-old children during a go/no-go task showed frontal and parietal activation during both go and no-go trials, whereas adult neural activation was more specific, with right fronto-parietal activation during no-go trials only (Moriguchi & Hiraki, 2013). Studies using fMRI in older children and adults found stronger activation of the ventral prefrontal cortex (PFC), right dorsolateral PFC, and right parietal cortex in "no-go" versus "go" trials when performing a traditional go/no-go task (Durston et al., 2002). Using event-related potentials (ERPs), Chavan, Manuel, Mouthon, and Spierer (2013) found a specific pattern of activation of right fronto-parietal areas just prior to the no-go stimuli was associated with successful inhibition in a no-go trial. Together these results indicate that successful inhibitory control performance is linked with frontal-parietal networks, particularly the right frontal and parietal regions, in children and adults with some variations in neural activation in young children.

In accordance with the building evidence of the underlying neural mechanisms of various forms of executive function, Ordaz et al. (2013) described three specific neural circuits involved in inhibitory control. The first network is involved in the planning of goal-directed behavior and includes both the ventrolateral prefrontal cortex (VLPFC) and the dorsolateral prefrontal cortex (DLPFC). The second network is a motor response network, which includes the supplementary motor area (SMA), pre-supplementary motor area (preSMA), the posterior parietal cortex, and

putamen. The third network monitors and processes errors and includes the dorsal anterior cingulate. Both functional imaging studies of activity in these specific areas as well as connectivity studies (Shang, Wu, Gau, & Tseng, 2013) support the involvement of these networks in inhibitory control.

The first network includes the VLPFC, which includes the inferior frontal cortex and is thought to play a vital role in the process of disengaging and reorienting attention in order to inhibit a response (Logemann et al., 2013). Aron, Robbins, and Poldrack (2014) discussed the importance of the role of the right inferior frontal cortex in behavioral inhibition of many types, including complete suppression of a response and partial suppression of a response (pausing). Most response over-riding tasks (such as the stop signal task and the go/no-go task) demonstrate activity in the right IFC that is considered critical for performance on these tasks. Both lesion studies of the right IFC and studies of temporary disablement of the pars opercularis portion of the IFC have implicated its role in inhibitory control (Aron et al., 2014; Barnes, Dean, Nandam, O'Connell, & Bellgrove, 2010). Both fMRI studies (Roth et al., 2006) and ERP studies (Logemann et al., 2013) confirm the involvement of the right IFC in inhibitory control. Some studies show left IFC involvement, but this seems to be true when the go/no-go trials are 50/50 so that the task becomes a decision task, rather than an inhibition of a prepotent response task (Aron et al., 2014). Evidence against right IFC's involvement in inhibitory control is the argument that IFC is involved in signal detection, not task inhibition, since it is activated on both go and no-go trials, but Aron et al. argued that there was a pause on the go trials as well indicating that there was a partial inhibition occurring during the go trials. Furthermore, a connectivity study by Shang et al. (2013) found the connectivity along the left orbitofrontal and ventrolateral tracts was related to EF performance, including inhibitory control. Despite some

evidence of left VLPFC involvement, right VLPFC appears to be more strongly implicated in inhibitory control. Based on human and animal studies, the right IFC is thought to inhibit behavior via the subthalamic nucleus (STN) of the basal ganglia. Lesions of the right IFC in animals and humans lead to slower stop signal reaction times on inhibitory control tasks, and functional MRI's in human studies show increased activation of the STN associated with better inhibitory control performance (Aron et al., 2003; Barnes et al., 2010).

Although not specifically named in Ordaz's three neural networks, several studies point to the involvement of the orbital frontal cortex (OFC) in inhibitory control as it interacts with the adjacent VLPFC and the limbic system. The strongest evidence for the involvement of the OFC in inhibitory control is based on lesion studies in both humans and animals. Few neuroimaging studies have demonstrated an association between the orbitofrontal cortex and inhibition even though many lesion studies of the OFC have demonstrated impaired inhibitory control. Roth et al. (2006) suggests that the lack of findings in imaging studies may be the result of technical limitations that make it difficult to measure activity in this area, likely due to the OFC's location not being near to the surface of the head and, therefore, more difficult to image. A recent study using functional imaging did demonstrate activation of the OFC on stop trials (Whelan et al., 2012). Using fMRI in adults and children, Casey et al. (1997) found the activity in the OFC to be correlated with performance on a go/no-go task, consistent with lesion studies in humans and animals. In contrast, Aron et al. (2014) argued that animal studies of OFC and inhibition are actually looking at reversal learning (the adaptation of behavior in accordance with changes in stimulus-reward contingencies) and not response inhibition. They argued that the role of the right IFC is much more important to inhibition performance than the OFC. Some studies of OFC corroborate this conclusion that OFC is not related directly to inhibitory control. Using

structural MRI to find OFC volumes, Krueger et al. (2011) found that the OFC was not related to a broad measure of executive function, which included a Stroop measure of inhibitory control. They did find that socioemotional behavioral disinhibition, conceptually similar to behavioral disinhibition or impulsivity, as measured by self-report was related to OFC volume, with smaller OFC volume predicting greater behavioral disinhibition. Socioemotional behavioral disinhibition is used to refer to a lack of inhibition that is related to poor risk assessment, impulsivity, and a disregard for social conventions. Because this study used a broad measure of executive function, it is unclear if inhibitory control alone correlated with OFC volume. Mahone et al. (2011) found that children with ADHD had reduced OFC volumes generally compared to controls, but these volumetric reductions were not related to go/no-go performance. Some suggest that differences in the orbital frontal cortex in children with ADHD may not be due to inhibitory control deficits but instead due to comorbidity with conduct disorder, which is associated dysfunctional activation of the OFC during reward performance tasks (Rubia, et al., 2009). Although the OFC's involvement in inhibitory control is somewhat controversial, several lesion and functional imaging studies have suggested that the OFC is necessary for inhibitory control performance even if the exact mechanisms are not yet well understood.

In addition to the VLPFC, the DLPFC also plays a role in inhibitory control as part of this first network described by Ordaz et al. (2013). The DLPFC includes the posterior half of the middle frontal cortex. Functional MRI studies have demonstrated activation of both the dorsal and lateral prefrontal cortices (Casey et al., 1997; Chambers et al., 2006; Roth et al., 2006). Generally they found activation in similar locations for children and adults, but the volume of activation was larger in children in comparison with adults (Casey et al., 1997). Cieslik et al. (2012) studied the right DLPFC and its role in cognitive control of behavior by examining

connectivity of this area to other networks. They found two different subregions based on this connectivity: a posterior subregion and an anterior subregion. The posterior subregion was well connected with the bilateral intraparietal sulci and was implicated in the execution of actions and in working memory, whereas the anterior subregion was well connected with the anterior cingulate cortex and was implicated in attention and action inhibition processes. Aron et al. (2014) disagree with evidence pointing to the involvement of the DLPFC in inhibitory control. They argued that although the DLPFC was activated during inhibitory control tasks, it was more active during tasks that required conditional stopping (like the go/no-go task) than simple stopping tasks, indicating the DLPFC's involvement in decision making, not inhibition. Since the DLPFC was active during the task cues while the right IFC is active during the actual action inhibition, they argue that the IFC is responsible for the actual inhibition of behavior while the DLPFC is more involved in the decision and task-understanding process. Another study (Figner et al., 2010) used transcranial magnetic stimulation (TMS) to impair the left DLPFC and found that the participants tended to prefer immediate small rewards over later big rewards, but Aron et al. (2014) argued that this task is not measuring inhibitory control, but rather rule implementation. In summary, the DLPFC appears to be active during inhibitory control tasks, but the task-impurity problem makes it unclear if this involvement is related to the actual inhibition of behavior or to other neurocognitive processes involved in the inhibitory control tasks.

According to Ordaz et al. (2013), another network involved in inhibitory control is related to motor response and includes the SMA and the preSMA, which are located in the posterior portion of the superior frontal cortex. Connectivity between the right IFC and the preSMA is related to the speed of inhibition, but research is mixed considering which of these

structures is activated first and when the subthalamic nucleus plays a role (Aron et al., 2014). In a study using transcranial stimulation (Hsu et al., 2011), the superior medial frontal cortex (preSMA) was stimulated during an inhibitory control task and was found to improve inhibitory control performance when the area was "excited." When this area was transcranially suppressed, inhibitory control performance was impaired (Hsu et al., 2011). Furthermore, ERP studies have shown that the SFC is involved in successful inhibition of response (Kenemans & Kahkonen, 2011; Lansbergen, Bocker, Bekker, & Kenemans, 2007; Logemann et al., 2013). Further evidence that the SFC may be involved with inhibitory control comes from imaging studies of children with ADHD, who tend to have deficits in inhibitory control. Mahone et al. (2011) demonstrated reduced volume in the left SMA and left lateral premotor cortex for boys and girls with ADHD; however, the differences in the lateral premotor cortex were confined to the gray matter for girls and the white matter for boys. The reduced left SMA volumes predicted poor inhibitory control as measured by higher commission error rates on a go/no-go task. In contrast, studies that have looked at the superior frontal cortex as a whole have concluded that the SFC is not involved in inhibitory control. For example, one study of human right prefrontal lesions concluded that damage to the right IFC, not the SFC, accounted for the decreases in stop-signal reaction time (Aron et al., 2003). Thus, although the SFC as a whole does not appear to be related to inhibitory control, evidence from connectivity studies, transcranial stimulation, ERP, and structural MRI all indicate that the posterior portion of the SFC (the SMA and preSMA) are implicated in inhibitory control.

The final network involved in inhibitory control involves the cingulate cortex, particularly the anterior portion, which is believed to be involved in error processing. Van Boxtel, Molen, & Jennings (2005) used ERP during a stop-signal task to examine differences in

brain activity by comparing a normal response trial with an erroneous response trial in order to control for motor activity. The error positivity (Pe), which occurs after the error-related negativity (ERN/Ne) is more evaluative in function and is likely generated by the anterior ACC, whereas the ERN/NE, which reflects the detection of errors, seems to arise from the posterior ACC. Interference trials from a Stroop task were associated with activation of the anterior cingulate gyrus in PET studies and fMRI studies. However, other PET and fMRI studies have demonstrated a lack of association of the cingulate with inhibitory control as measured during the Stroop task. One theory for this lack of correspondence is that Stroop measures many cognitive processes other than response inhibition. Another difference between Stroop and the other inhibitory tasks is that Stroop requires inhibition of one response and activation of another response, whereas the other inhibitory tasks only require the inhibition of a response.

Genetic and Neurochemical Contributions to Inhibitory Control as an Executive Function

Executive function is highly heritable, with heritability estimates of about 99% for the broad concept of executive function (Friedman et al., 2008), 43% - 75% at the latent variable level (Friedman et al., 2008; Miyake et al., 2012), and 22-55% at the individual task level (Miyake & Friedman, 2012). Both a general genetic factor common across executive function and specific genetics factors contribute to the individual aspects of executive function, such as inhibitory control, working memory, and shift (Friedman et al., 2008). The common factor of executive function also explained 99% of the variability in inhibitory control, but just 43% and 44% of the variance in working memory and shift, respectively (Friedman et al., 2008). This is consistent with factor studies which demonstrate inhibitory control being completely subsumed by the higher factor of executive function and potentially being a 'core' EF component (Jacques & Marcovitch, 2010).

More specifically, several specific dopaminergic-related genes have been associated with inhibitory control (Congdon et al., 2009; Cornish et al., 2005; Greene et al., 2008); however, other studies have reported contradictory findings (Barnes et al., 2011). Generally, these genetic variations have been associated with decreased dopamine levels in the synapse, and this decreased dopamine has been associated with decreased neural activation during inhibitory control tasks. Supporting the connection between lower dopamine levels and improved inhibitory control, Markett, Montag, Walter, Plieger, and Reuter (2011) found that those with a specific dopaminergic genetic variant (DRD2 A1+), which is associated with lower density of D2 receptors in the striatum, demonstrated better inhibitory control by being better able to suppress previous information that is no longer relevant to the task. However, even studies of this dopamine associated neural activation are mixed, with studies indicating different variations of the same gene demonstrating greater neural activation, specifically in the left striatum, right dorsal premotor cortex, and the right temporoparietal area (Bedard et al., 2009).

Some evidence indicates that serotonergic genes are associated with inhibitory control performance; however, several studies have failed to confirm this conclusion (Barnes et al., 2011; Greene et al., 2007). Although molecular studies of specific serotonergic genes have failed to relate these genes to inhibitory control performance, functional imaging studies have indicated that individual differences in neural activation during inhibitory control tasks is related to specific serotonergic genes (Barnes et al., 2011). Although often treated separately from inhibitory control, error monitoring via the anterior cingulate cortex plays a major role in inhibitory control tasks like the go/no-go task. Studies of error monitoring have implicated both dopaminergic and serotoninergic genetic variations being associated with ERP activations during learning tasks requiring error monitoring (Barnes et al., 2011).

Consistent with these genetic studies, dopamine and serotonin neurotransmitters as well as noradrenaline have been implicated in the neural mechanism of inhibitory control. Animal studies manipulating these three neurotransmitters have shown that noradrenergic mechanisms enhance inhibitory control, whereas dopamine mechanisms enhance overall reaction time but not stop signal reaction time (SSRT) specifically (Barnes et al., 2011). Results with serotonin reuptake inhibitors were mixed, with one study finding no effect on overall reaction time or SSRT and others arguing that serotonin plays a role in action restraint but not action cancellation, which is essential to SSRT tasks (Barnes et al., 2011). Psychopharmacological studies have not provided support for the role of serotonin in inhibitory control; however, studies of dopaminergic stimulants in both clinical and nonclinical populations have generally supported the conclusion that dopamine plays an important neuromodulatory role in improving inhibitory control (Barnes et al., 2011).

There is some pharmacological evidence of the involvement of noradrenergic systems, but genetic studies linking noradrenergic genes with inhibitory control are inconclusive and focus mostly on particular disorders like ADHD or personality disorders (Barnes et al., 2011). One pharmacological study (Logemann et al., 2013) demonstrated that clonidine (a noradrenergic attenuator) was connected with poor performance on a stop signal reaction time (SSRT) task and that clonidine's inhibitory effect was restricted to the superior frontal gyrus, according to ERP data. Methylphenidate, a commonly used medication for improving attention and inhibition in individuals with ADHD, affects both dopaminergic and noradrenergic mechanisms. It is unclear which of these neurotransmitters directly impacts performance on inhibitory control tasks (Logemann et al., 2013).

In conclusion, there is evidence that executive function and inhibitory control, more specifically, are highly heritable. Although the evidence is mixed, dopaminergic and serotonergic genes are implicated in inhibitory control, whereas studies of noradrenergic genes have been inconclusive. Pharmacological studies of the role of these neurotransmitters in inhibitory control are similarly mixed but again suggest that dopamine, serotonin, and noradrenaline may be involved in inhibitory control.

Psychopathology and Inhibitory Control as an Executive Function

Inhibitory control as an executive function has been associated with various forms of adaptive functioning as well as psychopathology. In terms of adaptive functioning, good inhibitory control has been associated with the development of academic skills and social competence (Blair et al., 2005) along with mental health and physical health in children and adults (Wiebe et al., 2014a). Executive function is actually a better predictor of school readiness than intelligence (Wiebe et al., 2014a), with inhibitory control being associated with language development, reading proficiency, and mathematical skills (Wiebe et al., 2014a). In children, inhibitory control plays a role in social development and the development of theory of mind, which is important for being able to take other people's perspectives (Wiebe et al., 2014a). In adults, inhibitory control plays an important role in both career and marriage satisfaction (Wiebe et al., 2014a).

Poor inhibitory control has been associated with a variety of psychopathology, including ADHD, autism, schizophrenia, aggression, personality problems, and emotional dysregulation. Generally, poor inhibitory control, as measured by go/no-go accuracy and other executive function measures, predicted weaker adaptive functioning, weaker academic performance, and more psychiatric symptoms in a sample of 8- to 12-year-old children (Vuontela et al., 2013).

More specifically related to ADHD, Nigg (2001) hypothesized that ADHD is due to a deficit in the executive function form of inhibition, distinguishing this form of inhibition from inhibition motivated by fear. Several studies have supported that inhibitory control is a key deficit in children with ADHD. Pauli-Pott, Dalir, Mingebach, Roller, and Becker (2013) found that inhibitory control and delay aversion were associated with ADHD symptoms and partially mediated the relationship between these symptoms and familial risk. In another study, the Behavior Regulation Index (BRI) from the BRIEF was the strongest predictor of ADHD in 8- to 11-year-old boys, indicating the key role of inhibition of behavior in ADHD (Shimoni, Engel-Yeger, & Tirosh, 2012). Within the BRI, significant differences in the Inhibit and Emotion Control scales were found between boys with ADHD and controls, but Shift did not show group differences. Also using the BRIEF in children ages 6- to 16-years old, Reddy, Hale, and Brodzinsky (2011) found that the BRI and the Metacognition Index were able to predict group membership (ADHD diagnosis versus controls) about 80% of the time. In studies of executive function, children with ADHD showed deficits in inhibitory control (Brocki, Randall, Bohlin, & Kerns, 2008; Walcott & Landau, 2004; Wiebe et al., 2014a), but the decision time (the time necessary for acquiring information and making a decision to respond or not respond) seemed to mediate these deficits in executive function (Karalunas & Huang-Pollock, 2013), suggesting that processing speed may mediate inhibitory control deficits in children with ADHD.

Deficits in executive function, including inhibitory control, are not only associated with ADHD but also with several other forms of psychopathology. Studies have shown inhibitory control deficits in children with autism spectrum disorder (Wiebe et al., 2014a) and adults with schizophrenia, which is associated with poor frontal functioning in general (Jacques & Markovitch, 2010). Consistent with these findings, Greene et al., (2007) presented evidence of

abnormal brain activity during inhibitory control tasks in individuals with schizophrenia, ADHD, and autism spectrum disorders. Aggressive behavior also has been associated with deficits in inhibitory control in both children and adults. In preschool children, problems with executive function (inhibitory control) were associated with greater aggressive behavior even after controlling for attention problems (Raaijmakers et al., 2008). In adults, poor executive functioning was associated with a higher likelihood of committing crimes (Wiebe et al., 2014a). Several measures of personality dysfunction (dependency, impulsivity, manipulativeness, and workaholism) were associated with executive function measures of inhibitory control in a sample of young adults (Hallquist, 2010).

Poor inhibitory control has been associated with poor emotional regulation as well. Carlson & Wang (2007) found that children with poor inhibitory control also tended to have poor emotional control as measured in the lab and corroborated with parent-rated measures of these constructs. In terms of mood disorders, individuals with major depressive disorder (MDD) have demonstrated abnormal brain activation during executive function tasks, like inhibitory control tasks, in many functional neuroimaging studies (Arnsten & Rubia, 2012). In their review, Arnsten and Rubia (2012) emphasized the relationship between behavioral regulation (inhibitory control) and emotional regulation. They identified two major regulation networks: the dorsolateral and inferior prefrontal cortex network, which regulates attention and cognitive/inhibitory control, and the orbital and ventromedial structures network, which regulates motivation and emotion (Arnsten & Rubia, 2012). These two networks are consistent with the theory of "cool" and "hot" EF, as described by Zelazo et al. (2010). Children with ADHD demonstrate deficits in the "cool EF" network involving the inferior PFC, whereas children with conduct disorder and MDD demonstrate deficits in the "hot EF" network involving the orbital

frontal and ventromedial structures. Children with OCD, who also demonstrate abnormal brain activation during inhibitory control tasks, demonstrated problems in the orbital frontal, "hot EF," network as well as problems in a fronto-parietal attention network (Arnsten & Rubia, 2012). Although inhibitory control and emotional control have been associated, evidence seems to suggest that they may involve different neural networks.

Studying the role of inhibitory control in these various forms of psychopathology is especially important since recent interventions have targeted executive function, and thereby reduced levels of psychopathology. For example, interventions targeted at improving EF have shown positive effects on school performance and a reduction in psychopathology (Wiebe et al., 2014a). Other studies have found that interventions and preventive strategies are effective in improving EF in preschool children as well as older children, adolescents, and adults with ADHD symptoms, which has implications for treatment and prevention for a variety of forms of psychopathology (Zelazo & Carlson, 2012). In addition to behavioral interventions, stimulant medications operating on the dopamine system have demonstrated improvements in inhibitory control as an executive function (Nandam et al., 2011), and the review by Arnsten & Rubia (2012) emphasizes the link between psychopathology, executive function performance, functionality of brain structures, and neurochemical manipulation of these structures to improve performance.

Inhibitory Control: An Integrated Understanding of Personality/Temperament and Executive Function

There are many similarities and differences between inhibitory control in the personality/temperament literature and inhibitory control in the executive function literature. In this section, I am integrating the literature in these two fields in terms of definitions, theory,

factor structure, measurement, development, underlying biological mechanisms, genetic and neurochemical findings, and links to psychopathology. As I discuss this more comprehensive understanding of inhibitory control, I present theoretical and empirical evidence that supports an integrated understanding of inhibitory control.

