ANALYSIS OF ASSESSMENT AND HEMODYNAMIC ACTIVATION IN THE PREFRONTAL CORTEX: AN INVESTIGATION OF EXECUTIVE FUNCTION

A Dissertation

by

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ABSTRACT

Executive function (EF) refers to the group of cognitive processes that guide human behavior. EF dysfunction is characteristic of a number of clinical conditions such as ADHD. Functional Near-Infrared Spectroscopy (fNIRS) is an economical and less invasive means to image the cortex during tasks of EF to visualize cognitive processes. Measuring hemodynamics in those with and without ADHD during EF tasks, and comparing hemodynamics, EF performance and ratings of EF in daily functioning can yield additional insight into the functional relationship of the cortex and behavior.

This study utilized the EXecutive Abilities: Measures and Instruments for Neurobehavioral Evaluation and Research (EXAMINER), Trail Making Test (TMT), Twenty Questions (20Q) task from the Delis-Kaplan Executive Function System (D-KEFS), and the Behavior Rating Inventory of Executive Function-Adult (BRIEF-A) Behavior Regulation Index (BRI) and Metacognition Index (MCI). NIRS data was collected during the EF performance tasks and results were calculated based on average hemodynamic responses. Additional questions were addressed regarding the association of EF ratings to EF performance, whether there was an association between digital and non-digital EF tasks, and whether performance differed between those with and without ADHD in terms of hemodynamics and performance or only performance variables.

A moderate association was found between BRI and decreased oxygenated hemoglobin (oxyHb) in the left DLPFC during Set Shifting. Higher MCI was moderately associated with decreased oxyHb in the left DLPFC during a task of

inhibition and sustained attention, and improved performance on N-Back was moderately associated with increased oxyHb in bilateral DLPFC during Set Shifting. No statistically significant differences were found between ADHD and Non-ADHD groups in PFC hemodynamics during EF tasks; however, ADHD participants exhibited greater impairment on ratings of EF. No statistically significant associations between digital and non-digital tasks were found.

Findings confirm deficits in everyday EF in those with ADHD; however, continued use of digital tasks to assess EF constructs, and use of those results for diagnostic purposes is not consistently supported in the literature. Additional information regarding use of EF tasks in those with and without ADHD may provide additional insight into the connection between neurophysiology and everyday function.

DEDICATION

The entirety of this body of work is dedicated to my family, without whom none of this would have been possible. It is my husband, Jason, and children, Michael, Catherine, and Abigail, for whom this dissertation was written. For his long-suffering patience, kind heart, selfless giving, and endless encouragement to reach my goal, however, it is my husband who deserves the credit for this accomplishment.

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CHAPTER I

INTRODUCTION

Understanding the complex relationship between brain function and behavior has gained increasing attention in past decades. This interest has been spurred in part by the development of new technologies, but also by growing recognition of the complexities of the human mind. The physiology and anatomy behind human thought; how plans are developed and carried out; attempts to understand these complexities have been the subject of many neurocognitive and neuropsychological investigations as psychologists search for the link between processes and their neurological correlates. Cognitions and plans are products of executive function.

Executive Function

Executive function (EF) generally refers to the group of cognitive processes that guide human behavior (Barkley, 1997; Denckla, 1996; Hughes, 2011; Lezak, 1982; Miyake & Friedman, 2012; Zelazo, Carter, Reznick, & Frye, 1997). As such, the ability to mentally conceptualize a problem, develop a plan, evaluate and adapt complex goal-directed behavior have been identified as the products of higher-order thinking and EF (Barkley, 1997; Lezak, 1982; Miyake, Friedman, Emerson, Witzki, & Howerter, 2000). Accomplishing everyday tasks, from the simple to the complex, requires coordinating processes to ensure tasks are completed correctly; it is EF and its processes that subserve these behaviors (Hughes, 2011; Miyake & Friedman, 2012; Lezak, 1982).