Inhibitory Control: Integration of Definitions and Theory

Similarities in definitions of inhibitory control in personality/temperament and in executive function are the most obvious indicator that these two areas of the literature may be discussing the same concept. In the temperament literature, the definition of inhibitory control is described as the ability to plan and inhibit "inappropriate" responses under instructions or in novel situations (Rothbart et al., 2001). In the executive function literature, the definition of inhibitory control is a little narrower, with inhibitory control being described as effortful inhibition of prepotent responses (Greene et al., 2008). Both definitions include the effortful inhibition of a response. In both definitions, instructions (or implied social demands) must inform the person that the dominant or inappropriate response must be inhibited in order for effortful inhibition to occur. The type of response being inhibited differs slightly between the two definitions. In temperament, this response, if not inhibited, would be inappropriate, given either the overt instructions or implied social demands of the situation. In contrast, the executive function definition states that the inhibited response is the dominant response, but not necessarily socially inappropriate. The broader definition of inhibitory control in temperament includes many kinds of inhibition, such as inhibiting the urge to interrupt others, being quiet when asked, or delay of gratification. In contrast, the field of executive function treats the delay of gratification as a process separate from inhibitory control. Interestingly in the executive function literature, Eigsti et al. (2006) demonstrated that delay of gratification performance at 4- to 5-

years-old predicted go/no-go performance fourteen years later as young adults. This finding suggests that the broader definition of inhibitory control in temperament should be extended to inhibitory control in executive function, as both delay of gratification and inhibitory control may be part of the same construct or, at the very least, seem to have related underlying mechanisms.

In comparing personality/temperament and executive function more generally, I do not think that any researchers would argue that these are the same constructs in broad terms; however, some overlap in these concepts should be noted. Personality and temperament include individual differences in emotional reactivity, self-regulation, and cognition (Rothbart, 2012; Shiner & Caspi, 2012), whereas executive function is defined as effortful cognitive processes that regulate "cognition, behavior, and emotion" (Roth et al., 2006, p. 2). In looking at these definitions, self-regulation seems to be where these broad concepts overlap, with inhibitory control being a portion of this self-regulation in both of the larger concepts. In terms of conceptual factor structure, inhibitory control is just one lower order trait of the broader temperament/personality concept of effortful control/conscientiousness. In contrast, the executive function literature describes inhibitory control as one of the three major factors of EF, likely the most dominant of these three. Because temperament is a broader concept including both reactivity and self-regulation, inhibitory control plays a smaller role. Inhibitory control plays a much more important role in executive function, which shares some conceptual similarities with the self-regulation portion of temperament and emphasizes the importance of regulation and control.

The theoretical model of hot and cool EF may help provide a conceptualization for the interaction between personality/temperament and EF. Hot EF includes the interaction between executive function and emotional reactivity, which in terms of traits would relate to the

personality/temperament constructs of extraversion/surgency and neuroticism/negative

emotionality. Effortful control/constraint is a self-regulative factor, similar to EF, which can be

applied in emotional situations (engaging the hot EF networks) or in non-emotional situations

(engaging the cool EF networks). In addition to this shared self-regulative component, both

temperament and executive function describe individual differences, are genetically based, and

have specific underlying biological mechanisms. These similarities, with regard to inhibitory

control specifically, will be discussed in greater detail below.

Inhibitory Control: Integration of Measurement Issues

Assessing the similarities and differences between inhibitory control measurement

methods in both fields is essential to understanding whether or not similarities and differences in

the constructs are due to actual differences or due to problems in measurement. In the

temperament/personality literature, the preferred modality of measurement of inhibitory control

is parent- and self-report, whereas the executive function literature depends largely on

laboratory-based measures of inhibitory control. Kochanska et al. (1997) created a battery of

laboratory-based behavioral measures to assess effortful control/inhibitory control in

temperament. The one task that was most similar to the executive function behavioral measures

of inhibitory control was the "Simon Says" task, in which the child must inhibit a prepotent

response (to follow the directions given) when a cue (the examiner not saying "Simon says") is

given. This is similar to the stop-signal task in that a cue is given to indicate that the participant

should inhibit a prepotent response. Unfortunately, the lab-based measures of effortful control

are mostly limited to children under the age of 7 and are not useful for assessing inhibitory

control in older children and adults. The only other lab-based measures of inhibitory control in

temperament were actually designed as measures of executive function (e.g., go/no-go). Several

temperament researchers, particularly when attempting to explain the underlying mechanisms of temperament, make the assumption that inhibitory control, as measured in executive function by the go/no-go task, is the same as inhibitory control in temperament (e.g., Rueda, Posner, & Rothbart, 2005). This assumption appears to be largely theoretical and not based on empirical evidence linking go/no-go performance to report-measures of temperament. In comparing studies of "temperament" and executive function, one must be certain that the measures used are actually designed to assess the intended construct.

Measurement issues have muddied several studies that have attempted to compare temperament or personality with executive function. Measurement modality has been a major confound in some studies that have directly linked inhibitory control in personality/temperament and executive function. For example, Unsworth et al. (2009) compared a latent EF variable of response inhibition (based on flanker and antisaccade EF tasks) to a report-measure of personality and found no significant correlations with any of the scales, although the highest correlation (-.11) was with conscientiousness as one would expect. The non-significant correlation could be the result of differences in measurement modality (comparing a lab-based measure to a questionnaire measure), antisaccade being a poor measure of inhibitory control, or true lack of correspondence between inhibition in personality and executive function. Without addressing this cross-modality measurement issue, conclusions about the relationship between temperament and executive functioning cannot be made with confidence.

The use of the same measure to describe temperament in one study and to describe executive function in another study makes the comparison of the two constructs even more complicated. In a sample of 3- to 6-year-olds, Reck and Hund (2011) found significant correlations between parent-reported inhibitory control in temperament and lab-based measures

of "executive function;" however, three of the four measures of executive function (bear/dragon, day/night, whisper, and gift delay) were designed to measure inhibitory control in temperament, not executive function. The first measure, bear/dragon, is similar to "Simon says" and was used by Carlson, Moses, and Breton (2002) to study executive function even though previously it had been used by Reed, Pien, and Rothbart (1984) and by Kochanska et al. (1996) to measure temperament. Whisper and delay were both part of Kochanska et al.'s (1997) battery of lab-based temperament measures. Only day/night, which is a Stroop-like task in which the child has to inhibit the prepotent response to label sunny scenes as "day" when they were instructed to do the opposite (Simpson & Riggs, 2005), was designed and generally used as a measure of executive function. Although bear/dragon and day/night involve inhibition of a prepotent response in a sense, it is unclear if they both actually measure temperament or executive function. Another measurement issue in the Reck and Hund study is that gift delay, which was used to represent "inhibitory control," actually measures delay of gratification, which is separate from inhibitory control in the executive function literature. A temperament measure of inhibitory control could include both of these types of tasks, but Reck and Hund describe these as executive function measures of inhibitory control.

Inhibitory Control: Integration of Developmental Pathways

The developmental trajectories of inhibitory control in temperament/personality and in executive function are not incompatible, but they do use different methods. In the study of temperament/personality, longitudinal or cross-sectional studies emphasize the rank-order stability of traits over time. After the preschool years, inhibitory control/effortful control does demonstrate rank-order stability, meaning the children who are high in inhibitory control relative to their peers at one age are likely to remain high in inhibitory control when compared to same-

age peers at a later age. In the years prior to grade school, rank-order stability of inhibitory control is seen over shorter time increments but not over longer ones. This mild instability in the early years may be due to the fact that certain facets of Effortful Control, like Inhibitory Control, are still developing during this time period. Mean-level inhibitory control in temperament does improve with age, and mean-level conscientiousness continues to increase in young adulthood and middle age (Caspi, Roberts, & Shiner, 2005) with some mean-level decrease of effortful control in the adolescent years (Vijayakumar et al., 2014). This decrease in effortful control during adolescence is likely due to normative adolescent increases in independence and decreases in compliance, not necessarily to a decrease in the ability to inhibit behavior. The improvements in conscientiousness seen later in life during middle adulthood also may be due to aspects of conscientiousness other than inhibitory control.

Unlike the temperament/personality literature, the executive function literature does not emphasize rank-order stability, but it instead focuses on the emergence and development of executive function skills over time due to maturation. In the executive function literature, inhibitory control first emerges and is measureable at about 10 months of age. By three years old, most children are able to do simplified versions of most adult inhibitory control tasks. By age 5 or 6, inhibitory control is considered fully developed, with improvements in efficiency continuing through young adulthood. The period at which inhibitory control as an executive function is fully developed coincides with the point at which inhibitory control in temperament becomes stable. Integrating what is known about the development of inhibitory control from both fields of study, early inhibitory control seems to emerge at about 1 year of age and then go through a period of instability as it develops. Basic inhibitory control skills are present by early grade school, and improvements in efficiency continue at least through adolescence or young

adulthood. Although inhibitory control becomes stable in terms of rank order, the mean level of

effortful control/inhibitory control continues to improve with age, at least into young adulthood.

These improvements coincide with periods of rapid growth in prefrontal cortex.

Inhibitory Control: Integration of Underlying Biological Mechanisms

Several temperament and personality researchers have described the underlying

biological mechanisms of inhibitory control/effortful control, but these explanations are largely

theoretical and are mostly based on empirical studies of executive function, not temperament.

Temperament researchers emphasize the role of the DLFPC, VLFPC, anterior cingulate cortex,

and orbital frontal cortex in inhibitory control, and research on executive function supports the

role of all of these structures in inhibitory control to various extents, along with the motor

planning areas of the superior frontal cortex (SMA and pre SMA). One reason for the lack of

studies directly linking these functional areas with temperament and personality is that

temperament and personality are largely measured by questionnaires, not lab-based tasks during

which ERP and functional imaging studies can inform us about brain functionality. Although

there are no functional imaging studies that link temperament-based inhibitory control to specific

cortical areas, a couple of structural imaging studies have linked larger cortical brain volumes,

specifically the left orbital frontal cortex, with higher levels of effortful control in temperament.

This study looks specifically at the cortical volumes of the orbital frontal cortex (OFC)

and superior frontal cortex (SFC) in relation to inhibitory control as measured both as a

temperament/personality subtrait and as an executive function. These two structures were

selected because they are implicated in inhibitory control, whereas their relationship to inhibitory

control is less well-studied than other structures, like the inferior frontal cortex. The OFC is

located on the ventral prefrontal cortex directly above the eye sockets. The OFC has been

implicated in many different functions including sensory processing, social reasoning, learning and reasoning abilities, emotional control via the limbic system, and inhibitory control (Hof, Mufson, & Morrison, 1995; Kahnt, Chang, Park, Heinzle, & Haynes, 2012; Lezak, Howieson, Bigler, & Tranel, 2012). Interestingly, Spinella (2002) found correlations between several measures associated with OFC function, including a correlation between go/no-go performance and left nostril smell identification. Since smell tends to be ipsilateral, meaning that left nostril smell is likely to be associated with the left cortex, this could suggest that go/no-go performance is more associated with the left OFC than the right, consistent with temperament studies that suggest that the left OFC volume is correlated with inhibitory control performance. In conclusion, although several studies suggest the role of the bilateral OFC in inhibitory control, the structural studies of the OFC in temperament suggest larger left OFC volume will correlate with better inhibitory control.

In terms of connections between smaller regions of the OFC and inhibitory control, more general studies of the role of the prefrontal cortex in inhibitory control suggest that the lateral portions of the PFC are most active during inhibitory control tasks, although due to the difficulty of getting quality functional imaging in the OFC, it is unclear if this emphasis on the lateral prefrontal cortex extends all the way down to the OFC. Many of these tasks are cognitive, so they could be argued to assess 'cool' EF. Wilbertz et al. (2012) found that reward sensitivity and impulsivity (perhaps more emotional or 'hot' EF) were associated with the medial OFC in a functional MRI study, suggesting different functional roles for the medial and lateral regions of the OFC. Because the OFC is believed to contain different functional areas based on cytoarchitecture and connectivity studies, I parcellated the OFC to discover if differences in volume in more lateral areas are related to inhibitory control as suggested by the literature

75

linking the lateral prefrontal cortex with inhibitory control. The method of parcellation is described in greater detail in the method section.

In addition to the OFC, the other prefrontal cortical area that this study examines is the superior frontal cortex (SFC). The SFC begins just above the OFC at the most anterior tip of the brain, which is sometimes labeled as the frontal pole. The SFC then extends up and back along the medial dorsal portion of the cortex and ends with the precentral gyrus. The area of the SFC that is just anterior to the precentral gyrus is the supplementary motor area (SMA), and just anterior to that is the preSMA. The SMA and pre SMA are involved in preparation for movement, the execution of complex movements, and control of goal-directed movements (Lezak et al., 2012). The current understanding of the functionality of the anterior portion of the SFC is very vague, involving executive function, monitoring of all nervous system activities, and higher levels of cognitive processing on a very broad level. Inhibitory control has been functionally connected with the more posterior areas, the SMA and the preSMA. Some studies have suggested only right posterior SFC involvement in inhibitory control, but others have found only left posterior SFC involvement. Based on these findings, I expected to find that both right and left posterior SFC volume would be associated with inhibitory control.

In conclusion, the underlying biological mechanisms of inhibitory control are assumed to be the same in both temperament and personality. However, there is a little empirical evidence that both share similar mechanisms since the majority of the research connecting the brain with inhibitory control is in the executive function literature. This study examines the relationship between two particular areas, the OFC and the SFC, and inhibitory control as defined in both the personality/temperament literature and EF literature. Since the posterior SFC and the OFC, possibly restricted to the left OFC and to more lateral regions of the OFC, are implicated,

parcellating these structures will provide more information about how these structures are related to inhibitory control.

Inhibitory Control: Integration of Genetic and Neurochemical Contributions

Inhibitory control demonstrates levels of heritability around 50% both for effortful control in temperament and for factor scores of inhibitory control tasks in executive function. Performance on individual tasks tends to demonstrate lower heritability estimates (30-40%), whereas one study of the broad area of executive function showed very high estimates of heritability (Friedman et al., 2008). However, both domains of research suggest that genetics are not the only contributing factor, with the environment also playing a vital role in the development of inhibitory control. Both areas of research suggest that serotonergic and dopaminergic genes may play a role in inhibitory control (Barnes et al., 2011; Congdon et al., 2009; Cornish et al., 2005; Greene et al., 2008; Nederhof et al., 2010; Sheese et al., 2012; Smith et al., 2012) although the evidence is mixed (Barnes et al., 2011). The overlap of underlying brain mechanisms, genetics, and neurochemistry suggest that inhibitory control either is the same construct or at least has similar underlying mechanisms in both domains of research.

Inhibitory Control: Integration of the Relationship of Inhibitory Control with Psychopathology

Inhibitory control in temperament/personality and inhibitory control in executive function have been associated with many of the same outcomes, including emotional regulation, social competence, ADHD, and depression. The temperament/personality literature also has demonstrated connections between inhibitory control and conduct problems and personality dysfunction, whereas problems with inhibitory control in executive function are linked with academic problems, schizophrenia, and OCD. The areas of psychopathology that do not

77

demonstrate links with inhibitory control may simply be areas that not have been well-studied across both domains. For example, personality researchers are likely to look for connections between inhibitory control and personality disorders, but executive function researchers are more likely to look for connections between inhibitory control and neurodevelopmental disorders, which are known to be associated with the brain.

Several studies have looked at the relative contributions of temperament/personality and executive function to psychopathology simultaneously. Hall and Fong (2013) found that better executive function and conscientiousness both contributed to improved health outcomes and eating habits. Neuenschwander, Cimeli, Rothlisberger, & Roebers (2013) found that both executive function (inhibition, updating, and shifting) and personality (extraversion, openness, and conscientiousness) were related to academic performance, although the relationship between conscientiousness and academic performance was not evident when the predictors were considered together. Lahat et al. (2012) found that the temperament trait of exuberance and executive function (not inhibitory control specifically) jointly predicted risk-taking behavior in childhood. These studies looked at the contributions of executive function and temperament/personality to the development of various outcomes, but few look at the relative contributions of inhibitory control from both domains in order to see if one offers a better explanation of the outcome variable than the other or if they explain the same shared variance with the outcome variable, indicating that they may, in fact, be the same construct.

The link between inhibitory control and psychopathology underscores the importance of understanding inhibitory control across both domains of study. An integrated understanding of inhibitory control has the potential to expand our understanding of forms of psychopathology typically associated with just temperament/personality or just executive function. An improved

understanding can lead to better prevention and intervention for these disorders. Improved

treatment is especially important in light of recent studies that have demonstrated promising

results for interventions designed to improve executive function in children with ADHD (Zelazo

& Carlson, 2012).

Empirical Evidence Directly Linking Inhibitory Control in Temperament/Personality and

Executive Function

Generally, executive function (EF) and temperament/personality have been directly

associated in several studies. In a series of studies, Bridgett, Oddi, Laake, Murdock, and

Bachmann (2013) found consistent overlap between effortful control in temperament and the

broad construct of executive function. In their first study, they found correlations between report

measures of temperament and executive function as measured by the BRIEF. In the second and

third studies, they added lab-based measures of EF, including a Stroop-like measure of inhibitory

control. However, the lab-based measure of inhibitory control did not correlate with a

questionnaire measure of effortful control even though other measures of executive function did.

In another study, Gerardi-Caulton (2000) found that executive function performance on a

conflict-resolving task predicted individual differences in effortful control and negative

emotionality. Hongwanishkul, Happaney, Lee, and Zelazo (2005) found that cool EF tasks (self-

ordered pointing and DCCS) were associated with effortful control, although controlling for age

removed this association, perhaps indicating that this association is a result of general

maturation.

Both theoretical and empirical evidence indicates that effortful control in temperament is

linked with executive attention (Posner & Rothbart, 2009; Putnam & Stifter, 2008; Rothbart,

Ahadi, Hershey, & Fisher, 2001; Rothbart, Sheese, & Posner, 2007). For example, Rothbart et

al. (2001) found that factor analyses of a temperament measure of effortful control revealed dimensions of attention shifting, attention focusing, and inhibitory control. The previously cited work of Gerardi-Caulton (2000) empirically linked effortful control with executive attention as well. In contrast, when Ellis, Rothbart, and Posner (2004) studied the relationship between effortful control and cognitive tasks of executive attention, they found no relationship between self-reported effortful control and EF performance. They did find a low correlation between mother-rated effortful control and EF performance, however. Because EF was measured behaviorally and temperament was measured via a report measure, it is unclear whether the weak association is due to the differences in measurement modality or to actual differences between the constructs. Although these studies link effortful control with executive function overall, they do not link effortful control with inhibitory control specifically.

More specific studies linking inhibitory control in executive function and inhibitory control/effortful control/conscientiousness in temperament personality are rare, and those that do exist are complicated by measurement issues as explained previously in the integration of measurement section. A study by Wolfe & Bell (2004) looked directly at inhibitory control in executive function and inhibitory control in temperament. In studying 4-year-olds, they used Rothbart's temperament measure of inhibitory control, but they measured executive function with lab-based tasks using the temperament measures designed by Kochanska. They found a significant correlation (.38) between CBQ inhibitory control and inhibitory control as measured by a Stroop-like task from Kochanska's battery. Wolfe and Bell also found significant correlations between the broader dimension of effortful control and two other tasks from Kochanska's battery (tongue and wrapped gift), but these significant correlations could be due to the fact that all of the measures were designed as measures of temperament. Morasch and Bell

(2011) studied inhibitory control in toddlers using both a parent-report temperament measure and lab-based inhibitory control measures, an A-not-B task and a delay task. These measures both demonstrated a significant but low correlation (around .27) with the temperament measure of inhibitory control. Here, differences in measurement modality may have weakened the perceived strength of this relationship between EF and temperament. In addition to the measurement problems, these studies were conducted with younger children and may not apply to older children with more fully developed inhibitory control.

Hallquist (2010) studied self-reported effortful control and laboratory-based measures of inhibitory control as an executive function in adults with personality disorders. He found that effortful control did not correlate well with most laboratory-based measures of inhibitory control as an EF. Nonetheless, he did find two aspects of inhibitory control that were significantly related to effortful control: the number of errors on incongruent flanker trials and the number of failures to inhibit responses to fear faces in a variation of a go/no-go task. Hallquist hypothesized several different measurement issues that could account for the lack of relationship between the other executive function measures and the temperament measure. One of these possible measurement issues was the difference in measurement modality between laboratory-based measures and a questionnaire. Addressing this measurement issue, my study uses both a lab-based measure (go/no-go) and a parent-report measure of executive function, along with the parent-report measure of temperament-based inhibitory control. Another possible reason for the lack of correspondence between the executive function measure and the temperament measure could be that Hallquist used the broader concept of effortful control, of which inhibitory control is only a part. By using just the inhibitory control aspect of effortful control, I am better able to assess the hypothesized relationship between the two constructs.

Gonzalez, Fuentes, Carranza, & Estevez (2001) conducted a similar study of inhibitory control in temperament and executive function in 7-year-olds. Inhibitory Control was measured using parent-report on the Children's Behavior Questionnaire (CBQ), and inhibitory control in executive function was measured using a flanker task and a Stroop interference task. Interestingly, they found different aspects of temperament affected each of the two inhibitory tasks. Interference on the flanker task was related to aspects of the negative emotionality temperament factor. In contrast, the Stroop interference was related more to the effortful control factor, with children low in inhibitory control demonstrating a higher Stroop interference effect than children high in inhibitory control. For both tasks, Gonzalez et al. found an interaction between negative affect and inhibitory control, with high negative affect and low inhibitory control predicting the highest interference effects. This study empirically demonstrated the relationship between inhibitory control in temperament and inhibitory control in executive function despite using measures that cross modalities.

Yucel et al. (2012) studied the effect of temperament on inhibitory control performance in executive function in adolescents. Both parent-reported and self-reported Effortful Control in temperament predicted inhibitory control as measured by interference on a modified Stroop task; however, analysis of an interaction between effortful control and sex indicated that higher effortful control only predicted lower interference effects for females, not males. Interestingly, higher intelligence also was associated with better performance on the inhibitory control task, consistent with other studies of executive function demonstrating greater efficiency in both performance and use of neural mechanisms during executive function tasks in those with higher intelligence (Yucel et al., 2012). The study by Yucel et al. provided further evidence of the relationship between effortful control and inhibitory control task performance (at least for

82

females), despite using measures that cross modalities and despite using the broader concept of effortful control as opposed to the more specific temperament trait of inhibitory control.

Together, the similarities in the definitions, concepts, developmental pathways, biological mechanisms, genetic evidence, and neurochemistry of inhibitory control in temperament/personality and executive function are strong enough to suggest that these are at least overlapping constructs. They may represent the same construct, executive function could be the regulatory aspect of temperament, and/or they could share similar underlying mechanisms. A few studies have directly linked these concepts, but my study offers improvements over the past studies. In terms of addressing inhibitory control as both a temperament/personality trait and an executive function, this study addresses the measurement issues present in previous studies by including both a lab-based and a parent-report measure of executive function along with a parent-report measure of temperament. The measures selected for this study were chosen to represent the constructs they were designed to represent without making assumptions that a traditional measure of temperament can be used to measure executive function or vice versa. (Ideally, a lab-based measure of temperament would also have been included, but given the archival nature of this study, no lab-based temperament measure was available.) Because this is a study based on archival data, a previously established measure of temperament was not available. Using Rothbart's temperament measures as a guide, a temperament-based inhibitory control measure was created from items on available parent-report questionnaires.

Another advantage is that this study looks at these constructs in older children (8- to 12-year-olds), who are presumed to have inhibitory control that is developed, unlike many of the previous studies which looked at children under the age of 5 when inhibitory control is not yet considered stable. In terms of the underlying biological mechanisms, my study also offers

several unique contributions over previous studies of this topic. Most studies of the neurological mechanisms of inhibitory control are based on functional studies, whereas this study will examine cortical volumes. These structural measurements can be related to both questionnaires and lab-based tasks. Although both the SFC and OFC have been associated with inhibitory control, my study will be the first to study inhibitory control in relation to parcellated regions of these structures based on evidence that both of these large cortical areas are believed to have different areas of functionality. My method of parcellation is innovative using connectivity studies, cytoarchitecture, and functional studies to inform the choice of parcellation markers. In studying these underlying biological mechanisms, my study uses a factor score to measure inhibitory control, including a parent-report measure of temperament, a parent-report measure of executive function, and a computerized measure of executive function. This procedure demonstrates an improvement over previous studies in which inhibitory control was based either on report-measures of temperament or on laboratory-based measures of executive function.

Purpose of current study

The goal of this study is threefold. The first goal is to determine whether inhibitory control is best conceptualized as a singular factor spanning two separate areas of research or as two or more factors representing different, but related, constructs. The second goal is to relate inhibitory control to structures in the prefrontal cortex, which will contribute to the understanding of the underlying neural mechanisms involved in inhibitory control. The two cortical structures of interest for this study are the orbital frontal cortex (OFC) and the superior frontal cortex (SFC). The third goal is to relate inhibitory control to smaller, more specific regions of the OFC and SFC by parcellating these regions.

Hypotheses

1. **Factor structure:** After establishing internal consistency for my constructed measure of temperament, I predicted that a confirmatory factor analysis of my one-factor model of inhibitory control would yield a "good" fit. Correspondingly, I predicted that the temperament measure of inhibitory control would load well with the executive functioning measures of inhibitory control on the overall factor of inhibitory control. This proposed model is provided in Figure 1.

2. **Relationship of inhibitory control to the unparcellated structures**: I predicted that greater bilateral OFC volume and bilateral SFC volume would be associated with higher factor scores of inhibitory control.

3. **Relationship of inhibitory control to the parcellated structures**: I predicted that greater right and left lateral OFC volume would be associated with higher factor scores of inhibitory control, and greater bilateral posterior SFC volume would predict higher factor scores of inhibitory control.

CHAPTER 3

METHOD

Participants

Participants for this project are seventy-nine 8- to 12-year-old children recruited as part of a larger NIH/NICHD funded project (R15 HD065627). Demographics for this sample are provided in Table 1. Using a mixed sample, the children in this study have either diagnosed ADHD (both combined type and predominantly inattentive type), reading disability, both ADHD and reading disability, or neither of these diagnosed. Children for this study were recruited through advertising at public schools, private schools, family doctors, and pediatricians. Families who participated in the study were compensated by receiving a full neuropsychological evaluation and report for their child. Each child who participated also received a university t-shirt and a print-out of pictures from his/her MRI scan.

Participants were screened through a phone interview with the parent at intake and confirmed with the parent interview on the day of neuropsychological testing. Children with a history of birth trauma, traumatic brain injury or other significant psychological, neurological, or developmental disorders, as assessed by parent-report, were excluded at intake. The only comorbid disorders allowed were language disorders and mild oppositional/conduct problems because of their high comorbidity with reading disabilities and ADHD, respectively. As some people were not completely forthcoming at intake, an 'other' category was formed if individuals had significant social problems, birth complications, or diagnoses (e.g., history of physical abuse and malnutrition, significant maternal stress during pregnancy, oxygen necessary after birth, and Cognitive Disorder Not Otherwise Specified) that were discovered during the interview or testing.

Diagnoses of ADHD and reading disabilities were based upon information gathered from a parent interview, questionnaires given to parents and teachers, behavioral observations during the testing, and neuropsychological testing. Although these diagnoses are not the focus of this study, using this mixed sample is advantageous since it will allow for wide range of inhibitory control levels. As stated previously, ADHD is associated with poor inhibitory control, whereas one would expect normal inhibitory control skills in the controls and in some with reading disabilities. The larger study had already been approved by the Human Subjects Office of Southern Illinois University Carbondale Institutional Review Board, and this specific use of the data also was approved by this board before parcellations unique to this study were conducted.

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Measures

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Demographic Measures

The children's mother's educational level was used as an approximation of the family's socioeconomic status. Our measure is based on the education scale from the Hollingshead Four-Factor Index of Socioeconomic Status (SES). Our scale's ratings are as follows: 0 = not applicable or unknown; 1 = less than 7th grade education; 2 = junior high school, including 9th grade; 3 = partial high school, including 10th or 11th grade; 4 = high school graduate; 5 = some college or at least one year of specialized training; 6 = standard college or university graduate; 7 = master's degree; 8 = doctorate degree. Handedness was measured using the Edinburgh Handedness Inventory. It is a scale with 10 items that measure handedness for particular tasks (i.e., writing, drawing, using a broom). The score provided is expressed as a percentage of right-handedness. People who use their right hand for all ten tasks would score 100% on the Edinburgh, whereas those who use their left hand for all ten tasks would receive a score of 0%.

Measure of Inhibitory Control as a Temperament/Personality Trait

A measure of inhibitory control was created for this study using items from the parent-report form of the Big 5 personality measure and the parent-report form of the Behavioral Assessment System for Children (BASC). Because Rothbart's model of temperament is being used in this study, the items for the temperament measure were selected from the above measures based on Rothbart's measures of inhibitory control from the Children's Behavior Questionnaire-Short Version (CBQ-SV), the Temperament in Middle Childhood Questionnaire (TMCQ), and the Early Adolescent Temperament Questionnaire-Revised (EATQ-R). When combined, there were 19 items with several that had nearly identical content, such as "Has a hard time following instructions" from the CBQ- SV and "Is good at following instructions" also from the CBQ-SV. Others had overlapping concepts, such as "has an easy time waiting to open a present" from the TMCQ and "can wait before entering into new activities if s/he is asked to" from the CBQ-SV. Seventeen of the nineteen items had overlapping content and fit into seven major concepts: being able to stop when told, being able to slow down when needed, waiting for good things with ease, waiting to take turns to speak, using caution in dangerous situations, planning before acting, and following directions. Each of these major concepts had comparable items on the Big 5 or the BASC-2 questionnaires. Only two items of the Rothbart inhibitory control temperament items did not fit into these concepts, and they did not have any comparable items on the Big 5 or the BASC, so these items were dropped. The dropped items were "Is able to keep secrets" from the TMCQ and "Has trouble sitting still when s/he is told to (at movies, church, etc.)" from the CBQ-SV. As these concepts from these two items are not found across the three measures of inhibitory control, they are unlikely to be critical to the measurement of this concept. Table 2 shows the list of original Rothbart inhibitory control concepts as well as the corresponding items

selected from the Big 5 and from the BASC-2. In the end, nine items were selected since they captured the major inhibitory control concepts and were available on both the child and adolescent version of the BASC-2. The mean score for each child was used in the data analyses. After the temperament-based measure of inhibitory control was calculated from the mean of the selected items (reversed as appropriate), Cronbach's alpha ($\alpha = .691$, $n = 73$) was obtained and found to be consistent with internal reliability of other similar temperament measures.

Another issue in the construction of this scale is that the Big 5 questionnaire is measured on a three point scale with 1 = Rarely, 2 = Sometimes, and 3 = Almost Always and the BASC-2 is measured on a four point scale with 1 = Never, 2 = Sometimes, 3 = Often, and 4 = Almost Always. After data were collected, the scores from both scales were transformed to a 12 point scale so that items from both measures could easily be recoded on the same scale. Once the items were re-scaled and the reversed items were appropriately recoded, the mean of all nine items was used to represent the temperament inhibitory control measure for each child. Since the temperament measure assesses inhibitory control while the executive function measures assess inhibitory control problems, the temperament measure was reversed in the later analyses so that all of the inhibitory control measures would assess inhibitory control in the same direction.

This measure of temperament is based on Rothbart's measures of temperament, which as discussed previously have been well-established in the literature (Ahadi, Rothbart, & Ye, 1993; Putnam, Rothbart, & Gartstein, 2008; Rothbart, Ahadi, Hershey, & Fisher, 2001). Generally, the questionnaire most appropriate to the age group in this study (Early Adolescent Temperament Questionnaire-Revised) has internal consistency ranging from .65 to .82 and test-retest ranging from .55 to .85 (Gartstein, Bridgett, & Low, 2012). The internal consistency of my temperament measure of inhibitory control was .69, which is consistent with similar temperament measures.

Parent-rated Measure of Inhibitory Control as an Executive Function

As discussed previously, the BRIEF is a parent-report measure of executive function in children. Parents rate 86 items on how well they describe their child on a scale of 1 to 3 (1=never, 2=sometimes, and 3=often). These items fall into 8 scales. The scales of interest for this study are the three that make up the Behavioral Regulation Index (Inhibit, Shift, and Emotional Control). Internal consistency as measured by Cronbach's alpha ranged from .80 to .98, and test-retest reliability ranged from .76 to .85 (Gioia et al., 2000). Of the three subscales, Inhibit is most like inhibitory control as described in the executive function literature. Examples of items from the Inhibit subscale are "Does not think before doing," "Has trouble waiting for turn," and "Blurts things out." All three subscales contribute to the BRI, which is a measure of the regulatory aspects of executive function and is likely to relate to both inhibitory control performance and temperament.

Computer-based Behavioral Measure of Inhibitory Control as an Executive Function

Our go/no-go task is an auditory version of the task presented on a computer using E prime. For the go/no-go task, the child is instructed to press the space bar only when they hear the low tone and not press anything when they hear the high tone. After 10 practice trials, the child receives a series of go/no-go trials with varying times in between presentation, ranging between 500 and 2500 milliseconds between stimuli. There are 200 "go" trials with the low tone, and 50 "no go" trials with the high tone. These 250 trials are administered in a random order so that the person cannot guess the interstimulus interval or whether it will be a low or high tone. Consistent with the literature, inhibitory control was measured by accuracy on the no-go trials, how often they can successfully inhibit the prepotent response to press the space bar.

Prefrontal Cortex Volumes

The author accomplished manual tracing using Analyze 11.0 Region of Interest (ROI). Boundaries for the superior frontal and orbital frontal cortices were established using the boundaries set by Crespo-Facorro et al. (2000) and referencing the diagrams in Damasio (2005). Inter and intra-rater reliability on the manual tracing of the OFC and SFC on the right and left were established with reliabilities greater than .9. Both structures were primarily traced in the coronal plane, tracing on only the odd slices for the sake of time since these structures extend through a large portion of the brain. For the superior frontal cortex, the posterior boundary was marked by the precentral gyrus, which had been previously traced reliably (r > .9). The ventral boundary of the posterior section of the superior was the dorsal border of the cingulate gyrus, which had been previously traced reliably as well (*r* > .9). The ventral boundary of the anterior section of the superior (when the cingulate was not present) was the frontomarginal sulcus, which is the frontal boundary between the superior frontal gyrus and the orbital frontal gyrus. The lateral boundaries of the superior gyri were the superior frontal sulci.

For the orbital frontal cortex, the anterior boundary was the front of the cortex, and the posterior boundary was marked in the sagittal view. The lateral boundary was the inferior frontal cortex, which was previously manually traced by another tracer who had also achieved both inter- and intra-rater reliability for that structure at levels greater than .90. The anterior medial dorsal boundary was the frontomarginal sulcus where the OFC bordered the SFC.

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Parcellation Method

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I parcellated the structures by manual tracing with ROI in Analyze 11.0. A full slice cut was made through the coronal plane at the anterior tip of the corpus callosum. A second and third sagittal cut were made at the most medial slice of the inferior frontal sulcus on the right and

left hemispheres, respectively. These cuts resulted in four regions for each OFC (anterior medial, anterior lateral, posterior medial, and posterior lateral) and two regions for each SFC (anterior and posterior). See Figures 2-4.

These parcellation methods for the OFC were designed based on the following studies. Previous studies that have looked at specific areas of the OFC were based on connectivity studies, cellular analysis studies, and fMRI studies. Since the OFCs sulci and gyri demonstrate a great deal of inter-individual variability (Nakamura et al., 2008), there are no consistent sulcal markers used for parcellation within the OFC. Based on the functional imaging studies of inhibitory control cited above, I chose to divide the OFC into medial and lateral areas as well the anterior and posterior areas. This produced four areas (Figure 2). I selected my markers for dividing these areas based on studies of connectivity and the cytoarchitecture of the OFC. My sagittal cut, which divided the lateral and medial regions of the OFC, was made at the most medial point of the inferior frontal sulcus, which marks the boundary between the inferior and middle gyri more laterally (Figure 3). My coronal cut, dividing the anterior and posterior regions of the OFC, was at the genu of the corpus callosum (Figure 4). Studies supporting my parcellation markers are presented below.

One of the most relevant studies of parcellating the OFC was the study by Kahnt et al. (2012), who used connectivity studies to parcellate the orbital frontal cortex. Their results identified 6 areas based on connectivity. The three lateral areas identified were connected to the dorsal lateral prefrontal cortex (DLPFC), which is heavily implicated in inhibitory control. The small central region was connected with the dorsal anterior cingulate cortex and the lateral prefrontal cortex, which are areas also implicated in inhibitory control. The more medial and posterior areas demonstrated different connectivity, with the medial prefrontal cortex and

92

posterior cingulate cortex along with areas of the parietal and temporal lobes. This connectivity study suggests that the more lateral areas demonstrate different connectivity from the more medial and posterior areas of the OFC. The connections between the lateral OFC and other areas of the brain seem to indicate that the anterior lateral areas of the OFC are most likely to be involved in inhibitory control. Although the study by Kahnt et al. (2012) supports the need to divide the OFC into smaller areas for analysis, it does not provide guidelines for sulci to use in manual parcellation. However, the sagittal cut I designed approximately separates the three lateral connectivity regions from the two more medial connectivity regions. Unfortunately, the small, centrally-located connectivity region, which is connected with the ACC, may have ended up in the more medial section, the more lateral section, or split between the two given the variability of the OFC structure across individuals. Because of its small size and lack of anatomical markers, identifying this central region using manual tracing is not possible. Although Kahnt et al. did not provide specific markers for manual tracing, the connectivity regions from this study were very helpful and used as the basis for this study's divisions. It should be noted, however, that the study by Kahnt et al. examined connectivity in adult brains, whereas this study is examining these cortical regions in children, who may demonstrate different connectivity than adults due to developmental differences.

Another helpful study in determining the desired regions of the OFC was an immunochemical study which parcellated the OFC according to its cytoarchitecture (Hof, Mufson, & Morrison, 1995). The most posterior portion of the OFC demonstrated a different distribution of pyramidal cells than the other areas, suggesting that the posterior section may have different functionality than the other areas. There were also differences in cytoarchitecture between the posterior medial and posterior lateral areas of the OFC. Although the implications

for inhibitory control are not clear, this study provides further evidence that the anterior, posterior, medial, and lateral sections of the OFC may represent different functional areas. My anterior/posterior cut separates only the most posterior region of the OFC consistent with this study of the cytoarchitecture of this region.

Due to the relative lack of studies that have attempted to parcellate volumes of the SFC, the parcellation method for the SFC was based on the following research. Few studies have attempted to parcellate volumes of the SFC. The SFC, as part of the prefrontal cortex, contains a great deal of inter-individual variability, so no particular sulcus or gyrus marks the boundaries that separate the preSMA from the anterior portion of the SFC. In examining cortical SFC volumes in relation to inhibitory control, it was important to parcellate the SFC into an anterior and a posterior portion of the SFC in order to separate the SMA and preSMA from the rest of the SFC. In conducting a study of the associations between cortical volume and ADHD, Filipek et al. (1997) parcellated the entire cortex into three major areas using the front and back tips of the corpus callosum to mark the coronal cuts between the precallosal, pericallosal, and retrocallosal regions. The pericallosal was then divided further into an anterior and posterior section based on the anterior commissure so that the frontal lobe was divided from the anterior portion of the parietal lobe. Within the anterior pericallosal region, the frontal lobe was analyzed separately from the temporal lobe so that the superior anterior pericallosal region included the SMA and pre SMA portions of the superior frontal cortex along with the posterior portions of the middle frontal cortex and inferior frontal cortex. Smaller volumes of this area in the right hemisphere were associated with ADHD. Although this study did not look specifically at inhibitory control, inhibitory control deficits are often a core deficit in ADHD, indicating possible relevance for this study. The boundary used to split the anterior and posterior was easy to identify and provided

meaningful volumetric differences. Filipek et al. (1997), however, did not separate the superior, middle, and inferior gyri, so it is unclear if these individual differences in cortical volume are due to the superior frontal (preSMA and SMA) or the inferior frontal (pars operculus), which are both strongly implicated in inhibitory control. For their study of transcranial stimulation of the preSMA portion of the superior cortex and its impact on inhibitory control performance, Hsu et al. (2011) first marked the area by using cranial markers from structural MRI along with documenting a motor twitch from transcranial stimulation to mark the motor cortex. Their methods resulted in stimulation of the superior cortex that was posterior to the anterior tip of the corpus callosum. Division of the superior cortex at the genu of the corpus callosum appears to be consistent with prior research and a clear marker to use for a coronal cut separating the anterior and posterior sections of the SFC for this study (Figure 5).

Procedure

Children and their parents came to the Child Neuropsychology Lab at Southern Illinois University Carbondale for a full-day of neuropsychological testing. The children completed a variety of neuropsychological tests, including a computer-based go/no-go task as well as many other measures of intelligence, executive functioning, and academic achievement. The parents completed a clinical interview and filled out parent-report measures of personality, behavior, and executive function. In order to obtain 3-D MRI images of the children's brains, the majority of the children were scanned for 8 minutes using a 1.5 Tesla Philips Intera scanner at a local hospital on a separate day. Fourteen of the children were scanned using 3T scanner. Although the images from the two scanners may differ in the quality of the images, the volumes obtained from both scanners should demonstrate no quantitative differences since tracing uses native space defined by the same parameters. T-1 weighted images were collected (TR = 30, TE = 4.6,

FOV = 22, flip angle = 35°, pixel matrix = 256 x 256, 200 axial slices, 0.8 mm gaps, thickness =
1.6 mm). After loading the raw DICOM images into the Analyze 11.0 software package, the
scans were aligned according to the anterior commissure-posterior commissure axis, the
longitudinal fissure, and the optic area to align the brain in all 3 planes. Before I began tracing
the OFC and the SFC, white matter maps were extracted, and the cingulate and precentral gyrus
were reliably traced by other graduate students. All measures, including inhibitory control
measures and brain volumes, were standardized by converting them to z scores for analysis so
that all measures would be on a similar scale.