EF and Brain Function

Of the many processes identified, defined, or purported to be essential to daily functioning, working memory, inhibition, and shifting are often associated with the activation of the prefrontal cortex (PFC; Barkley, 1997; Best & Miller, 2010; Miyake et al., 2000). Though Denckla (1996) and many others (see Banich, 2009; Barkley, 1997; Lee, Riccio, & Hynd, 2004; Romine & Reynolds, 2005; Stuss & Alexander, 2000; Zelazo et al., 1997) have iterated that the PFC is not solely responsible for EF and its subcomponents, the PFC most assuredly is a key neurological region subserving the integration and execution of EF. Denckla (1996) noted the necessary pairing, in a neuropsychological orientation, of EF with intact frontal lobe functioning, specifically the PFC. Conversely, many of the behaviors associated with higher-order function and the PFC are subsumed under the umbrella term of EF. Despite all the research to date, researchers continue to investigate this relationship utilizing a variety of cognitive tasks and neural imaging techniques. Critical to current research are issues related to EF development and neurodevelopment, as well as relevance to clinical populations such as individuals with Attention-Deficit/Hyperactivity Disorder (ADHD).

EF and Development

To understand EF and its models, a developmental perspective is necessary. Developmental progression in learning, memory, emotional control, attention, language, and other higher-order cognitive processes occur throughout childhood, adolescence, and into adulthood (Miyake & Friedman, 2012; Romine & Reynolds, 2005). These progressions appear concurrent to periods of synaptic pruning (i.e., removal of

unnecessary/unused connections in the frontal lobes), improved myelination of the PFC allowing increased signal integrity and speed, and changes to the receptivity and production of neurotransmitters dopamine and serotonin (Romine & Reynolds, 2005). Similarly, Miller and Cohen (2001) posited the emergence of some basic forms of EF appearing as early as infancy, with the sequence of cortical development, myelination, and maturational processes leading to distinct patterns of EF development. Though the described sequence is the expected trajectory for typically developing individuals, EF development has also been considered in regard to clinical disorders, particularly ADHD.

EF and ADHD

The Diagnostic and Statistical Manual of Mental Disorders—Fifth Edition (DSM-5; American Psychiatric Association, 2013), estimates the prevalence of ADHD at 5% of the population. Despite the relatively low frequency, the ADHD diagnosis rate in children and adolescents increased 66% from 2000 to 2010 making it one of the most diagnosed psychological conditions in the United States (Garfield et al., 2012). Diagnostically, ADHD is often characterized as a disorder of EF (Barkley, 1997; Barkley & Murphy, 2010; Lee, et al., 2004; Schreiber, Possin, Girard, & Rey-Casserly, 2014).

In particular, many theories of ADHD include disinhibition as a key behavioral symptom (see Barkley, 2012; Hughes, 2011; Shallice et al., 2002 for discussion), while others have focused on deficits in working memory (Baddeley, 2000; Baddeley & Hitch, 1974; Rapport, Chung, Shore, & Isaacs, 2001). In addition, impairments in attentional

control and shifting/cognitive flexibility are implicated in symptom descriptions of ADHD (Barkley, 1997; Brown, 2006; Willcutt, Doyle, Nigg, Faraone, & Pennington, 2005). Still others have investigated the neurological correlates of ADHD with a focus on the frontal lobes as the area of the brain most implicated in EF deficiencies (Robinson, Calamia, Gläscher, Bruss, Tranel, 2014; Shallice, et al., 2002).

Imaging and EF

Neuropsychological investigation of EF has been supplemented by a variety of imaging methods to isolate the neurophysiological correlates for EF (Strait & Scheutz, 2014). Functional magnetic resonance imaging (fMRI), event-related potentials (ERPs), single-photon emission computerized tomography (SPECT), and functional near-infrared spectroscopy (fNIRS) have been utilized to evaluate cerebral activation patterns for many years. Research suggests using any of these imaging methods will sufficiently demonstrate areas of activation in the cortex (Bush, Valera, & Seidman, 2005; Joanette et al., 2008; Weyandt, Swentosky, & Gudmundsdottir, 2013). Of the neuroimaging options available, however, functional near-infrared spectroscopy (fNIRS) has been increasingly utilized to assess patterns of cortical activation in children, adolescents, and adults due to its portability, cost efficiency, and ease of use (Strait & Scheutz, 2014).