CHAPTER 4

RESULTS

Preliminary Analyses of the Temperament Measures

Participants with less than 10% go accuracy for the no-go task ($n = 5$) were eliminated from the analyses as their performance likely represented a lack of response generally, which could make them appear to have good inhibitory control when they, instead, were minimally responding to the stimuli indiscriminately. Ten percent was selected as the cut-off because it is the standard cutoff invalidating similar clinical measures of inhibition including the TOVA (Leark et al., 2007) and the CPT (Conners et al., 2000). Cases with missing data were eliminated listwise for each analysis. Before conducting the factor analyses, the inhibitory control measures were examined for the criteria necessary for analysis. When examining the standardized scores of the temperament inhibitory control measure, BRIEF Inhibit, BRIEF Emotional Control, BRIEF Shift, and no-go accuracy, all were found to have a normal distribution, with no significant skewness or kurtosis. (No-go accuracy was calculated as the percentage of correct omissions in response to the no-go stimuli.) Visual inspection of bivariate scatterplots revealed evidence of generally linear relationships between the variables. The correlations among the parent-report measures, which ranged from .40 to .68, were high enough to indicate a significant relationship between the variables, but not so high that they suggested singularity. In contrast, no-go accuracy did not correlate significantly with any of the parent-report measures, and, therefore, it would not be appropriate to include it in a confirmatory factor analysis with the other measures. Using the Mahalanobis distance from the centroid, no multivariate outliers were found at the $p = .001$ level.

Factor Structure

All measures were standardized prior to the factor analyses to place no-go accuracy and the parent-report measures on a similar scale. The proposed model of inhibitory control was a one-factor model, which tests whether or not all of the measures contribute to the same latent variable. However, because the correlations between no-go accuracy and the other measures of inhibitory control were not significant, no-go accuracy was not included in the following factor analyses. One participant was dropped from the factor analyses in order to correct a problem with significant multivariate kurtosis, Mardia's coefficient = 8.45, $p < .05$. On closer examination, this participant was found to have had several perinatal medical issues that could identify this participant as an outlier who is not part of the intended population. Once this participant was dropped, multivariate kurtosis was no longer a problem in the analyses, Mardia's coefficient = -1.05, $p < .05$.

The EQS for Windows software program was used to conduct all of the confirmatory factor analyses. Maximum likelihood estimation was used in the following models. The hypothesized one-factor model is over-identified, meaning that the model has more data points than parameters to be estimated so that the analysis can be run. The model converged indicating that there was no evidence of singularity, as required in confirmatory factor analysis. The independence model for the variables was significant, χ^2 (6, $N = 73$) = 95.70, p < .001, indicating the hypothesis that the variables are not correlated can be rejected. The one-factor hypothesized model of parent-rated inhibitory control demonstrated some evidence of a good fit, χ^2 (2, $N = 73$) = 14.41, $p < .001$, CFI = .86, GFI = .91, RMSEA = .29, although there was some problems with the fit as well. A chi-square difference test demonstrated that the hypothesized model was significantly different from the uncorrelated independence model. The model with factor

loadings is presented in Figure 6. The oval represents the latent variable, and the rectangles

represent the indicators of the variable. Although the CFI and GFI indicate a good fit, the

RMSEA, which should be less than .08, indicates that there are problems with the residual. In

looking at the standardized residual matrix, the residual from the BRIEF emotional control and

the residual from the BRIEF shift were correlated (r = .26), when such residual correlations

should be below .1. This relationship between BRIEF Emotional Control and BREIF Shift is

consistent with recent evidence-based modifications to the BRIEF (Gioia, 2015).

Based on the evidence of the correlated residuals and the findings from Gioia (2015), an

alternative model was tested which allowed the error from BRIEF Emotional Control and BRIEF

Shift to correlate. The resulting model demonstrated an excellent fit, χ^2 (1, N = 73) = .01, p =

.920, *CFI* = 1.00, *GFI* = 1.00, *RMSEA* < .001. This alternative model with factor loadings is

presented in Figure 7. Since the original model is nested within this alternative model that

allows the error terms to correlate, the two models can be directly compared. Using a chi-square

difference test, the alternative model is significantly better than the original model, p < .001.

Because this second model has a significantly better fit than the original model, factor scores of

inhibitory control were obtained from the second model for use in the following analyses. EQS

was used to derive the factor scores for each participant. According to Bentler and Chou (1987),

a confirmatory factor analysis should have at least five participants per free parameters. Given

that the first model has 8 free parameters and the second has 9 free parameters, the sample size

of 73 is adequate for these analyses.

Preliminary Analyses of the Brain Volumes

The raw brain volumes, both the unparcellated and parcellated volumes, demonstrated normality, with no significant skewness or kurtosis. Visual inspection of scatterplots of the relationship between the brain volumes and inhibitory control showed no evidence of nonlinear relationships. Scatterplots of the residual and predicted residual demonstrated little evidence of heteroscedasticity. In order to determine the appropriate covariates for the regression analyses, correlations between the parent-rated inhibitory control factor score and several potential covariates, including age, gender, total brain volume, ADHD status, reading disability status, and full scale IQ, were calculated. The only significant correlation was between the inhibitory control factor and ADHD, $r = .54$, $p < .001$. Correlations are presented in Table 3. For the analyses predicting no-go accuracy, eight additional participants with less than 20% go accuracy were eliminated from the analyses because their no-go accuracy was thought to misrepresent their inhibitory capacity. Evidence for this was seen on visual inspection of the data, which showed that those with go accuracy below 20% also tended to have no-go accuracy over 90%, likely representing a tendency not to respond probably due to inattention to the task. The correlations between no-go accuracy and the potential covariates were also examined, and only gender demonstrated a significant correlation with no-go accuracy ($r = .50$, $p < .001$). In order to be consistent across analyses, gender and ADHD status were selected as covariates for the regressions predicting inhibitory control and no-go accuracy. Descriptive statistics for the inhibitory control measures and the brain volumes are provided in Table 4.

Relationship of the Inhibitory Control Factor to the Unparcellated Structures.

A series of hierarchical linear regressions, using the Enter method, were used to predict the factor scores of inhibitory control from the various cortical brain volumes. Six cases were

eliminated listwise due to missing data. On the first step, gender and ADHD status were entered as covariates. On the second step, the brain volumes (right OFC, left OFC, right SFC, and left SFC), which were expressed as percentage of total brain volume, were entered. The overall model was significant, $F(6, 60) = 6.56$, $p < .001$. The only significant predictor of the parent-rated inhibitory control factor was ADHD status, $\beta = .61$, $p < .001$. The other variables in the equation were not significant predictors of parent-rated inhibitory control. The results of all planned linear regressions predicting inhibitory control from the parcellated and unparcellated cortical regions are provided in Table 5.

Relationship of the Inhibitory Control Factor to the Parcellated Structures

Hierarchical linear regressions were conducted using the Enter method to examine the relationship between the parcellated structures and the parent-rated inhibitory control factor scores. Brain volumes are expressed as percent of total brain volume in the following analyses. With gender and ADHD on the first step and the four superior regions (right anterior SFC, right posterior SFC, left anterior SFC, and left posterior SFC) entered on the second step, the overall equation was significant, $F(6, 60) = 7.34$, $p < .001$. However, none of the superior brain segments were significant predictors of inhibitory control. The only variable that predicted inhibitory control was ADHD status, $\beta = .59$, $p < .001$. The findings were similar for the right OFC segments (right anterior medial OFC, right posterior medial OFC, right anterior lateral OFC, and right posterior lateral OFC). The overall equation was significant, $F(6, 60) = 7.08$, $p < .001$, but only ADHD status was a significant predictor, $\beta = .63$, $p < .001$, of inhibitory control. For the left OFC, the overall equation was significant, $F(6, 60) = 7.15$, $p < .001$, and ADHD status predicted inhibitory control, $\beta = .61$, $p < .001$. The left OFC segments did not predict inhibitory control.

Relationship of No-go Accuracy to the Unparcellated Structures

Parallel analyses were conducted predicting the computer-based measure of inhibitory control, no-go accuracy, instead of the parent-report inhibitory control factor, from brain volumes expressed as percent of total brain volume. Four cases were eliminated listwise due to missing data. With gender and ADHD status on the first step and the unparcellated brain volumes (right OFC, left OFC, right SFC, and left SFC) on the second step, the overall model was significant, $F(6, 54) = 4.95$, $p < .001$. No-go accuracy was predicted by gender ($\beta = -.47$, $p < .001$) and left SFC ($\beta = -.34$, $p = .028$). The right OFC demonstrated a trend toward predicting no-go accuracy, but it was not a significant predictor, $\beta = .38$, $p = .063$. The other variables in the equation were not significant predictors of inhibitory control as measured by no-go accuracy.

Relationship of No-go Accuracy to the Parcellated Structures

Similar hierarchical linear regressions were conducted using the Enter method to examine the relationship between the parcellated structures and the inhibitory control as measured by no-go accuracy. Brain volumes are again expressed as percent of total brain volume in the following analyses. With gender and ADHD entered on the first step and the four superior regions (right anterior SFC, right posterior SFC, left anterior SFC, and left posterior SFC) entered on the second step, the overall equation was significant, $F(6, 54) = 4.16$, $p = .002$. However, none of the superior brain segments were significant predictors of no-go accuracy. The only variable that predicted no-go accuracy was gender, $\beta = -.48$, $p < .001$, whereas the posterior left SFC demonstrated a trend toward being a predictor, $\beta = -.25$, $p = .080$. For the right OFC segments (right anterior medial OFC, right posterior medial OFC, right anterior lateral OFC, and right posterior lateral OFC), the overall equation was significant, $F(6, 54) = 3.42$, $p = .006$, but only gender was a significant predictor, $\beta = -.50$, $p < .001$, of inhibitory control. For

the left OFC, the overall equation was significant, $F(6, 54) = 3.44$, $p < .001$, and gender was the only significant predictor of inhibitory control, $\beta = -.49$, $p < .001$. The left OFC segments did not predict inhibitory control as measured by no-go accuracy.

Since this study used archival data, a post hoc power analysis was conducted using G*Power to determine the power for examining the significance of a single regression coefficient in a linear multiple regression. For six predictors, sample size of 73, the probability of an alpha error equal to .05, and a moderate effect size (.15), the power is .90. However, as the effect size is decreased (.02), power decreases down to .22. Although very few studies have used cortical brain volumes to predict inhibitory control, the few that do tend to have smaller effect sizes. Therefore, the current study may be missing effects due to its relatively small sample size and low power.

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Exploratory Analyses

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Exploration of Gender Differences in Go/No-go Performance

A multivariate analysis of variance was conducted to explore the relationship between the previously used covariates of gender and ADHD status with no-go accuracy and go-accuracy. In a 2 x 2 between-subjects MANOVA, the independent variables were gender and ADHD status. There were no univariate or multivariate within cell outliers found at $p < .001$. No-go accuracy varied significantly with gender, with $F(1, 59) = 16.65$, $p < .001$, $\eta^2 = .22$, but it did not vary significantly with ADHD status, with $F(1, 59) = .14$, $p = .715$, $\eta^2 = .002$. Girls tended to have higher no-go accuracy, with m ($n = 26$) $= 82.77$, $SD = 8.54$, whereas boys tended to demonstrate lower no-go accuracy, with m ($n = 37$) $= 66.92$, $SD = 17.09$. In examining go-accuracy, the MANOVA revealed that go-accuracy varied significantly with gender, $F(1, 59) = 7.62$, $p = .008$, $\eta^2 = .11$, but it did not vary significantly with ADHD status, $F(1, 59) = .12$, $p = .731$, $\eta^2 = .002$.

Girls tended to have lower go-accuracy, m ($n = 26$) = 47.79, SD = 17.79, and boys tended to have better go-accuracy, m ($n = 37$) = 62.12, SD = 18.86. Girls having higher no-go accuracy and lower go-accuracy appears to indicate that girls respond less often than boys respond, regardless of the condition. There was no interaction between gender and ADHD status for no-go accuracy, $F(1, 59) = .11$, $p = .918$, $\eta^2 < .001$, nor go accuracy, $F(1, 59) = .52$, $p = .472$, $\eta^2 = .009$. Using SPSS, the observed power for these corrected models was .95 for no-go accuracy and .73 for go-accuracy.

Exploratory Hierarchical Analyses of the Factor Scores from the Simple One-factor Model of Inhibitory Control

In order to gain additional understanding of the relationship between parent-rated inhibitory control and the OFC and SFC brain volumes, exploratory analyses were conducted. The near perfect fit indices of the more complex model may be an overestimation of fit related to statistical issues with a model that is barely overidentified ($df = 1$), so the following exploratory analyses used the factor scores from the simpler one-factor model. The hierarchical linear regression performed above predicting factor scores of inhibitory control from the more complex one-factor model which allowed the error from BRIEF- Emotional Control and BRIEF- Shift to correlate were repeated but predicting factor scores from the simple one-factor model instead. For the unparcellated structures (right OFC, left OFC, right SFC, and left SFC), which were expressed as percent of total brain volume, the overall model was significant, $F(6, 60) = 6.08$, $p < .001$. The only significant predictor of the parent-rated inhibitory control factor was ADHD status, $\beta = .60$, $p < .001$. The other variables in the equation were not significant predictors of parent-rated inhibitory control. For the parcelled SFC structures (right anterior SFC, right posterior SFC, left anterior SFC, and left posterior SFC), the overall equation was significant,

$F(6, 60) = 6.81$, $p < .001$. However, none of the superior brain segments were significant predictors of inhibitory control. The only variable that predicted inhibitory control was ADHD status, $\beta = .57$, $p < .001$. The findings were similar for the right OFC segments (right anterior medial OFC, right posterior medial OFC, right anterior lateral OFC, and right posterior lateral OFC). The overall equation was significant, $F(6, 60) = 6.69$, $p < .001$, but only ADHD status was a significant predictor, $\beta = .61$, $p < .001$, of inhibitory control. For the left OFC, the overall equation was significant, $F(6, 60) = 6.53$, $p < .001$, and ADHD status predicted inhibitory control, $\beta = .59$, $p < .001$. The left OFC segments did not predict inhibitory control.

Exploratory Backward Analyses of the Unparcellated Structures with Inhibitory Control

Exploratory linear regressions were conducted using the backward method, which places all variables in the equation simultaneously and uses lenient criteria for inclusion (p < .10) in the final equation to determine which variables are significant predictors of the dependent variable. It considers all the independent variables simultaneously before excluding non-significant ones, in order to attain the best combination of predictive variables. It should be noted that the backward method can capitalize upon chance, which is why it is considered more appropriate for exploratory analyses such as these. In this case, gender, ADHD status, right SFC, left SFC, right OFC, and left OFC were all entered (1) to predict the parent-rated factor scores of inhibitory control and (2) to predict inhibitory control as measured by no-go accuracy. In the exploratory analyses, the raw cortical volumes were used instead of expressing cortical volumes in terms of their percentage of total brain volume. The raw volumes were used for two reasons. First, total brain volume did not correlate with any of the measures of inhibitory control, suggesting that there was no need to account for its variability in the analyses. Second, especially for the parcellated OFC, the percentages of total brain volume tended to be very small, thereby reducing

the variability in volumes, which could, in theory, mask relationships between variability in cortical volume and other variables. The backward regression for the parent-rated inhibitory control factor score was significant, $F(1, 65) = 35.35$, $p < .001$, but the only significant predictor was ADHD status, $\beta = .59$, $p < .001$. Children with ADHD tended to have more problems with inhibitory control. The backward regression of no-go accuracy was also significant, $F(2, 58) = 13.23$, $p < .001$. Both gender, $\beta = -.42$, $p < .001$, and raw left superior cortex volume, $\beta = -.26$, $p = .025$, were significant predictors of no-go accuracy, consistent with the main analyses above. Girls tended to have better no-go accuracy, and smaller left SFC volume was associated with better no-go accuracy. Results from the exploratory linear regressions using the backward method of entry to predict inhibitory control from the unparcellated cortical regions are presented in Table 6.

Exploratory Analyses of the Parcellated SFC with Inhibitory Control

A linear regression, using the backward method, was conducted to examine inhibitory control with the potential predictors including gender, ADHD status, right anterior SFC, left anterior SFC, right posterior SFC, and left posterior SFC. The resulting linear regression of the simple parent-rated inhibitory control factor score was significant, $F(3, 63) = 14.58$, $p < .001$, and the factor scores were significantly related to ADHD status, $\beta = .57$, $p < .001$, and to anterior left superior volume, $\beta = -.20$, $p = .049$. Gender was not a significant predictor, $\beta = .18$, $p = .076$, but remained in the final equation. Children with ADHD tended to have more problems with inhibitory control, and larger left anterior superior volume was associated with better inhibitory control. The backward regression of no-go accuracy was also significant, $F(2, 58) = 13.98$, $p < .001$. Both gender, $\beta = -.43$, $p < .001$, and left posterior superior cortex volume, $\beta = -.28$, $p =$

.014, were significant predictors of no-go accuracy. Girls tended to have better no-go accuracy, and smaller posterior left SFC volume was associated with better no-go accuracy.

Exploratory Analyses of the Parcellated OFC with Inhibitory Control

Similar backward regressions were conducted to examine inhibitory control with the potential predictors including gender, ADHD status, the parcellated right OFC structures, and the parcellated left OFC structures. In the analysis of the inhibitory control factor score with the parcellated right OFC, the dependent variables initially entered into the backward regression were gender, ADHD status, right anterior medial OFC, right anterior lateral OFC, right posterior medial OFC, and right posterior lateral OFC. The resulting linear regression of the simple parent-rated inhibitory control factor score was significant, $F(3, 63) = 14.75$, $p < .001$, and the factor score was significantly related to ADHD status, $\beta = .60$, $p < .001$, and to right anterior medial orbital volume, $\beta = -.21$, $p = .041$. Gender was not a significant predictor, $\beta = .19$, $p = .066$, but remained in the final equation. Children with ADHD tended to have more problems with inhibitory control, and larger anterior medial right orbital volume was associated with better inhibitory control. The backward regression of no-go accuracy was also significant, $F(1, 59) = 19.78$, $p < .001$. Only gender, $\beta = -.50$, $p < .001$, significantly predicted no-go accuracy. None of the right OFC parcellated segments predicted no-go accuracy.

For the parcellated left OFC, the resulting linear regression of the simple parent-rated inhibitory control factor score was significant, $F(3, 63) = 14.38$, $p < .001$, and the factor score was only significantly related to ADHD status, $\beta = .603$, $p < .001$. However, both anterior medial left OFC volume, $\beta = -.19$, $p = .060$, and gender, $\beta = .17$, $p = .089$, remained in the final equation, even though they were not significant predictors at the $p = .05$ level. Children with ADHD had more problems with inhibitory control, and results suggest that, similar to findings

for the right OFC, larger anterior medial left orbital volume tended to be associated with better

inhibitory control. The backward regression of no-go accuracy was also significant, $F(1, 59) =$

19.78, $p < .001$. Only gender, $\beta = -.50$, $p < .001$, significantly predicted no-go accuracy. None

of the left OFC parcellated segments predicted no-go accuracy.

All twelve parcellated brain regions were entered in a backward regression next in order

to understand trends toward the parcellated brain regions and inhibitory control. The backward

regression of parent-rated inhibitory control was significant, $F(1, 59) = 19.78$, $p < .001$. Both

ADHD status, $\beta = .57$, $p < .001$, and the anterior region of the left superior, $\beta = -.20$, $p = .049$,

significantly predicted parent-rated inhibitory control. Gender also remained in the equation, $\beta =$

.18, $p = .076$. The backward regression of no-go accuracy with all of the brain regions was also

significant, $F(2, 64) = 20.84$, $p < .001$. Gender, $\beta = -.42$, $p = .001$, and posterior left superior, $\beta =$

-.28, $p = .016$, significantly predicted no-go accuracy. Results from the exploratory linear

regressions using the backward method of entry to predict inhibitory control from the parcellated

cortical regions are presented in Table 7.

CHAPTER 5

DISCUSSION

The purpose of this study was, first, to determine whether or not inhibitory control is best represented a single construct and, second, to examine the relationship between inhibitory control and the superior and orbital frontal cortices. This study was unique in its use of parcellated regions of the SFC and OFC and in the way it addressed the measurement issues present in previous studies by including both a lab-based and a parent-report measure of executive function, along with a parent-report measure of temperament. This study's findings on the relationships between the SFC and OFC with inhibitory control may advance the understanding of various forms of psychopathology that include problems in inhibitory control, as findings were present even when ADHD diagnosis was controlled.

Inhibitory Control as a Single Construct

Executive Function and Temperament

This study provides some empirical support for inhibitory control as a single construct across temperament and executive function, especially when using the same methodology. The first hypothesis of this study was that a simple one-factor model of inhibitory control incorporating inhibitory control measures from both fields would yield a "good" fit. A one-factor model of inhibitory control was supported, with a minor modification to the model that allowed the error terms of BRIEF-Shift and BRIEF-Emotional Control to correlate, as suggested by recent research on the BRIEF (Gioia, 2015). The similarity in inhibitory control across temperament and executive function measures is consistent with the previously discussed similarities in the developmental trajectory of inhibitory control as well as the brain mechanisms, neurochemistry, and genetics reported across both areas of the literature.

With regard to development, both areas of the literature suggest that early inhibitory control emerges around 1 year of age and goes through a period of development marked by rank-order instability, during which a child who is high in inhibitory control relative to their peers at one age may not remain high in inhibitory control when compared to same-age peers at a later age. Inhibitory control is fully developed around five or six years of age (Caspi, Roberts, & Shiner, 2005; Pritchard & Neumann, 2009; Vijayakumar et al., 2014), after which time, it continues to improve in efficiency, but rank-order stability remains relatively consistent (Jacques & Marcovitch, 2010).

Support for inhibitory control being the same concept across temperament/personality and executive function is also provided by the literature on the underlying biological mechanisms involved in inhibitory control. Both areas of the literature implicate the involvement of the DLPFC, the VLPFC, the anterior cingulate cortex, and the orbital frontal cortex in inhibitory control (Chavan et al., 2013; Durston et al., 2002; Fan & Posner, 2004; Luna, Padmanabhan, & O'Hearn, 2010; Mervielde & De Pauw, 2012; Ordaz et al., 2013; Posner & Rothbart, 2009; White et al., 2012; Zhang, 2010). Broadly, the brain mechanisms of inhibitory control are very similar across the two areas of study, despite some inconsistencies both within each field of study and across the two fields of study.

Similarly, the neurochemical and genetic underpinnings of inhibitory control demonstrate similarities across temperament/personality and executive function. Both areas of the literature suggest significant heritability of inhibitory control, with an important environmental contribution as well. More specifically, serotonergic and dopaminergic genes may play a role in inhibitory control, as seen in both domains of research (Barnes et al., 2011; Congdon et al., 2009; Cornish et al., 2005; Greene et al., 2008; Nederhof et al., 2010; Sheese et al., 2012; Smith et al.,

2012). In addition to genetic factors, a variety of environmental factors (i.e., parent personality, parenting styles, school environment, socioeconomic status) have been implicated in the development of temperament (Rothbart, 2012) and inhibitory control, or executive function more broadly (Dishion, 2016; Gagne & Saudino, 2010; van Lier & Deater-Deckard, 2016). These similarities in the understanding of inhibitory control in both the temperament/personality literature and the neuropsychological literature provide additional support for the finding that both areas of research are studying the same concept in slightly different contexts.

Theoretical Implications of Joining Temperament and Executive Function

This study provides evidence that executive function and temperament have at least one overlapping construct, inhibitory control. This part of the Effortful Control factor from Rothbart's three-factor model of temperament appears to overlap with the inhibitory control factor from Miyake's three-factor theory of executive function, likely measuring the same underlying construct. This overlap can be conceptualized visually and is presented in Figure 8. In Rothbart's model, the inhibitory control portion of the superfactor of Effortful Control may be the one piece that overlaps with executive functions, or, alternatively, other portions of effortful control (e.g., Attentional Control) also may overlap with executive function, as these were not studied. For example, attentional control is seen across both areas, with "controlled attention" being a vital component of working memory, one of the primary factors in the theory of executive function proposed by Miyake et al. (2000). In the same manner, Attentional Focusing is an important piece of the Effortful Control factor in the temperament model espoused by Rothbart et al. (2001).

Another explanation for this overlap, which is complementary to the first, is that "hot" executive function is the area where executive function overlaps with temperament. The

temperament concept of effortful control may be conceptualized as the application of executive function in emotional and social situations, thus, qualifying as "hot" EF, whereas the neuropsychological construct of executive function may be utilized in either non-emotional ("cold") or emotional ("hot") contexts (Zelazo & Carlson, 2012). In temperament, surgency/positive emotionality and negative emotionality are the two areas of emotional functioning, also called reactivity or motivational systems, that are then regulated by effortful control, which includes inhibitory control (Mervielde & De Pauw, 2012; Rothbart, 2012; Rothbart, et al., 2001). Impulsivity in temperament is a great example of this interaction, as it is thought to include both high approach/surgency and poor inhibition/regulation of that tendency toward sensation seeking (Sharma, Markon, & Clark, 2014). The reactivity portion of temperament has been connected with the arousability of the limbic system (particularly the amygdala) as well as other areas, whereas the regulation of these areas is strongly connected with the anterior cingulate cortex and the lateral prefrontal cortex (Fan & Posner, 2004, Posner & Rothbart, 2009; White et al., 2012). Similarly, in explaining hot EF, Zelazo et al. (2010) state that hot EF is thought to engage the orbital frontal cortex and sometimes the anterior cingulate cortex, which provide emotional information from the thalamus and amygdala for higher processing in the lateral prefrontal areas of the brain, such as the OFC, VLPFC, DLPFC, and rostrolateral PFC. The level of engagement of the amygdala, OFC, and ACC is related to the degree to which an EF task is emotionally-driven, in other words, how "hot" the EF is. The similarity in the underlying processes involved in the application of self-regulative processes in emotional contexts across temperament and hot EF provides further support for this conceptualization of effortful control in temperament being the same concept as hot EF.

This joint understanding of inhibitory control may allow research in the two areas of the literature to inform one another. Research on inhibitory control in the executive function literature can offer insights into inhibitory control in the temperament literature and vice versa. Being able to join the two areas may provide faster advances in our understanding of the development, biology, genetic basis, and measurement of inhibitory control. This overlap between the domains also opens the door for research directly examining the nature of this overlap between temperament and executive function.

Modality Issues in the Measurement of Inhibitory Control

This study provides empirical support that inhibitory control is a single construct that spans both temperament and executive function fields, when measured within the same modality of parent-report. However, the computer-based measure of inhibitory control (no-go accuracy) did not correlate significantly with any of the parent-report measures of inhibitory control, regardless of whether they were temperament or executive function measures. This finding of differences in inhibitory control by measurement method are consistent with research that has found that the balance of genetic and environmental contributions also differs by measurement method, with genetics accounting for 38% of the variance in laboratory-based inhibitory control and 58% of the variance in parent-rated inhibitory control (Gagne & Saudino, 2010). Although some studies have supported significant correlations between parent-rated or self-rated temperament measures of inhibitory control and lab-based measures (Goldsmith & Gagne, 2012; Logan, Schacher, & Tannock, 1997; Reck & Hund, 2011), other evidence in the literature, like this study, has demonstrated no or weak correlations between lab-based measures of inhibitory control and report measures of personality and executive function (Bodnar et al., 2007; Huizinga et al., 2006; Unsworth et al., 2009). In a recent study, two performance-based inhibitory control

measures were found to be inconsistent with parent-report measures of effortful control (Samyn, Roeyers, Bijttebier, Rosseel, & Wiersema, 2015). The lack of correspondence between parent-report and lab-based measures may be the result of measurement error in either or both methods, or it may reveal that the lab-based measure and the parent-report measures are not measuring the same construct.

There may be several reasons why the no-go task does not appear to be measuring the same construct as the parent-report measures. First, the differences may be due to measurement errors, such as various forms of parental bias and the accuracy of the parents' memory. Also, report measures that examine behaviors in daily life can be affected by many factors (i.e., life demands, emotional context, reward contingencies) other than executive function. The lab-based measure may be a more "pure" measure of inhibitory control, as several types of studies suggest that parents are not always good raters of their children. Parent-report measures often demonstrate moderate to low inter-rater correlations with other types of raters (Gartstein, Bridgett, & Low, 2012), and some studies have suggested that teachers are better raters than parents, especially with regard to hyperactivity and inattention (Dyer et al., 2013). Of the studies that did demonstrate significant correlations between parent-rated temperament and lab-based measures, two were looking at these measures in toddlers, who may be easier for parents to rate accurately because they likely spend more time with them than they do with older children (Goldsmith & Gagne, 2012; Reck & Hund, 2011).

Second, the reverse may be true in that parent-ratings are more accurate as broad measures that examine the child's behavior over time across many situations, making it a more accurate measure than a one-time, rather simple, lab-based computer task. Additionally, a one-time computer task may be a poor measure of inhibitory control because it is measuring more

than one skill, as per the task impurity problem (Miyake & Friedman, 2012). The one task may measure multiple skills, and consequently multiple skill weaknesses can lead to the same poor performance on a single lab-based measure. For example, the go/no-go task is also heavily influenced by the attentional skills of the child. A child with inattention may miss many no-go responses accidentally, inflating his/her overall no-go accuracy. Although this study sought to adjust for this problem by eliminating children with low go-accuracy from the study, the variability in no-go performance across children may still be heavily influenced by their attentional capabilities, although this is unlikely as ADHD status did not predict no-go accuracy. Other researchers have purported that the go/no-go task actually measures set shifting in that the child has to be able to switch quickly from one set of rules to another as the stimulus demands (Miyake & Friedman, 2012). Hence, no-go accuracy may measure inhibitory control along with attentional control and set shifting. In summary, no-go accuracy may be a poor measure of inhibitory control either because it measures inhibitory control in a single task at a single moment in time, unlike broader parent-report measures, or because it measures more than one skill (i.e., inhibitory control, attention, and/or set shifting). Most likely, both the weaknesses of parent-report measures and the weaknesses of our lab-based measure contributed to the lack of relationship between the two types of measures in this study.

Another explanation for the differences across measurement modality is that parent-report measures are examining inhibitory control within an emotional or social context, indicating that parent-report measures of executive function may be examining "hot" executive function, as opposed to many lab-based measures, like the one in this study, that measure "cool" executive function. No published studies have directly linked "hot" inhibitory control performance with a parent-report executive function measure of inhibitory control. However,

one study looked at the relationship between lab-based measures of "hot" and "cool" executive function with parent-report measures of temperament (Hongwanishkul et al., 2005). Interestingly, the study found that "hot" EF was not related to any of the temperament measures, whereas the "cool" EF measures were related to parent-rated Effortful Control, although this relationship became non-significant after controlling for chronological age. The study by Hongwanishkul et al. examined this relationship between temperament and executive function in three to five year olds, an age at which inhibitory control is still thought to be developing. Further research is needed to explore whether lab-based "hot" executive function measures correlate with the parent-report measures of inhibitory control in both temperament and executive function in older children and adults. Additionally, the two "hot" EF measures in the study by Hongwanishkul et al. did not correlate with one another, indicating that these hot EF measures are either measuring different facets of a complex, multi-faceted construct or two different constructs. In future research, it may be helpful to explore hot EF's relationship with parent-report measures by using a variety of hot and cool EF measures in order to reduce possible problems in measurement error. The study by Hongwanishkul et al. also used very different cool and hot EF tasks, so that they may have been measuring different aspects of executive function. In future studies, it may be beneficial to use an established cool EF measure, like the go/no-go task, and add a motivational component in order to make the task hot. By using this method, one can compare performance on tasks that, in theory, should only differ in whether or not the task involves an emotional component. Any differences in how the hot EF and cool EF tasks relate to parent-report measures then would be attributable to their hot or cool status.

116

Setting measurement error aside, the constructs measured by the parent-report measures and the go/no-go task simply may be different constructs or constructs with very little overlap. No-go accuracy may represent a small aspect of inhibitory control that is sufficiently small that it does not correlate well with the much broader parent-report measures of inhibitory control. For example, the parent-report measures examine the child's ability to apply his/her inhibitory control skills in daily life. This application of inhibitory control requires the child to understand the social situation, to determine what the correct response should be, to inhibit an undesirable but prepotent response, and to coordinate all of these skills, whereas go/no-go tasks do not require coordination of all of these additional skills. Correlations between parent-reported inhibitory control and performance-based measures (i.e., a go/no-go task or Stroop tasks) tend to be low or nonsignificant but can vary by the performance-based measure used (Ritter, Perrig, Steinlin, & Everts, 2014). Bodnar, Prahme, Cutting, Denckla, & Mahone (2007) examined the relationship between commercially available go/no-go tasks and parent-rated Inhibit on the BRIEF. They found that CPT-II scores (r = -.12) and TOVA scores (r = -.02) demonstrated very low correlations with the BRIEF Inhibit scale. In fact, they found no significant correlations between any of the BRIEF scales and CPT-II or TOVA performance.

Several studies have examined the relationship between the BRIEF Inhibit scale and inhibitory control performance on Stroop tasks. Ritter et al. (2014) found no significant correlation between interference errors on a standard Stroop task and parent-rated Inhibit from the BRIEF in 8- to 12-year-old children with a history of preterm birth. Sorensen et al. (2014) found that Stroop interference errors did predict parent-rated BRIEF Inhibit scores; however, these errors only explained 4 percent of the variance after controlling for age and reaction time for the task, neither of which predicted the Inhibit score. Lalonde et al. (2013) found strong

correlations between the BRIEF Inhibit scale and commission errors made on a virtual reality version of the Stroop task, whereas the correlations were low between the BRIEF Inhibit scale and commission errors on a paper and pencil version of the Stroop task. The virtual reality task had a virtual person giving the directions and naming the colors either correctly or incorrectly throughout the task. The child then had to respond whether or not the virtual person was correct. The use of interaction with a virtual person may make this task more similar to everyday situations that are measured on the BRIEF. Consistent with this idea, Lalonde et al. also found non-significant correlations between the BRIEF Inhibit scale and a more difficult version of the virtual reality Stroop task that did not include a virtual person in the actual task, just in the instructional phase. This second task does not involve "interpersonal" interaction during the task, and its difficulty is thought to be higher, perhaps exceeding the difficulty of most everyday situations. One explanation for these varied results is that the more similar the performance-based task is to real life demands and difficulty, the more likely it is to correlate with a parent-report measure. Therefore, these parent-report measures, whether they are executive function measures or temperament measures, are looking at the application of inhibitory control within the context of a wide range of other types of social skills and social knowledge.

As an explanation for poor correlations between parent-report and performance-based measures of inhibition, some researchers distinguish between cognitive inhibition and behavioral inhibition, with Stroop performance falling into the first category and go/no-go tasks and the BRIEF falling into the second category (Ritter et al., 2014; Sorensen et al., 2014). However, the research does not support this distinction. If this were true, performance on go/no-go tasks should correlate more highly with the BRIEF, which is not supported by the above-mentioned literature or this study. In fact, both Stroop tasks and go/no-go tasks seem to demonstrate

similarly low or nonsignificant correlations with parent-rated inhibitory control. Further, Friedman & Miyake (2004) found that performance-based measures of cognitive and behavioral inhibition collapsed into a single coherent variable within a structural equation model and were not empirically distinguishable. Taken together, the lack of correlation between the parent-report measure of inhibitory control and no-go accuracy is more likely due to the differences in measurement method (parent-report vs. performance based measure) and the resulting constructs being measured than the difference between cognitive and behavioral forms of inhibitory control.

Relationship of Inhibitory Control to the Cortical Structures

The Relationship of Inhibitory Control to the Unparcellated Structures

The second hypothesis was that larger bilateral OFC and bilateral SFC volume would be associated with better inhibitory control. Because the laboratory-based inhibitory control measure did not fit into the factor model of parent-rated inhibitory control, the relationship of the brain regions and these inhibitory control measures was analyzed separately. After controlling for gender and ADHD status, none of the unparcellated frontal structures predicted the factor score of parent-rated inhibitory control in the planned analyses. In contrast, left SFC volume and, to a lesser degree, right OFC volume predicted inhibitory control as measured by no-go accuracy. Interestingly, smaller left SFC volume was associated with better inhibitory control, contrary to the original hypothesis, which predicted that larger bilateral SFC volume would be associated with better inhibitory control. Although not statistically significant, the trend toward larger right OFC volume being associated with better inhibitory control was consistent with the original hypothesis. The lack of bilateral findings is discussed in greater depth with regard to the parcellated structures in later sections.

Explanations for the Weak Correspondence between Parent-rated Inhibitory Control and the Unparcellated Brain Regions

One reason that this study did not find a significant relationship between the parent-rated IC factor and the unparcellated OFC and SFC may be that the power was too low to find a small effect. According to the power analyses, the sample size in this study is adequate for finding a medium or large effect size, but it may be too low to find a small effect size, which may exist but not be detected by this study. One example of this was the study by Whittle et al. (2008), which found small, but significant effects, when relating volumetric differences in prefrontal structures to parent-reported emotional control. Another possible reason for the lack of relationship between the unparcellated SFC and OFC and parent-rated inhibitory control is that these brain regions each as a whole incorporate many functions, and inhibitory control may only be one of the many functions of the OFC and SFC, thereby, only accounting for a tiny proportion of the volume of these structures. The OFC is implicated in smell identification, sensory processing, delayed alternation, response inhibition, perceptual reasoning, social reasoning, learning abilities, and emotional control (Hof, Mufson, & Morrison, 1995; Kahnt, Chang, Park, Heinzle, & Haynes, 2012; Lezak, Howieson, Bigler, & Tranel, 2012; Schilling et al., 2011; Spinella, 2002), and the SFC is implicated in planning and execution of complex movements, control of goal-directed movements, executive function more generally, monitoring of all nervous system activities, and higher level cognitive functioning (Lezak et al., 2012). Although the unparcellated cortical areas in the present study did not relate to the parent-rated inhibitory control factor, a few of the parcellated regions did (anterior left superior as well as left and right anterior medial OFC). This relationship between parent-rated inhibitory control and specific

regions of the OFC and SFC provides additional support that only portions of these structures are involved in inhibitory control, whereas other regions likely have other functions within the brain.

Conversely, the OFC and SFC are both thought to be only a part of a larger inhibitory control network, as described previously. More specifically, the OFC interacts with the VLPFC and DLPFC as part of a planning and goal-directed behavior network, and sections of the SFC (SMA and preSMA) play a primary role in a motor response network along with the posterior parietal cortex and the putamen. Some of the literature indicates that the OFC and SFC may play a role in inhibitory control, but they are not the key players in inhibitory control. For example, Aron et al. (2014) argue that the IFC, not the OFC, is the primary area involved in inhibitory control. Further support for the OFC's smaller role in inhibitory control is provided by a study comparing adults with OFC lesions with controls on the BRIEF scales of executive function (Lovstad et al., 2012). They found no difference between the two groups on the BRIEF Inhibit scale, which is thought to be the best measure of inhibitory control on the BRIEF. It should be noted that the OFC lesions were only partial, such that the area of the OFC that was damaged could affect the findings. According the findings of the present study, damage to the anterior medial regions of the OFC would be most likely to demonstrate problems in inhibitory control, whereas damage to other areas of the OFC may not produce such deficits. Also of note, the present study's parent-rated inhibitory control factor consisted of the temperament measure of inhibitory control as well as all three scales from the BRIEF's Behavioral Regulation Index (BRI). Interestingly, the study by Lovstad et al. did find group differences between those with OFC lesions and those without such lesions on the higher-order inhibitory factor of the Behavioral Regulation Index (BRI), which was driven by significant differences between groups on both BRIEF Emotional Control scale and the BRIEF Shift scale. The Lovstad et al. study

suggests that the OFC is likely involved in the more emotional and motivational aspects of inhibitory control. However, Lovstad et al. studied adults, whereas the present study examined children. In order to explore the Lovstad et al.'s findings within the present dataset, simple correlations were performed between the three BRIEF scales and raw volume of the unparcellated right and left OFC. Like the Lovstad et al. study, right and left OFC were not related to the Inhibit scale, $r = .02, p = .876$; $r = -.07, p = .563$, respectively, whereas Emotional Control was significantly correlated with left OFC ($r = -.30, p = .015$) and demonstrated a trend toward significant correlation with the right OFC ($r = -.23, p = .059$). Even though the two studies have very different methodology (i.e., comparing adults with and without lesions as opposed to studying OFC volume in children), the findings are similar, suggesting that the OFC is more involved in the emotional aspects of inhibition.

In the present study, it is likely that parent-rated inhibitory control, when measured in this manner, is a broad concept that, in addition to the inhibitory control networks, utilizes many areas of the brain, including areas related to social reasoning, social knowledge, social awareness, emotional regulation more broadly, impulsivity, etc. Thus, a weakness in emotional regulation, which engages other areas of the brain (i.e., the amygdala), could produce poor parent-rated inhibitory control scores, whereas another child may demonstrate a weakness in inhibitory control because of an actual weakness in the inhibitory processes that are associated with the OFC or SFC. In keeping with the concept of the brain working in networks, it is likely that no one structure is the "seat" of inhibitory control; rather, it is the coordination of several brain structures in network with one another. In summary, parts of the OFC and SFC appear to be part of larger neural networks that are involved in inhibitory control. The role of specific

areas of the OFC and SFC in inhibitory control is described in more detail in the following section.

Relationship of Inhibitory Control to the Parcellated Structures

The third hypothesis predicted that larger bilateral lateral OFC volume, as well as larger bilateral posterior SFC, would be associated with better inhibitory control. In the planned analyses, none of the parcellated regions of the SFC or OFC predicted the factor score of parent-rated inhibitory control. Similarly, none of the parcellated regions of the SFC or OFC predicted factor scores of no-go accuracy in the planned analyses. The lack of significant findings is likely due to low power due to an inadequate sample size to find smaller effects. It also may be due to controlling for total brain volume as it did not predict inhibitory control. Having controlled for it may have consumed variance that was explanatory rather than error. The exploratory analyses suggested that larger left anterior superior volume, larger right anterior medial orbital volume, and, to a lesser degree, larger left anterior medial orbital volume were associated with better parent-rated inhibitory control, whereas only smaller left posterior SFC volume was associated with better no-go accuracy. The fact that the parent-rated inhibitory control and no-go accuracy correlated with different regions of the brain provides further evidence that these are actually measuring at least somewhat different constructs, suggesting that these differences are not just due to differences in measurement error. Given that the results from the planned analyses may have been limited by statistical power or by other methodology used, the following discussion incorporates findings from both the planned analyses and the exploratory analyses in order to provide a richer discussion of inhibitory control and its relationship with the OFC and SFC.