Based on imaging studies across methods, fNIRS has provided an economical and efficient means to view EF and the frontal lobes (Joanette et al., 2008; Weyandt et al., 2013) in both clinical and nonclinical populations (Joanette et al., 2008; Negoro et al., 2010; Weyandt et al., 2013). Assessment and visualization during tasks requiring EF processes such as working memory, inhibition and set shifting indicate significant

activation in the PFC (Hirshorn & Thompson-Schill, 2006; Jacola, et al., 2014; Laguë-Beauvais, Brunet, Gagnon, Lesage, & Bherer, 2013; Weyandt et al., 2013). As a result, the PFC is often implicated in disorders of EF such as ADHD.

One of the issues relevant to EF and ADHD investigations is the difficulty in obtaining a pure measure of EF processes (see Barkley & Murphy, 2010; Nyhus & Barceló, 2009; Weyandt et al., 2013 for discussion) that can be isolated for imaging. Many studies and meta-analyses have attempted to clarify EF deficits in individuals with ADHD by examining activation patterns in the cortex during tasks requiring inhibition, updating/working memory, and set shifting/cognitive flexibility (e.g., Hege, Preissl, & Stingl, 2014; Herff et al., 2014; McCarthy, Skokauskas, & Frodl, 2014; Negoro et al., 2010; Stuss & Alexander, 2000; Weyandt et al, 2013); however, the complications associated with the assessment tasks are many due to overlapping EF constructs within these measures (Barkley & Murphy, 2010, 2011; Reynolds & Horton, 2008; Wasserman & Wasserman, 2013).

Assessment of EF in ADHD

Assessment of EF deficits in those with ADHD covers an enormous body of literature (e.g., Barkley, 1997, 2012; Bush, Valera & Seidman, 2005; Mulligan et al., 2011; Toplak, Bucciarelli, Jain, & Tannock, 2009; Jacola et al., 2014; Weyandt et al., 2013), much of which has been concerned with examining neuropsychological functioning associated with ADHD (e.g., Barkley, 1997; Duff & Sulla, 2015; Hale et al., 2009; Geburek, Rist, Gediga, Stroux, & Pederson, 2013; Kamradt et al., 2014; Nigg et al., 2005; Rohlf et al., 2012; Shallice et al., 2002). In order to do so, clinicians and

researchers utilize a variety of performance-based measures and rating scales to assess various EF processes (Barkley, 1997; Barkley & Murphy, 2010; Kamradt et al., 2014; Lezak et al., 2004; McCloskey & Perkins, 2013).

Additionally, the argument has been made that, though neuropsychological measures of EF may have adequate sensitivity (i.e., accurately identifying a positive condition), they may lack adequate specificity (i.e., accurately rejecting a true negative) for diagnostic purposes (Barkley, 1997; Barkley & Murphy, 2010; Duff & Sulla, 2015; Hale et al., 2009; Riccio, Reynolds, Lowe, & Moore, 2002; Shallice et al., 2002; Wasserman & Wasserman, 2012; Wodka et al., 2008). For example, many have found rating scales have inconsistent or minimal correlations with performance-based EF measures (Barkley & Murphy, 2010; Duff & Sulla, 2015; Kamradt, Ullsperger, & Nikolas, 2014; Lezak et al., 2004; Toplak et al., 2009). Frequent references are found describing the inadequacy of many performance-based EF measures' predictive power in ADHD diagnosis, whether due to medication effects, differences in construct definitions, or developmental factors related to the measures themselves (e.g., Barkley & Murphy 2010; Hale et al., 2009; Kamradt et al., 2014; Lee et al., 2004; Mahone et al., 2014; Shallice et al., 2002; Toplak et al., 2009). The use of multiple (potentially overlapping) measures of EF is recommended for clinical assessment (Duff & Sulla, 2015; Hale et al., 2009) as there is no single task with adequate specificity or sensitivity for ADHD diagnosis.

What remains unclear is the degree of association between everyday ratings of EF and performance-based tasks in those with ADHD. As ADHD has been

characterized as a disorder of more than one EF process (e.g., inhibition, working memory, shifting, behavioral control), imaging studies primarily utilize tasks that have been found to activate the PFC in previous research, but these tasks may not be reflective of EF deficits in everyday functioning. Though Kamradt and colleagues (2014) have recently noted adequate specificity on an infrequently used rating scale, many clinicians rely on a more popular scale—the Behavior Rating Inventory of Executive Function (BRIEF; Gioia, Isquith, Guy, & Kenworthy, 2000). Furthermore, relatively little is known about the relation between a variety of measures used in assessment of ADHD and brain activation patterns during these tasks.

Current Study

Although there is a plethora of research on both EF and ADHD, few examinations of brain activation using fNIRS and ADHD, and even fewer specific to the assessment of EF in young adults has been conducted. Further, the relation between EF task performance, everyday ratings of EF, and brain activation has not been established for a number of measures. For the purpose of this study, the focus was on the PFC as it clearly has been linked to EF (Denckla, 1996; Hirshorn & Thompson-Schill, 2006; Jacola, et al., 2014; Joanette et al., 2008; Laguë-Beauvais, Brunet, Gagnon, Lesage, & Bherer, 2013; Miyake et al., 2000; Weyandt et al., 2013). The Miyake and colleagues (2000) model of EF was used, as it focuses on young adults and includes EF processes of inhibition, shift/cognitive flexibility, and updating of working memory. This model was selected over other models because of its applicability to the population under investigation, e.g., young adults with and without ADHD, and the empirical support

found in the literature (e.g., Müller et al., 2014; Nigg et al., 2005). This study examined activation of the PFC in relation to performance on specific tasks and everyday reports of EF in individuals with and without diagnosis of ADHD.

Research Questions

Research Question 1: To what extent are hemodynamic differences in oxyHb and deoxyHb in the PFC related to results of performance on the EXAMINER tasks (e.g., CPT, Flanker, N-Back, and Set Shifting), 20Q, and TMT and ratings of EF as found on the BRIEF-A self-report? It was hypothesized that oxy/deoxy differences found in the DLPFC (bilaterally in regions AF7 and AF8) would be directly and positively associated with results of performance-based tasks and negatively associated with rating measures of EF (i.e., greater oxygenation is associated with better performance and normalized ratings of EF).

Research Question 2. Do ADHD and non-ADHD groups differ in DLPFC activation as measured by hemodynamics during EF tasks? It was hypothesized the non-ADHD group would demonstrate greater oxygenation bilaterally in the DLPFC (Left/AF7 and Right/AF8) as compared to the ADHD group during EF tasks.

Research Question 2a: Does gaming experience affect between group variances on hemodynamics? Based on available research, it was hypothesized that higher rates of gaming are associated with decreased oxygenation.

Research Question 3: Do ADHD and non-ADHD groups differ in performance on EF tasks and impairment? It is hypothesized that the ADHD group will evidence greater impairment as compared to the non-ADHD group.

Research Question 4: What is the level of association for results of computerized EF and non-computerized tasks? As there was no available research that considered computerized assessment of EF in relation to non-computerized tasks, the hypothesis was that there was no relation.

Research Question 5: To what extent are results of the BRIEF Self-Report consistent with results of computer-based (the EXAMINER) and non-computerized tasks? Based on currently available research, it was hypothesized there would be minimal to low correlations between rating scales and performance-based tasks.

Implications

The contrasting findings from studies of individuals with and without ADHD has made analysis of, and differentiation between, clinical and non-clinical levels of EF deficits problematic. Though EF rating scales are utilized in clinical assessment, these scales show inconsistent or minimal associations with performance-based measures, and have limited power to predict ADHD diagnosis. This study sought to investigate the nature of the relation between performance-based measures and rating scales, and if provided enough statistical power, measure their unique and shared predictive power for ADHD group membership.

Additionally, this study added to the literature regarding performance-based EF assessment measures and their corresponding areas of hemodynamic activation in the PFC. Significant differences between ADHD and non-ADHD individuals in activation patterns may predict ADHD status. Several EF tests, subtests, and tasks are only available in a computer-based administration, while many more are moving toward a

digital interface (e.g., iPads, tablets, or computers). Unfortunately, relatively little research has been completed to date regarding the differences, if any, between computer-based administrations and those requiring physical manipulation of materials (e.g., cards, pencil-paper, tiles). Furthermore, it is not known whether the differences in administration modalities have an effect on performance and whether these formats affect areas of activation in the brain as well.

CHAPTER II

LITERATURE REVIEW

The foundations of cognitive neuroscience date back to the earliest psychological experiments, from Helmholtz's study of nerve conductance and Wundt's examinations of physiological psychology, reaction time, and sensory experience (Benjamin, 2014). From the earliest theories of intelligence put forth by Galton, Spearman, Binet, and Thurstone, psychologists have sought to discover and measure those processes which differentiate individuals on the basis of their cognitive skills (Benjamin, 2014). Unraveling the mysteries of human cognition and neuroscience has been a challenge due to the innumerable complexities this task entails.