Right orbital frontal cortex and inhibitory control. In terms of the link between the OFC and inhibitory control, this study suggested stronger right than left involvement in both

parent-rated inhibitory control (stronger anterior medial right OFC than anterior medial left OFC involvement in the exploratory analyses) and in no-go accuracy (a trend toward unparcellated right OFC predicting no-go accuracy). Although this study's hypothesis and some studies suggest bilateral involvement of the prefrontal cortex in inhibitory control, including the orbital frontal cortex (Casey et al., 1997; Krueger et al., 2011; Whelan et al., 2012), many of the functional imaging studies of inhibitory control in executive function suggest the right prefrontal cortex, including the OFC, plays a larger role in inhibitory control than left, particularly for go/no-go tasks (Aron et al., 2014; Barnes et al., 2010; Chavan et al., 2013; Durston et al., 2002; Moriguchi & Hiraki, 2013). Some executive function studies suggest that the left inferior frontal cortex, which is directly adjacent to, and connected with the left OFC, is more active during go/no-go tasks, but this may be because the design of the go/no-go task differed slightly from the typical go/no-go task, making it more of a decision task than an inhibitory task (Aron et al., 2014). Generally, the modest connection found between right OFC volume and no-go accuracy in this study is consistent with the literature examining lab-based inhibitory control measures, like no-go accuracy (Casey et al., 1997; Whelan et al., 2012), but not with parent-rated temperament measures, which tend to correlate more with left prefrontal volumes than with right (Schilling et al., 2011; Whittle, 2008). However, only one of these studies looked at OFC structural volume, as opposed to OFC activity, in relation no-go accuracy, and they found no relationship between OFC and go/no-go commissions in a sample similar to the sample in this study (86 children with ADHD and controls between 8 and 13 years of age in Mahone et al., 2011). Similarly, in the present study, the relationship between OFC volume and no-go accuracy was not significant, although a trend was found toward right OFC volume predicting no-go accuracy. These subtle differences in findings may be due to low effect sizes and low power in

124

both studies. Alternatively, differences in the samples between the two studies (i.e., children with reading disabilities included in the present study only, different proportions of children with ADHD in each study) may have impacted the results. In Mahone's study, they found that the relationship between other prefrontal brain regions (i.e., left medial prefrontal cortex, left lateral premotor cortex, and left supplementary motor cortex) and no-go accuracy differed by gender, age, and ADHD status, which suggests that subtle differences in the samples could lead to different results. Another reason the study by Mahone may have found slightly different results is because their methods for segmentation of the brain areas were different and, therefore, may have had different boundaries capturing slightly different areas of the brain. Another possibility is that Mahone used a different cut off to remove non-responders (those with poor go-accuracy) from their data set, but they did not report whether they did this.

In both the planned and the exploratory analyses, the lack of relationship between the unparcellated OFC volume and parent-reported inhibitory control is not consistent with the executive function imaging studies which suggest that the OFC, particularly the right, is involved in inhibitory control. However, the one volumetric study of OFC volume and effortful control as measured by parent-report in the temperament literature indicated that the left OFC was involved in inhibitory control (Whittle, 2008), whereas the present study's planned analyses implicated the right OFC in inhibitory control, but only when measured by the no-go task. A similar study that found impulsiveness, a construct closely related to inhibitory control, was related to smaller left OFC volume, not right OFC volume (Schilling et al., 2011). One possible explanation for parent-reported temperament being more associated with left OFC is that the temperament measures incorporate a broader range of control in different contexts, as demonstrated by the Whittle (2008) study, which measured the broader construct of effortful control and by the

Schilling et al. (2011) study, which measured impulsivity which is a broader construct including both inhibitory control and a tendency to be outgoing and sensation seeking. Several studies have suggested that the left OFC plays a role in the conscious, intentional control of emotions (Dyer et al., 2015). Perhaps the reason this study did not find the link between the left OFC and parent-reported inhibitory control is that our measure of parent-reported inhibitory control is a narrower measure, focusing on inhibitory control specifically and less on other elements of emotional and behavioral regulation. Another explanation is that left and right OFC are involved in inhibitory control, but this bilateral contribution is seen more clearly when looking at specific regions of the OFC as we found in the exploratory analyses of the parcellated OFC.

Anterior medial orbital frontal cortex and inhibitory control. Even though the unparcellated OFC was not implicated in parent-reported inhibitory control in either the planned or the exploratory analyses, this study implicated the bilateral anterior medial OFC, but particularly the right anterior medial OFC, in inhibitory control as measured by parent-report in exploratory analyses. Although much of the temperament literature links lateral portions of the prefrontal cortex more generally to modulation of attention, emotion, and behavior (Luna, Padmanabhan, & O'Hearn, 2010; Fan & Posner, 2004; Posner & Rothbart, 2009; White et al., 2012), these conclusions are based mostly on functional imaging, not structural volume of these regions. The connectivity of the lateral OFC with the DLPFC and inferior prefrontal cortex, which are strongly implicated in inhibitory control (Kahnt et al., 2012), further supports the idea that the lateral regions of the OFC may be involved in inhibitory control. However, these functional differences and connectivity may not be reflected in volumetric differences, which could explain why no relationship was found between lateral OFC volumes and inhibitory control. In terms of the anterior medial OFC, this study suggested that it is related to parent-

reported inhibitory control, which is consistent with literature that links more emotional executive function (i.e., reward sensitivity and impulsivity) with the medial OFC in functional MRI (Wilbertz et al., 2012). Parent-rated inhibitory control is likely observed and measured by parents in emotional contexts of daily life, and parent-rated inhibitory control questionnaires may focus more on symptoms of impulsivity as well. In examining lateral versus medial OFC involvement, another complicating issue is the central region of the OFC, which demonstrates connectivity with the dorsal anterior cingulate cortex and lateral prefrontal cortex (Kahnt et al., 2012), both of which are strongly implicated in inhibitory control. Unfortunately, because this central region does not have any identifiable anatomical boundaries, it is not possible to know if this central region was captured in the lateral areas or the medial areas of the OFC. Depending on the parcellations of lateral versus medial, different studies could find that the lateral or the medial areas are more involved in inhibitory control based on whether the central region was captured in the lateral or medial regions.

Left superior frontal cortex and inhibitory control. Although this study's hypothesis suggested bilateral SFC involvement, the results suggested that only left SFC was implicated in inhibitory control This study is consistent with several studies that have demonstrated a link between response inhibition and the posterior portion of the SFC through studies examining connectivity (Aron et al., 2014), transcranial stimulation (Hsu et al., 2011), and ERP (Kenemans & Kahkonen, 2011; Lansbergen, Bocker, Bekker, & Kenemans, 2007; Logemann et al., 2013). However, these studies did not implicate the left specifically, as seen in both the planned analyses and the exploratory analyses. In terms of structural volumetric studies, the study by Mahone et al. (2011) demonstrated results very similar to the current study, with left SMA volume predicting poor performance on no-go accuracy. However, they found that reduced left

SMA volume predicted poor inhibitory control, whereas this study found that reduced left SFC was related to better inhibitory control. One reason for this difference could be that the posterior SFC in the present study may include not only the SMA but also the preSMA and other posterior regions of the SFC. These other regions may explain the differences in findings between the two studies. Alternatively, subtle differences in the samples may help explain the different findings. In the Mahone et al. study, left SMA volume was associated with age, but only among the controls, not among the children with ADHD. The differences in participant age and in the proportion of children with ADHD may explain why larger left SMA volume is sometimes associated with better no-go accuracy or sometimes worse. In older children and in children without ADHD, more pruning of unnecessary connections to improve efficiency in these areas is likely to have occurred and would be associated with better inhibitory control. However, if this were true, one would expect this study (with more ADHD kids and younger children) to have better accuracy associated with larger volumes in contrast to the Mahone study, which has a smaller proportion of ADHD kids and more older children. If the Mahone study used less stringent cut offs for go-accuracy, the trend might have been reversed, with non-responders looking like they have very good inhibitory control as measured by no-go accuracy.

In this study's exploratory analyses, larger anterior left SFC was related to better inhibitory control as measured by the parent-report factor, whereas smaller posterior left SFC was related to better inhibitory control as measured by no-go accuracy. These findings lend support to the idea that the parent-rated factor and no-go accuracy are measuring different constructs in that they are associated with different areas of the brain. The posterior SFC was expected to be related to no-go accuracy, based on the literature of the pre-supplementary motor and supplementary motor areas that are incorporated in this posterior region. The fact that this

finding was only true for the left posterior SFC, and not the right posterior SFC, was consistent with the literature, particularly the study by Mahone et al. (2011), and makes sense given that the majority of the participants in this study were right-handed and, therefore, would control right-handed movement in the no-go task with the left side of their premotor cortex. In contrast, parent-reported inhibitory control was related to the anterior left SFC. Although the SFC is implicated in inhibitory control as a performance monitoring region, no studies have specifically looked at the relationship between the anterior region of the SFC (right or left) and inhibitory control. Few studies have looked specifically at the functionality of the SFC more generally, but one study found activation of the anterior prefrontal cortex, specifically an area that appears to run along the lateral edge of the anterior superior frontal cortex, during a task requiring the person to hold goals in mind while exploring and processing secondary goals in an integration of working memory and attentional control (Koechlin, Basso, Pietrini, Panzer, & Grafman, 1999). Certainly, parent-rated inhibitory control, which measures the application of inhibitory control in daily life, in which there are likely to be many competing goals considered, is more likely to engage this integration of working memory and inhibitory control than the simple go/no-go computer task. Therefore, given that the anterior regions of the SFC are more tertiary and integrative than the more posterior regions of the SFC, the anterior frontal SFC's connection to parent-rated inhibitory control in this study may be due to this integration of competing goals in daily life.

<p style="text-align:center;">**Other Factors Affecting Inhibitory Control**</p>

Gender Differences in Inhibitory Control

In addition to the findings related to the stated hypotheses, this study demonstrated interesting findings concerning the relationship inhibitory control with gender, age, and ADHD

status. In this study, gender was a significant predictor of no-go accuracy, with girls having better no-go accuracy than boys. Regardless of ADHD status, which did not predict no-go accuracy, girls tended to have better no-go accuracy, whereas boys had better go-accuracy. Generally, girls tended not to respond and boys tended to respond whether they were supposed to or not. In contrast to this finding, a study of younger children (5 to 6 year olds) found that gender did not predict go accuracy or no-go accuracy, although it did predict response time, with girls responding more slowly (Torpey et al., 2011). Furthermore, on a similar task, the TOVA-Auditory Version, the norms for boys and girls are very similar for the number of omission errors (go accuracy). Nonetheless, the TOVA norms show that boys make slightly more commission errors (no-go accuracy) than girls up through age ten, but the average number of commission errors looks pretty similar between boys and girls by 11 years of age (Leark, Dupuy, Greenberg, Corman, & Kindschi, 1996). Much of the present study's sample was between the ages of 8 and 10, although it did include some children ages 11 and 12. No other studies seem to support the current finding that boys tend to respond more and girls tend to respond less overall. One possible explanation for this could be subtle differences in the test administration. For example, on the go/no-go task in this study, children were reminded to stay on task anytime their attention wandered away from the task. In contrast, commercial versions of this task (the TOVA and the CPT) do not allow redirection during the task. Offering redirection to the children during the task could have changed the children's pattern of responding, especially with regard to omissions which would affect go accuracy. However, it is unclear why the difference in directions would create a gender difference on both go accuracy and no-go accuracy. Another possible reason for this difference between boys and girls could be due to the subtype of ADHD expressed, with the current study's sample having twice as many boys ($n = 13$) as girls ($n = 6$)

130

with the combined type of ADHD (ADHD-C). (In contrast, the number of boys and girls with ADHD-PI was similar, $n = 15$ and $n = 17$, respectively.) This explanation, however, does not seem likely given the current study and previous research do not appear to support this idea, as discussed later in the ADHD section.

Gender was not a predictor for the parent-rated inhibitory control factor, likely because the BRIEF scales, which make up three of the four measures included in the factor, are normed by age and gender. However, the BRIEF norms are separated by gender because there are normative significant differences between the two groups; boys demonstrate slightly higher average inhibitory control problems than girls in the 8- to 10-year-old age group, although this difference is very small in the 11 to 13-year-old age group (Gioia et al., 2000). In the temperament literature, girls demonstrate better inhibitory control (Else-Quest, Hyde, Goldsmith, & Van Hulle, 2006), and this was true for our temperament measure as well, with a significant difference in the temperament inhibitory control problems expressed in z scores between boys ($M = .22$, $SD = .97$) and girls ($M = -.29$, $SD = 1.00$), $t(71) = -2.22$, $p = .030$.

Developmental Issues in Inhibitory Control

Although age was not a significant covariate in this this study, developmental issues may still be important to consider in interpreting the results. For the parent-rated inhibitory control factor, age was likely not a predictor because three of the four measures included in the inhibitory control factor were based on norms that were already based on age. Interestingly, age was not a predictor for no-go accuracy either, perhaps due to the high percentage of children with ADHD or due to the difficulty of balancing no-go accuracy with go omissions. Some studies have suggested that children's accuracy on a go/no-go task reaches a plateau while their response time continues to improve with age (Pritchard and Neumann, 2009). As stated in the

discussion above on gender, the normative data for the Auditory version of the T.O.V.A. indicates that children's omission errors (errors in go accuracy) and commission errors (errors in no-go accuracy) tend to plateau at about age 10 for girls and at about age 11 for boys (Leark, Dupuy, Greenberg, Corman, & Kindschi, 1996). This plateau may explain why age was not a significant predictor of no-go accuracy in this study.

Despite age not being a significant covariate predicting inhibitory control, age and developmental differences are likely explanations for some of the more unexpected findings concerning the relationship between specific prefrontal volumes and inhibitory control performance. According to the literature, the lateral prefrontal cortex, which can include portions of the orbital frontal cortex, is one of slowest developing brain regions (Wiebe et al., 2014a) and continues to develop throughout childhood and into adulthood. Previous research suggests that cortical connectivity and specific cortical areas mature at different rates (Smith et al., 2012), and increased connectivity in frontoparietal areas along with decreased connectivity within the parietal area are associated with better executive function more generally (Hwang, Velanova, & Luna, 2010). Cortical thinning in some cortical areas, particularly the left anterior cingulate, can be related to better effortful control in adolescents (Vijayakumar et al., 2013), whereas larger volumes of other cortical areas, the left supplementary motor cortex in particular, are associated with better inhibitory control in children 8 to 13 years old (Mahone et al., 2011). Functional imaging studies have demonstrated that younger children demonstrate larger areas of activation during inhibitory control tasks than seen in older children and adults, who tend to demonstrate more focused activation. While these larger areas of activation may be related to poorer performance, broader activation is not necessarily related to larger cortical volumes. During reward processing on an inhibitory control task, Padmanabhan et al. (2011) compared

OFC activation in children (8-13 years old), adolescents, and adults. The adults demonstrated increased OFC activation compared with the children and the adolescents during the task, whereas the children tended to show more prefrontal activation that may be related to increased effort. Although the task in the study measured "hot" EF, compared to the "cool" EF go/no-go task in the present study, the pattern of broader, less-focused activation during inhibitory control tasks in children seems to be evident in the "hot" EF task. In contrast, other studies have demonstrated very little activation in the right ventrolateral prefrontal cortex during a no-go task in comparison with the level of activation seen in this area in adults (Bunge et al., 2002). Taken together, the relationship between inhibitory control and areas of activation, the volume of the activation, and actual cortical volume can all vary by age, as the prefrontal cortex is continuing to develop and prune throughout development.

Generally, performance on tasks of inhibition is still variable in children, perhaps due to other skills that influence task performance that are still developing (Huizinga et al., 2006; Pritchard & Neumann, 2009), such as general cognitive efficiency or processing speed (Span, Ridderinkhof, & van der Molen, 2004). In addition, the relationship between inhibitory control and other skills also changes over development. For example, inhibitory control is highly correlated with emotional control in younger children (4 year olds) but less so in older children (5 year olds) (Carlson & Wang, 2007). It follows that as these skills become more differentiated from one another, so too their underlying neural correlates also change and differentiate over the course of development. Depending on the stage of development, different skills may contribute to performance on a go/no-go task, and inhibitory control in general, so that the cortical areas of importance to good performance may vary by the skills required for success on this task at different ages. Based on the literature, one would expect that the present study would

demonstrate an association between larger volumes and better inhibitory control in this age group. Contrary to the literature, this study demonstrated that smaller posterior left SFC volume was associated with better inhibitory control performance on the go/no-go task. Mahone et al. (2011) found the reverse; smaller SMA volume was associated with worse no-go accuracy, although this finding was only true for the children with ADHD, not for controls who demonstrated no association between SMA volume and no-go accuracy. Because the present study looked at SMA volume and no-go accuracy in a combined group of children with and without ADHD, the children without ADHD could contribute to differences in findings between the two studies.

As described previously, another possible reason for this difference is that the two studies used different methods and boundaries for defining the posterior portion of the superior frontal cortex. The area included in the study by Mahone et al. is smaller and focused on just the SMA, as opposed to this study which examined the entire posterior section of the superior frontal cortex, which includes the SMA, preSMA, and the more lateral regions of the SFC. Since the literature indicates that different cortical areas develop at different rates, it is possible that some of the posterior SFC region in our study has begun to demonstrate the pruning and thinning seen in older children and adolescents as their neurocognitive processes increase in efficiency. Thus, smaller posterior SFC volume would be associated with more efficient inhibitory control. It is unclear how the broader activation seen in the literature for children in our age range would be reflected in cortical volumes. These developmental differences seen in the literature do suggest, however, that the pattern of the relationship between inhibitory control and OFC and SFC is not likely to generalize well to adolescents and adults. Additional research is needed to explore these developmental differences.

ADHD and Inhibitory Control

Discussion of the effects of ADHD is particularly important, as approximately two thirds of the participants were diagnosed with ADHD. In this study, ADHD status was a significant predictor of parent-rated inhibitory control, but not of no-go accuracy. The relationship between parent-rated inhibitory control and ADHD is consistent with research demonstrating deficits in executive function, including inhibitory control, in children with ADHD (Brocki et al., 2008; Leark et al., 1996; Nigg, 2001; Pauli-Pott et al., 2013; Reddy et al., 2007; Shimoni et al., 2012; Walcott & Landau, 2004; Wiebe et al., 2014a). Although ADHD status is generally related to poor no-go accuracy, the literature provides evidence that performance on go/no-go type tasks is not always predictive of ADHD status (Hall et al., 2016). There are several proposed explanations for this finding. First, go/no-go tasks are usually administered in a quiet setting, one-on-one with an examiner, as opposed to a classroom or work setting with many people and many distractions. Second, individuals with ADHD may not have difficulty attending to a simple short task like a go/no-go style task, whereas they may find it more difficult to attend to more complicated tasks requiring extensive coordination of executive function, such as organization and self-monitoring. Third, the difficulties with attention and impulsivity in children with ADHD may lead to different patterns of performance in a go/no-go task. Children with ADHD may have difficulty with attending to the task and may not respond even when they are supposed to, or they may be impulsive and anticipate or respond when they are not supposed to respond. These patterns of responding may lead to either high or low no-go accuracy in children with ADHD.

In thinking through the relationship between ADHD status and inhibitory control, logic suggests that children with the combined subtype of ADHD (ADHD-C), which includes, by

definition, a hyperactive/impulsive component, would have more difficulty on an inhibitory control task than children with the predominantly inattentive subtype (ADHD-PI). However, prior research has indicated that children with both ADHD-C and ADHD-PI demonstrated similar problems with inhibitory control tasks (Huang-Pollock, Mikami, Pfiffner, & McBurnett, 2007). This was also true in the present study, as a 1 x 3 between-subjects multivariate analysis of variance demonstrated that ADHD subtype did not predict go accuracy, $F(2, 70) = 1.07$, $p = .348$, or no-go accuracy, $F(2, 70) = .97$, $p = .383$. Although children with both subtypes of ADHD demonstrate difficulties in inhibitory control, the children with the predominantly inattentive type of ADHD are not described as "impulsive." This finding is consistent with Sharma et al.'s (2014) conceptualization of impulsivity which incorporates both extreme approach/sensation-seeking and poor inhibitory control. In other words, children with the predominantly inattentive subtype of ADHD tend to have problems in inhibitory control, whereas children with the combined type of ADHD are likely to have difficulty with both aspects of impulsivity: poor inhibitory control and extreme approach/sensation-seeking.

Very little research has looked directly at the relationship between inhibitory control, ADHD, and cortical volumes. Mahone et al. (2011) found several differences in brain volume that varied by gender, ADHD status, and no-go accuracy. For example, Mahone et al. found that boys and girls with ADHD demonstrated reduced left supplementary motor complex (SMC) volumes, girls with ADHD demonstrated reduced left lateral premotor cortex (LPM) gray matter volumes, and boys with ADHD demonstrated reduced white matter volumes in the left medial PFC. In their study, smaller left SMC gray matter volumes predicted worse no-go accuracy, but only in children with ADHD. Smaller left LPM gray matter volumes were associated with more variability in go/no-go performance, but only in girls with ADHD. While ADHD status has been

associated with cortical differences, the present study demonstrated that some of the brain

structures (anterior left SFC, anterior medial right OFC, and to a lesser degree anterior medial

left OFC) were able to predict inhibitory control (as measured by the parent-rated factor scores)

above and beyond ADHD status, which also predicted parent-rated inhibitory control. In order

to explore variability due to ADHD status in the present dataset, two simple linear regressions

were conducted predicting no-go accuracy from posterior left SFC volume for each group,

similar to the study by Mahone et al. (2011). In our dataset, smaller posterior left superior

volume predicted better no-go accuracy in children with ADHD, $\beta = -.39$, $t(1, 37) = -2.60$, $p =$

.013, and demonstrated a trend toward the same effect in the children without ADHD, $\beta = -.43$,

$t(1, 19) = -2.09$, $p = .051$. Additional studies are needed to understand how ADHD status and the

cortical volumes contribute jointly and individually to inhibitory control. Understanding these

differences in cortical structure between children with and without ADHD can lead to an

improved understanding of the neural mechanisms involved in the development of ADHD. In

advancing our knowledge concerning the relationship between ADHD, inhibitory control,

temperament, executive function, and particular regions of the prefrontal cortex, a more

comprehensive understanding of the underlying mechanisms in ADHD can be established. This

more comprehensive understanding has implications for early identification, prevention,

diagnosis, and treatment of ADHD.

Theoretical Implications

In addition to clinical implications for children and adults with ADHD, which will be

reported subsequently, this study has theoretical implications for understanding many types of

psychopathology that involve problems in inhibitory control. First, by combining temperament

and executive function literature, we can get a richer understanding of the etiology and

symptomology of a variety of internalizing and externalizing disorders. A joint understanding of inhibitory control can allow both areas of the literature to inform one another, and this common understanding can make it easier to study combined effects and interactions between dimensions of temperament and executive function and how together they contribute to psychopathology. A few studies have looked at the contributions of executive function and personality/temperament to various outcome measures, such as academic performance and risk-taking behaviors (Lahat et al., 2012; Neuenschwander et al., 2013). However, few studies have examined the combined contribution of executive function and temperament to psychopathology, and more research is needed to understand these interactions fully informed by past research in both fields of study.

A joint understanding of inhibitory control also has implications for understanding the neural networks involved in inhibitory control as well as associated psychopathology. Specifically, in the present study, smaller left anterior SFC, smaller right anterior medial OFC, and to a lesser degree smaller left anterior medial OFC were associated with problems in parent-rated inhibitory control, above and beyond ADHD status when combining across temperament and executive function measures. Additionally, larger left posterior SFC was associated with problems in no-go accuracy, after controlling for ADHD status, although ADHD status was not a significant predictor of no-go accuracy. Even though ADHD is often conceptualized as a weakness in inhibition, ADHD status alone is not adequate to explain the variance in inhibitory control. Although ADHD status was able to account for some of the variability in parent-rated inhibitory control measures, specific cortical regions explained additional variance in inhibitory control above and beyond ADHD status. These cortical regions may be involved in aspects of inhibitory control that are not captured by ADHD criteria, or these cortical regions may be related to a spectrum of difficulties in inhibitory control that are not captured by the binary

nature of ADHD status. By combining what is known about the neural mechanisms involved in executive function and in temperament/personality, one can obtain a more complete understanding of how these underlying neural mechanisms interact and contribute to psychopathology and/or adaptive functioning.

Third, a joint understanding may challenge our conceptualization of the development of temperament over time. Although conceptualizations of temperament have varied over the decades, one traditional and well-accepted conceptualization of temperament suggested that it is biologically or genetically based, present at birth, and relatively stable. Over the last couple of decades, a richer understanding of temperament has been developed, acknowledging the impact of environment on the development of temperament. By thinking of inhibitory control as both a temperament trait and an executive function, we can consider a richer understanding of how it continues to develop throughout childhood and even into young adulthood, as many forms of executive function are thought to continue developing as the brain continues to develop into young adulthood. As this study defines temperament and personality as overlapping, if not equivalent, constructs, a joint understanding of inhibitory control may impact our understanding of the development of temperament and personality and the role executive function may play in that development across the lifespan.

Clinical Implications

Implications for Assessment

The findings of this study also have implications for the assessment of disorders involving inhibitory control problems, particularly ADHD. As the parent-report measures of inhibitory control were not related to no-go accuracy, reliance on purely performance-based measures (i.e., TOVA and CPT) or on purely parent-report measures (i.e., the BRIEF) may not

capture the inhibitory control difficulties a child may be experiencing. Similarly, assessment of ADHD with adults should involve both performance-based measures and self-report measures. The present study did demonstrate that ADHD status only predicted inhibitory control as measured by parent-report, providing some support for parent-report measures being more closely related to ADHD than performance-based measures. However, performance-based inhibitory control measures provides additional information that is not captured by parent-report measures. A study by Kamradt, Ullsperger, and Nikolas (2014) found that task performance and report measures were helpful in identifying different deficits in adults with ADHD. Tasks of arousal/activation and response inhibition predicted ADHD symptoms and severity generally. Executive function report measures of time management were associated with inattention, and ratings of restraint predicted hyperactivity/impulsivity over and above the task performance. Assessing inhibitory control in multiple ways may also be helpful in assessing a variety of disorders since deficits in performance-based measures and report measures of inhibitory control have been associated with a variety of psychopathology, including conduct problems, aggressive behavior, borderline personality disorder, and depression, as discussed previously. Thorough assessment of inhibitory control may be useful for refined diagnosis of ADHD and for assessing a variety of other possible separate or co-occurring disorders. A more refined assessment of inhibitory control may also provide information on risk-factors for other possible comorbid disorders.

Implications for Clinical Interventions

The findings of this study also have implications for clinical interventions for children and adults with ADHD as well as other forms of psychopathology with deficits in inhibitory control. By creating an understanding of temperament as something that is continuing to

develop throughout childhood, one opens up more possibilities for intervening and addressing the development of maladaptive temperament traits. In other words, by acknowledging that inhibitory control is still developing and is influenced by the environment, we allow room for preventative measures that could prevent forms of psychopathology related to poor inhibitory control. Along these same lines, interventions that target executive function also may be helpful in addressing some issues that were previously thought to be more temperament- or personality-based. Most interventions for executive function are based on improving working memory; however, Maraver et al. (2016) recently demonstrated a successful intervention for improving inhibitory control and found that this improvement generalized to performance on a reasoning task. This intervention involved a computer-based executive function training focused on building skills related to response inhibition and interference control. Although the intervention study by Maraver et al. was conducted with undergraduate students who were part of a non-clinical population, an intervention like this, which can improve inhibitory control performance and can generalize to other areas of functioning, has the potential to have a profound impact on many psychological and behavioral disorders (i.e., ADHD, depression, conduct problems, personality disorders, academic problems, schizophrenia, OCD, obesity, addiction) that are associated with poor inhibitory control.

Strengths, Weaknesses, and Future Directions

The strengths of this study, as previously stated, included the use of both temperament and executive function measures of inhibitory control and the inclusion of both computer-based and parent-report measures of inhibitory control to provide a broad assessment of inhibitory control. Additionally, the diversity of this sample, in terms of attention problems and ADHD, provides a wide range of inhibitory control abilities. Additionally, the inclusion of children with

reading disabilities contributes to the generalizability of the findings, as the comorbidity of reading disabilities with ADHD is 25-40 percent (Wilcutt et al., 2010). Given these diagnoses, the results are likely to generalize well to children seen in most outpatient clinics. In terms of the cortical brain volumes, the innovative parcellation of the orbital frontal cortex and the superior frontal cortex provided a method for examining specific areas of these structures. These parcellated brain regions are more specific and likely contain fewer functional areas than studies that have looked only at unparcellated regions. The utility of my parcellation method was supported by the specific relationships between inhibitory control, as measured in different ways, and different parcellated areas of the OFC and SFC.

Although this study offers several strengths, the study also demonstrates several weaknesses, some of which could have been addressed more easily if this were not an archival study. First, it would have been better to include more measures of inhibitory control in order to create an even more comprehensive inhibitory control factor. Ideally, at least two measures in each category of measure (parent-report executive function measures, parent-report temperament measures, lab-based executive function measures, and lab-based temperament measures) would have been ideal. Only the last of the four types listed was not represented at all in this study. Having multiple lab-based measures can help address the task impurity problem by providing multiple measures of inhibitory control which minimizes the impact of other skills needed for good performance on one specific task.

Additionally, a larger sample would have allowed for stronger power to detect small effect sizes, and it would provide the opportunity to compare groups. For example, with a larger sample size, I could have compared the relationship between inhibitory control and these prefrontal cortical volumes in children with ADHD, children with reading disabilities, children

with both disorders, and children with neither disorder. In particular, it would be helpful to examine whether these findings are driven by the high percentage of children with ADHD or whether these findings hold true in children regardless of ADHD status. Along these same lines, looking at inhibitory control and these prefrontal regions across childhood and into adulthood may be another important area of research, particularly because past research has suggested that children with ADHD demonstrate slower development of the prefrontal cortex than their peers without ADHD, and some abnormalities in development of cortical thickness also have been indicated (Krain & Castellanos, 2006). Future studies could explore this relationship in children, adolescents, and adults not only with ADHD but also with a variety of other forms of psychopathology. Possibly due to low power, several of the findings in this study were weak and only seen in the exploratory analyses, and replication is needed, especially because very few studies have looked at gray matter volumes in these regions in relation to inhibitory control.

Another direction for future research is exploring the relationship between temperament, inhibitory control, emotional control, and "hot" executive function. In this study, adding a couple of lab-based executive function measures that measure inhibitory control in an emotional context may have provided a better understanding for why this study's lab-based measure, which was a "cool" executive function measure, did not correlate with the parent-report measures of inhibitory control. More research is needed to explore the role of the emotional and social context in the questionnaires in contrast to a non-emotional lab-based measure.

This study only examined the volumes of two cortical structures, the orbital frontal cortex and the superior frontal cortex, in relation to inhibitory control. Future studies should examine the volume of other areas (i.e., VLPFC, DLPFC, and cingulate) that are implicated in inhibitory control. As used in this study, parcellation of these structures may provide additional

information about the specific areas and neural networks involved in inhibitory control. In addition to examining inhibitory control in relation to a variety of structures, future studies should explore a variety of other temperament/personality traits or executive functions and their relationship to the OFC and SFC, as parcellated in this study. In particular, it would be helpful to examine emotional control in relation to these structures. Future studies such as these would provide additional evidence validating the utility of my parcellation methods for dividing these structures into areas with functional differences.

Conclusion

Overall, this study contributes a richer understanding of inhibitory control in both the temperament literature and the executive function literature. This study provides evidence that the left superior frontal cortex (particularly the posterior section, but also the anterior section depending upon the function measured), the right orbital frontal cortex (particularly the anterior medial section), and to a lesser degree the left orbital cortex (particularly the anterior medial section) are related to inhibitory control. The specific brain regions varied by the type of measurement used (computer-based versus parent-report). In examining the roles of the different cortical regions, the OFC and the left anterior SFC appear to be more strongly related to inhibitory control when there is an emotional context, and the left posterior SFC is more strongly related to inhibitory control when the measure is motor-based, as in the go/no-go task.

These findings support the utility of a new parcellation method which could be applied to clarify the role of the different areas of the OFC and SFC in other forms of executive function, other temperament traits, and other emotional and behavioral problems (i.e., depression, anxiety, and aggression). Additionally, this study has implications for understanding many types of psychopathology (i.e., ADHD, depression, conduct problems, personality disorders, and eating

disorders), which are associated with problems in inhibitory control. In terms of clinical assessment, this study suggests that assessment of inhibitory control problems in ADHD and other disorders should incorporate more than one type of measurement modality. Because of recent research demonstrating interventions that can improve executive function, future research is needed to explore the utility of these interventions in treating a variety of psychological disorders related to inhibitory control deficits. Overall, this study contributes to a richer understanding of inhibitory control and its underlying neural mechanisms.

Table 1

Participant Demographics (n=73)

Gender		
	Male	39 (53%)
	Female	34 (47%)
Age (Range: 8 years, 0 months to 12 years, 8 months; Median = 9 years, 0 months, Mode = 8 years, 0 months)	Mean	9.81 years
	SD	1.42 years
Race/Ethnicity		
	African American	1 (1%)
	Hispanic/Spanish/Latino	4 (5%)
	Non-Hispanic Caucasian	63 (86%)
	Other	5 (7%)
Group/Diagnosis		
	ADHD	28 (38%)
	Reading Disability (RD)	12 (16%)
	ADHD and RD	21 (29%)
	Controls and Other	12 (16%)
SES score (Range: 3-8)	Median	6
(Maternal Education)	Mean	5.82
	SD	1.14
Handedness (Range: 0-100)		
Mean	Mean	84.52
SD	SD	19.58

Note: Handedness was scored as a percentage of right-handedness, ranging from 0 (left-handed) to 100 (right-handed). Other group/diagnosis includes those with an abuse history, birth complications, or psychological diagnoses that were missed on intake.

Table 2

The Concepts from Rothbart's Inhibitory Control Measure and the Corresponding Items for This Study

Matching inhibitory control concept (from Rothbart's measures of temperament)	Item for ages 8-11 [from our dataset (n = 65)]	Item for age 12 [from our dataset (n = 8)]
	BASC items (on a four point scale with 1 = Never, 2 = Sometimes, 3 = Often, and 4 = Almost Always)	
Can stop when told to	(reverse) Has poor self-control (BASC #148)	(reverse) Has poor self-control (BASC A# 45)
Can slow down when needed	(reverse) Is unable to slow down (BASC #20)	NONE
Ease of waiting turn to talk	(reverse) Interrupts others when they are speaking (BASC #102) (reverse) Cannot wait to take turn (BASC #6)	(reverse) Interrupts others when they are speaking (BASC A #80) (reverse) Cannot wait to take turn (BASC A #15)
Using caution in dangerous situations	Acts in a safe manner (BASC #35)	Acts in a safe manner (BASC A #33)
Plans ahead before acting	(reverse) Acts without thinking (BASC #116)	(reverse) Acts without thinking (BASC A #20)
Follows directions	Listens to directions (BASC #13)	Listens to directions (BASC A #65)
	Big 5 items (on a three point scale with 1 = Rarely, 2 = Sometimes, and 3 = Almost Always)	
Ease of waiting for something positive	(reverse) If my child wants to do something, he/she is not capable of waiting and has to do it immediately (Big 5 #39) (reverse) My child is not patient (Big 5 # 41)	(reverse) If my child wants to do something, he/she is not capable of waiting and has to do it immediately (Big 5 #39) (reverse) My child is not patient (Big 5 # 41)

Table 3

Correlations Between Factor Scores, No-go Accuracy, and Possible Covariates

	1	2
1.Factor score (N = 73)		
2.No-Go Accuracy (N = 63)	-.167	
3.Age in months	.054	-.135
4.Gender	.228	-.487*
5.FSIQ	-.046	.042
6.ADHD Status	.564*	-.104
7.RD Status	-.052	.004
8.Total Brain Volume	-.058	-.205

Note: *Correlation is significant at $p < .01$.

Table 4

Means and Standard Deviations (SD) for the Inhibitory Control Measures and Brain Volumes by ADHD Status and Gender

	Total	ADHD Status		Gender	
		ADHD	No ADHD	Male	Female
Inhibitory Control (IC)					
Temperament IC	6.98 (1.81)	6.23 (1.49)	8.50 (1.43)	6.55 (1.74)	7.47 (1.80)
BRIEF-Inhibit	56.9 (13.8)	61.3 (13.1)	47.7 (10.4)	58.5 (14.4)	55.0 (13.1)
BRIEF-Shift	54.9 (12.3)	57.2 (12.0)	50.1 (11.7)	57.8 (12.7)	51.4 (11.0)
BRIEF-Emotional Control	54.5 (11.8)	55.8 (10.6)	51.9 (13.8)	56.4 (11.6)	52.4 (11.9)
No-go Accuracy	75.5 (16.4)	74.9 (17.0)	76.8 (15.4)	67.3 (17.1)	85.0 (8.8)
Brain Volumes (percent of					
total brain volume)					
Right SFC	3.50 (.53)	3.51 (.50)	3.47 (.59)	3.45 (.57)	3.55 (.49)
Anterior Right SFC	2.02 (.16)	2.04 (.28)	1.97 (.38)	1.99 (.31)	2.04 (.33)
Posterior Right SFC	1.48 (.33)	1.47 (.34)	1.41 (.30)	1.46 (.34)	1.51 (.31)
Left SFC	3.29 (.52)	3.30 (.53)	3.27 (.50)	3.29 (.55)	3.29 (.49)
Anterior Left SFC	1.86 (.33)	1.86 (.31)	1.87 (.37)	1.84 (.36)	1.88 (.30)
Posterior Left SFC	1.42 (.34)	1.42 (.36)	1.40 (.29)	1.42 (.33)	1.41 (.34)
Right OFC	2.12 (.35)	2.18 (.34)	2.00 (.34)	2.08 (.38)	2.16 (.31)
Anterior Medial Rt OFC	.93 (.16)	.95 (.18)	.88 (.11)	.93 (.19)	.92 (.13)
Anterior Lateral Rt OFC	.74 (.20)	.78 (.19)	.67 (.19)	.71 (.20)	.78 (.19)
Posterior Medial Rt OFC	.30 (.09)	.30 (.09)	.30 (.10)	.29 (.11)	.30 (.08)
Posterior Lateral Rt OFC	.11 (.06)	.11 (.06)	.10 (.06)	.11 (.06)	.11 (.06)
Left OFC	2.03 (.28)	2.06 (.27)	1.97 (.30)	1.99 (.32)	2.08 (.23)
Anterior Medial Lt OFC	.90 (.16)	.92 (.14)	.87 (.18)	.89 (.16)	.92 (.16)
Anterior Lateral Lt OFC	.66 (.14)	.67 (.13)	.63 (.14)	.63 (.14)	.69 (.13)
Posterior Medial Lt OFC	.31 (.08)	.31 (.08)	.31 (.08)	.31 (.09)	.30 (.06)
Posterior Lateral Lt OFC	.11 (.06)	.12 (.07)	.11 (.05)	.11 (.07)	.12 (.06)

Table *5*

Hierarchical Multiple Regression Analyses Predicting Inhibitory Control from Parcellated and Unparcellated Cortical Volumes, Gender, and ADHD Status

| | Inhibitory Control | | | |
| | Parent-rated Factor | | No-go Accuracy | |
Predictor	ΔR^2	β	ΔR^2	β
Model of unparcellated OFC and SFC				
Step 1	.393***		.256***	
ADHD		.612***		-.154
Gender		.119		-.472***
Step 2	.004		.099*	
Right OFC volume		-.070		.380*
Left OFC volume		.023		-.183
Right SFC volume		-.022		.008
Left SFC volume		.061		-.344**
Model of Parcellated SFC				
Step 1	.393***		.256***	
ADHD		.593***		-.081
Gender		.117		-.479***
Step 2	.031		.060	
Right anterior SFC volume		.003		-.021
Right posterior SFC volume		.004		.022
Left anterior SFC volume		-.131		-.005
Left posterior SFC volume		.147		-.254*
Model of Parcellated Right OFC				
Step 1	.393***		.256***	
ADHD		.625***		-.076
Gender		.113		-.497***
Step 2	.022		.019	
Right anterior medial OFC volume		-.064		.034
Right anterior lateral OFC volume		-.062		-.009
Right posterior medial OFC volume		.002		.034
Right posterior lateral OFC volume		.112		.113
Model of Parcellated Left OFC				
Step 1	.393***		.256***	
ADHD		.607***		-.070
Gender		.128		-.493***
Step 2	.024		.020	
Left anterior medial OFC volume		-.080		.019
Left anterior lateral OFC volume		.007		-.051
Left posterior medial OFC volume		-.077		-.047
Left posterior lateral OFC volume		.149		.193

Note: All volumes are expressed as percent of total brain volume.