Of those processes necessary for survival and daily functioning, Lezak (1982) posited EF is essential to how the human mind directs itself (e.g., metacognition) and adapts to the changing conditions of his or her existence. Additional examinations of EF have led to models for EF and its processes, attempting to explain the connection between thoughts and behavior. Denckla (1996) suggested it is the interactions of these cognitive processes that allow one to accomplish a complex, multi-step task from start to finish. More recently, McCloskey and Perkins (2013) clarified that EF is responsible for directing and cueing cognition and behavior through independent but coordinated processing. In effect, EF directs and affects perception, emotions, thoughts, and actions through a variety of processes. McCloskey and Perkins proposed EF processes to be analogous to co-conductors (or section leaders) in a cognitive orchestra that allow an

individual to function. Summarily, it is now agreed that much of human behavior is dependent upon the integration of EF processes that produce the ability to adapt to circumstances, make decisions based on prior experience or knowledge, while keeping in mind the end goal. The mechanism for this integration of cognitive processes, however, has remained something of a mystery.

Defining Executive Function

Despite agreement on the importance of EF, there is no single, universally accepted model or definition for EF, in part due to its complexity. A considerable body of research has attempted to define EF (see Barkley, 2012; McCloskey & Perkins, 2013 for discussions). There are more than 35 readily available definitions and models used to conceptualize the construct of EF and its components (Naglieri & Goldstein, 2014), many offered by leading scholars (e.g., Barkley, 2011; Lezak et al., 2004; McCloskey & Perkins, 2013; Miyake et al., 2000; Stuss & Alexander, 1986). These definitions have ranged from those with multiple components to a more unitary construct. Some focus on a deficit model, as might be seen in individuals with disorders associated with EF dysfunction (e.g., ADHD, Autism), while others have adopted a more managerial or developmental model. After many years, models, and theories, the prominent consensus seems to be that EF is complex, multidimensional, and difficult to assess.

Historical Overview

Early conceptualizations of EF suggested the frontal lobes to be the neurological origin and director of other cognitive processes (Luria, 1966). More than 140 years ago Harlow's discussion (1848; 1868) of the frontal lobe injury sustained by Phineas Gage

and his subsequent recovery, marked the beginnings of exploration into the cognitive processes which guide human behavior, personality, and problem solving. Subsequent to his injury, Gage's changes in personality and behavior (i.e., his lack of social skills, impulse and anger control problems) revealed the complexity and interdependence of cognitive processes and neuroanatomy (Harlow, 1868), but the location of Gage's injury suggested these functions were subserved by the frontal lobes.

Over time, it became clear that early definitions of EF, as basic cognitive processes carried out by the frontal lobes, were inadequate to explain the complexity of interactions between processes and regions (Jurado & Roselli, 2007; Zelazo et al., 1997). It is now believed the frontal lobes are integrative, or coordinating, centers for EF rather than where these processes originate (Banich, 2009; Miyake et al., 2000; Reynolds & Horton, 2008; Stuss, 2011). Those with damage to the frontal lobes evidenced differential deficits in function, e.g., poor inhibition but intact memory, or poor memory but intact vocabulary (Lezak et al., 2004). More often than not, damage to the pre-frontal areas of the brain yielded deficits in inhibition, changes in personality, or difficulty regulating emotional responses (Stuss & Alexander, 2007). Neuropsychological studies of individuals with damage to the PFC (or frontal lobes in general) increased both interest in and hypotheses regarding these executive processes. Thus, researchers began to assert more complex and comprehensive definitions and models to explain human behavior (Hughes, 2011; Miyake et al., 2000).