* $p < .10$. ** $p < .05$. *** $p < .001$

Table 6

Exploratory Backward Multiple Regression Analyses Predicting Inhibitory Control from Unparcellated Cortical Volumes, Gender, and ADHD Status

| | Inhibitory Control | | | |
| | Parent-rated Factor | | No-go Accuracy | |
Predictor	*F*	β	*F*	β
Model of unparcellated OFC and SFC				
Model 1	6.693***		5.289***	
ADHD		.610***		-.166
Gender		.168		-.407**
Right OFC volume		-.105		.336*
Left OFC volume		-.073		-.155
Right SFC volume		-.003		.054
Left SFC volume		-.018		-.393**
Final Model	35.351***		13.234***	
ADHD		.594***		
Gender				-.417**
Left SFC volume				-.263**

Note: All volumes are expressed as the raw volume of the structure.
* $p < .10$. **$p < .05$. ***$p < .001$

Table 7

Exploratory Backward Multiple Regression Analyses Predicting Inhibitory Control from Parcellated Cortical Volumes, Gender, and ADHD Status

| | Inhibitory Control | | | |
| | Parent-rated Factor | | No-go Accuracy | |
Predictor	*F*	β	*F*	β
Models of parcellated SFC				
Model 1	7.517***		4.611*	
ADHD		.579***		-.094
Gender		.172*		-.400**
Right anterior SFC volume		-.099		-.036
Right posterior SFC volume		.065		.083
Left anterior SFC volume		-.181		-.032
Left posterior SFC volume		.087		-.335**
Final Model	14.578***		13.976***	
ADHD		.567***		
Gender		.179*		-.425***
Left anterior SFC volume		-.198**		
Left posterior SFC volume				-.283**
Models of Parcellated Right OFC				
Model 1	7.440***		3.543*	
ADHD		.629***		-.077
Gender		.164		-.528***
Right anterior medial OFC volume		-.147		.061
Right anterior lateral OFC volume		-.132		-.018
Right posterior medial OFC volume		-.033		.042
Right posterior lateral OFC volume		.106		.133
Final Model	14.752***		19.781***	
ADHD		.604***		
Gender		.187*		-.501***
Right anterior medial OFC volume		-.210**		
Models of Parcellated Left OFC				
Model 1	7.004***		3.490*	
ADHD		.599***		-.072
Gender		.169		-.504***
Left anterior medial OFC volume		-.117		.036
Left anterior lateral OFC volume		-.081		-.058
Left posterior medial OFC volume		-.073		-.002
Left posterior lateral OFC volume		.111		.176
Final Model	14.375***		19.781***	
ADHD		.603***		
Gender		.171*		-.501***
Left anterior medial OFC volume		-.191*		

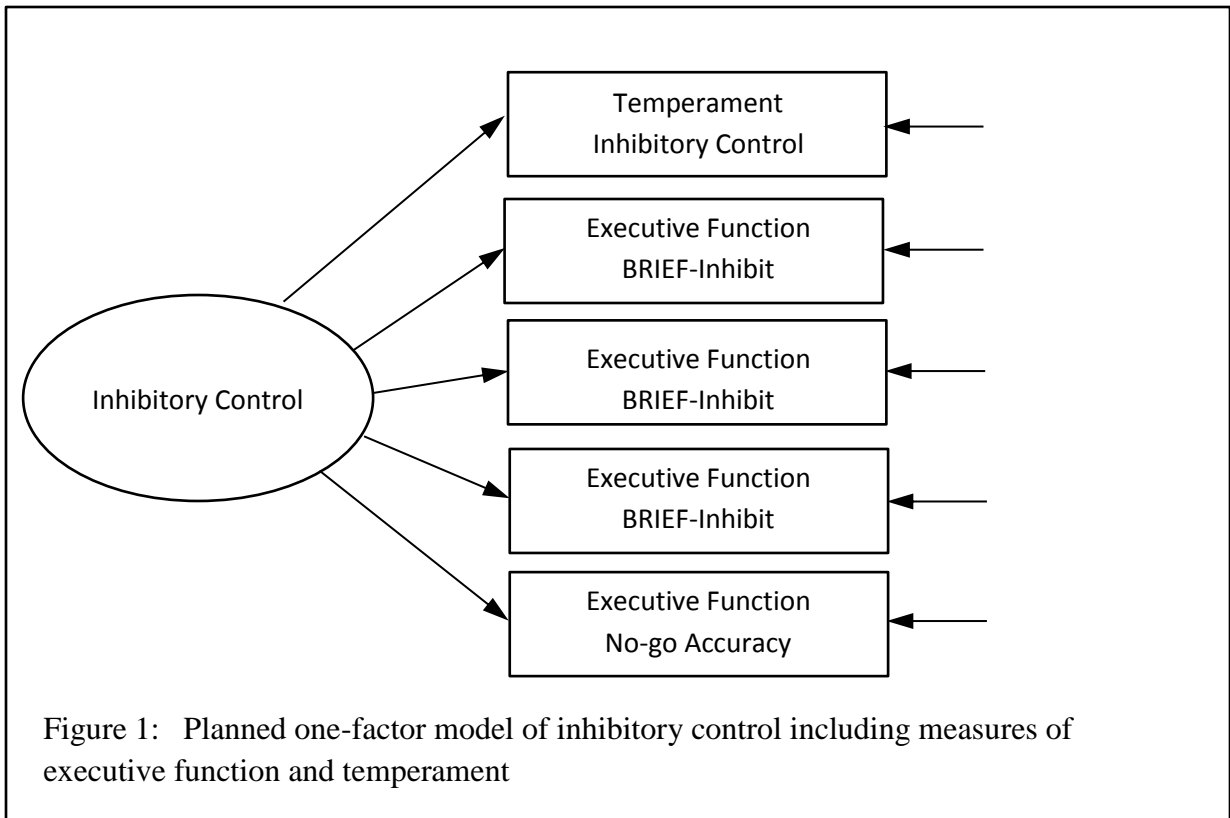*Note:* All volumes are expressed as the raw volume. *$p < .10$. **$p < .05$. ***$p < .001$

Figure 1: Planned one-factor model of inhibitory control including measures of executive function and temperament
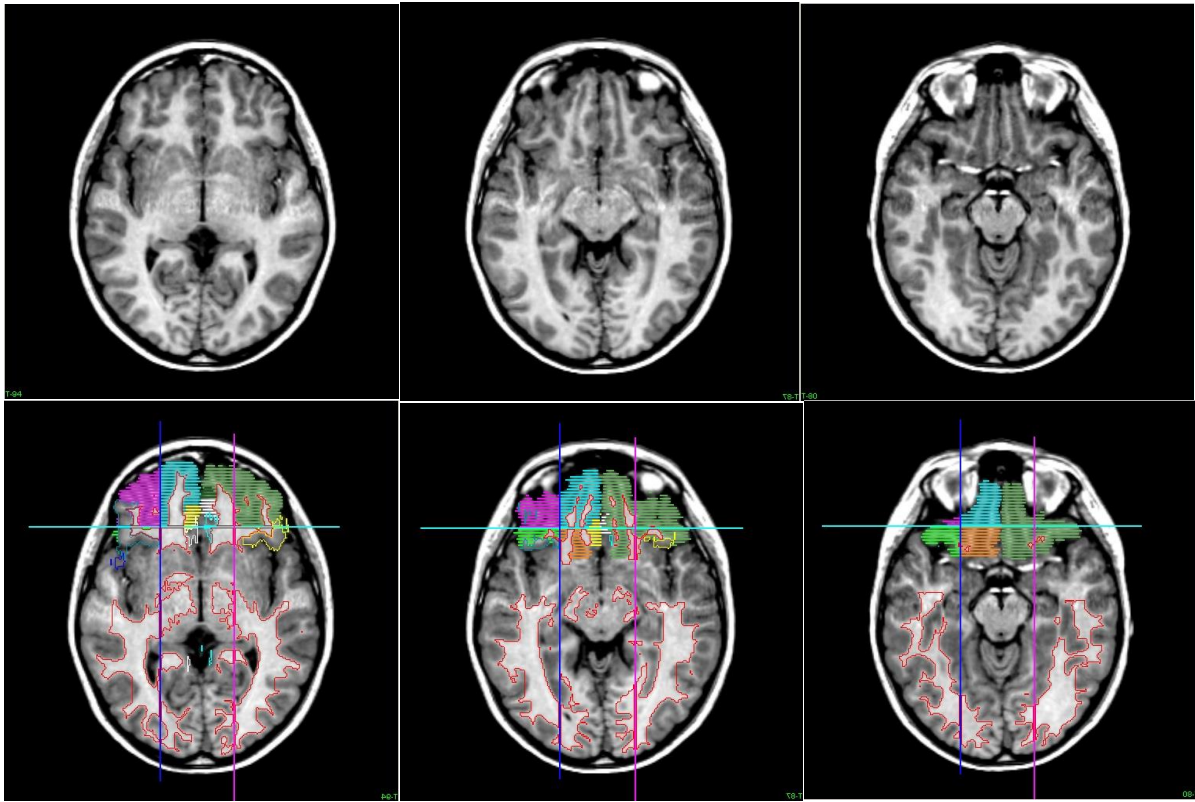
Figure 2: Transverse view of the parcellation of the orbital frontal cortex showing a dorsal, middle, and ventral slice (left to right)
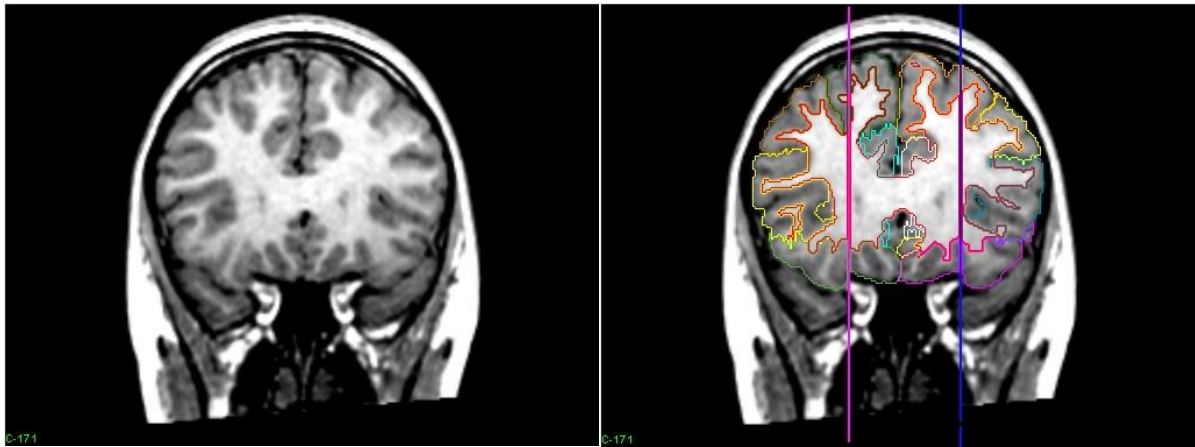
Figure 3: Coronal view of the sagittal cuts (pink and blue lines) separating the medial

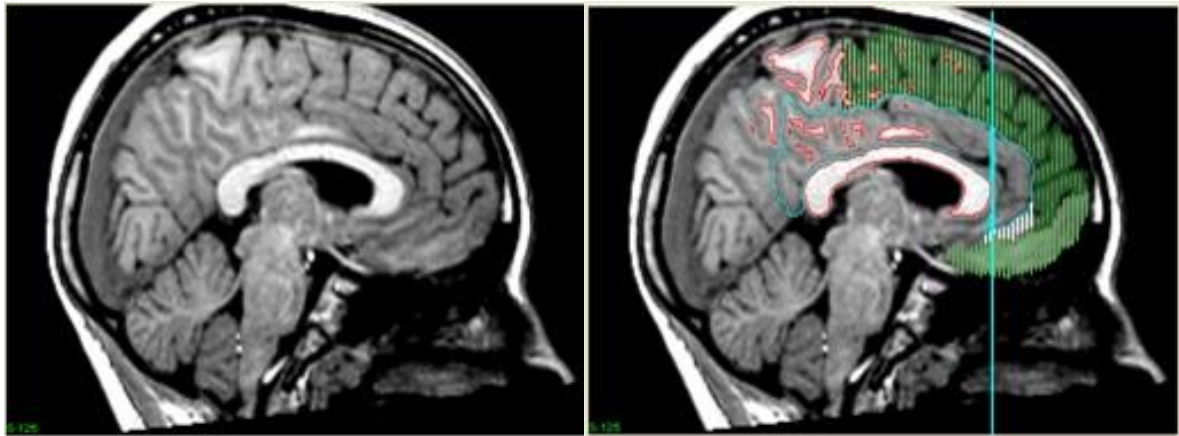and lateral sections of the right and left orbital frontal cortices

Figure 4: Sagittal view of the coronal cut separating the anterior and posterior sections of the superior (dark green) and orbital (light green) frontal cortices
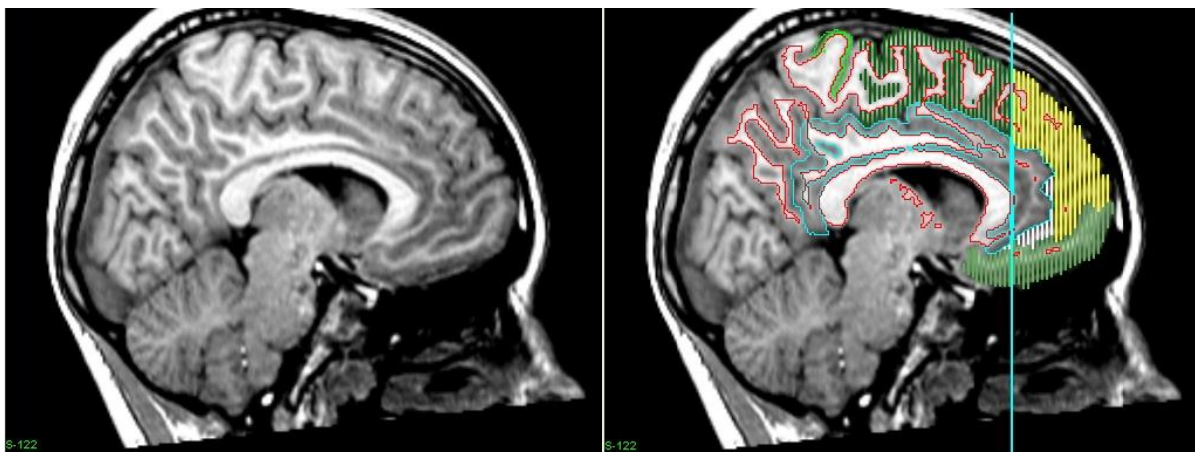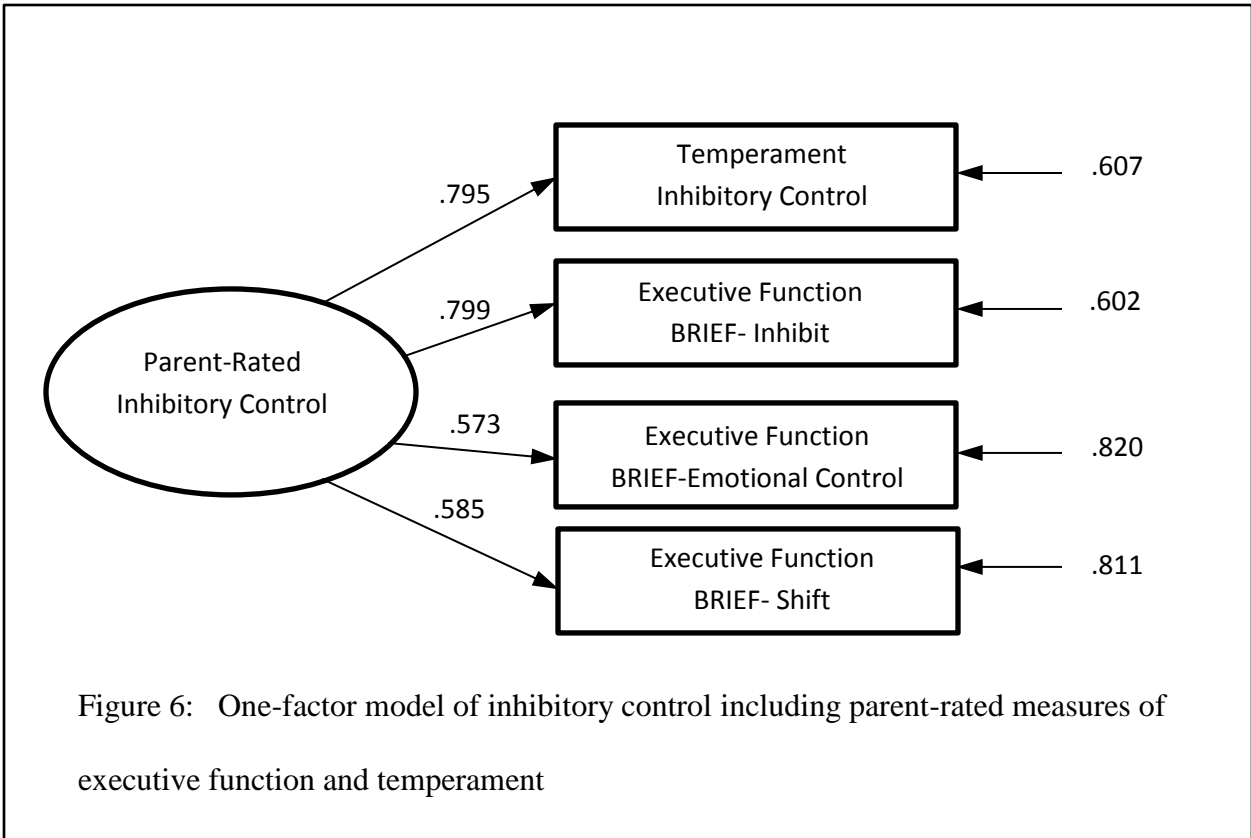
Figure 5: Sagittal view of the coronal cut separating the anterior (yellow) and posterior (dark green) sections of the superior frontal cortex

Figure 6: One-factor model of inhibitory control including parent-rated measures of executive function and temperament
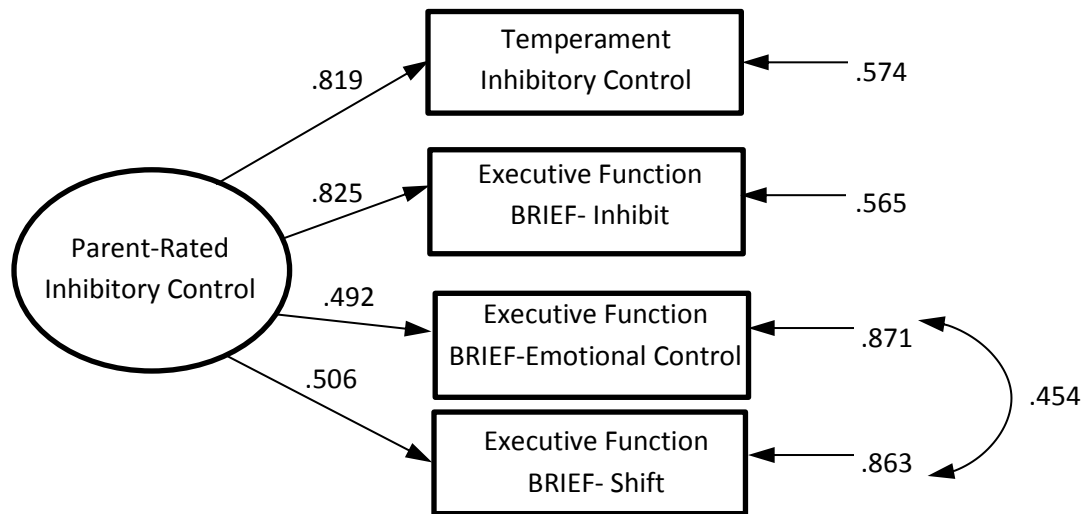
Figure 7: An alternative one-factor model of parent-rated inhibitory control using a temperament measure of inhibitory control and executive function measures of inhibitory control from the BRIEF.
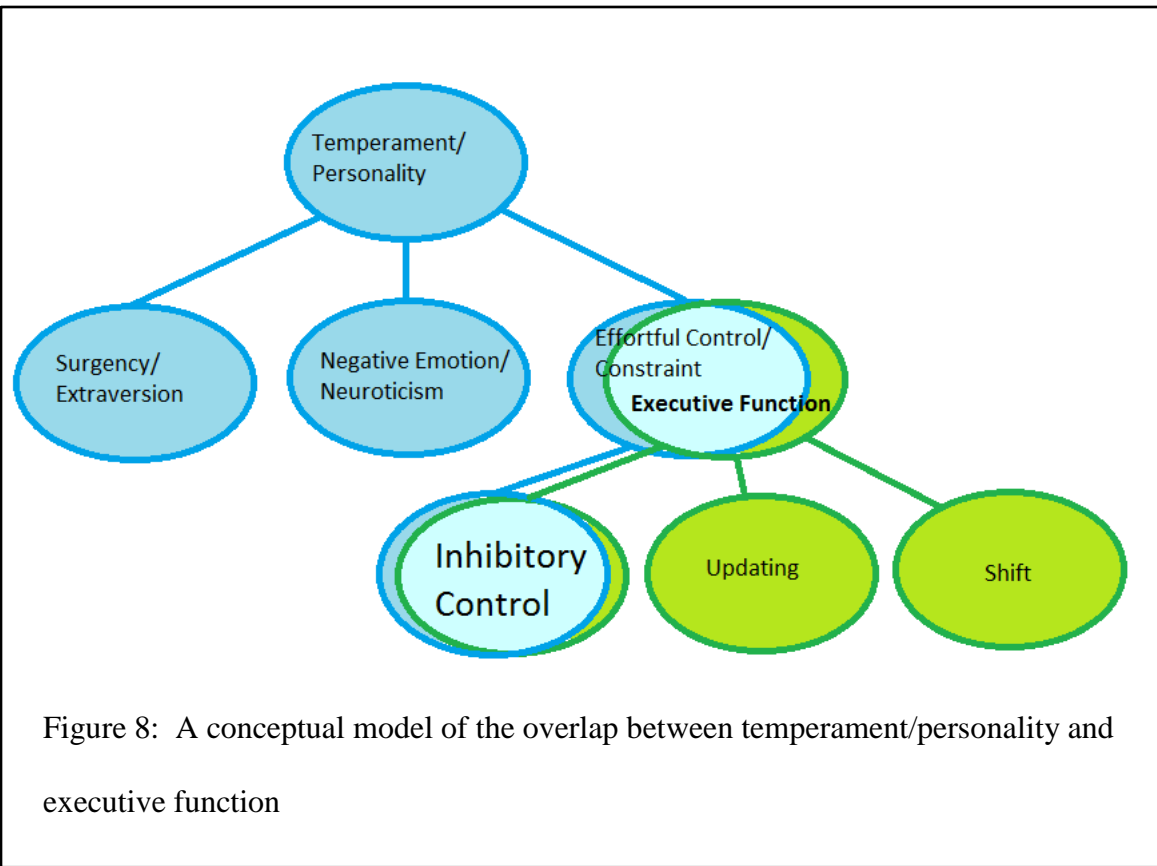
Figure 8: A conceptual model of the overlap between temperament/personality and executive function

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