A universally accepted definition is elusive because, as a construct, EF has been complicated by overlap between sub-processes, defined by its components, and

conceptualized to fit a new paradigm or theory (Barkley, 2011; Jurado & Rosselli, 2007; Wasserman & Wasserman, 2013). Reviewing a few seminal definitions, Lezak (1982) defined EF as the mental capacities required to formulate goals, plan their achievement, and carry out those plans effectively. Stuss and Benson (1986) defined EF as a variety of capacities that support purposeful, goal-directed behavior and included behavioral regulation, working memory, planning and organizational skills, and self-monitoring. Lezak et al. (2004) further refined a definition of EF as the mental capacities that enable a person to engage in autonomous, goal-directed, self-serving behavior. Barkley (2011) simply stated EF is self-regulation. Despite their differences, these and other definitions have many common elements such as goal-directedness, regulation of behavior, and design, execution and monitoring of a plan and its effectiveness (e.g., Barkley, 1997, 2011; Lezak, 1982; Lezak et al., 2004; Stuss & Benson, 1986; Welsh & Pennington, 1988). Ultimately, the differing definitions align with divergent models of EF.

Models of EF

With increasing similarities within the definition, explanatory models for EF emerged attempting to integrate discrete cognitive processes. There has been extensive research on EF since Luria (1966) described the frontal lobes as the seat of higher cortical functions or EF. Some of this research has been in relation to typical development. Miyake et al.'s (2000) research on the structure of EF examined inhibition, updating, and shifting/cognitive flexibility through a factorial analysis of task performance. More recently, studies have begun investigating the trajectories of development and age-related differences in EF of children relative to adults (Reynolds &

Horton, 2008). Banich (2009) suggested an anatomically-based cascade of processes based on data from functional imaging studies of the PFC and medial areas of the neocortex. These neurologically-based models have focused more on how the brain subserves the process rather than on the steps in the process (Reynolds & Horton, 2008).

In contrast to research on EF and frontal lobe function across development, others have studied the role of EF in relation to clinical disorders. Many of the more current definitions and models of EF have evolved from research examining deficits in EF associated with ADHD, Autism spectrum disorders, and others (De Luca & Leventer, 2008). For example, Barkley (1997) characterized ADHD as a disorder of inhibition, utilizing a centralized model controlling affect, emotions and behavior; working memory; internalization of speech; and reconstitution (e.g., analysis and synthesis of experiences and behavior). In contrast, for individuals with autism spectrum disorders, delays or deficits have been noted in EF processes, including inhibition, attentional control, cognitive flexibility, and initiation (Anderson, 2008; Hughes, 2011).

An increasing amount of research has found interdependent associations between EF components and learning, carrying out daily activities, and setting and attaining goals (Wasserman & Wasserman, 2013). Regardless of the model's focus (typical or atypical behavior), there are multiple models of EF (see Table1). These models vary in the number of components and the interaction of processes and cognitive complexity of the task demands. Many of these theories posit a multi-factor model for EF as an interaction between broader processes such as working memory, shifting, and inhibition (see Baddeley & Hitch, 1974; Banich, 2009; Brown, 2000, 2006; Lezak, 2004; McCloskey,

Perkins & Van Divner, 2009; Miyake et al., 2000; Stuss & Benson, 1986; Welsh & Pennington, 1988; Zelazo et al., 1997). In contrast, others indicate a narrower two-factor model comprised of controlled and automatic processing (Norman & Shallice, 1986; Schneider & Chein, 2003).

Table 1 Models of Executive Function

Theoretical Model	Components	Structure	Supported by Research/Factor Analysis
Anderson, Northam, Hendy, & Wrenall (2001)	Attentional Control; Cognitive Flexibility; Goal Setting	Not specified	None identified
Baddeley & Hitch (1974); Baddeley (2000) Working memory model	Central Executive controls and coordinates input and manages Visuospatial Scratchpad, Phonological Loop, and the Episodic Buffer	Hierarchical	Baddeley, 2000; research on WM tasks supports auditory and visual STM regulated by some other component
Banich (2009)	Bias to task-relevant processes; Bias to task-relevant representations; Selection of information to guide responding; Evaluation of the response	Hierarchical	Silton et al., 2010; Spielberg et al., 2011
Barkley (1997) Self-Regulatory Model	Inhibition is central to: Internalization of speech/language, Reconstitution, Working memory, Self-regulation of affect/motivation/arousal	Hierarchical	None identified
Brown (2000, 2006)	Activation, Focus, Effort, Emotion, Memory, Action	Developmental	None identified
Denckla (1996)	Central control processes involve inhibition, delayed responding, maintenance of anticipatory set/preparedness to act, planning of sequences of selected actions	Developmental	None identified

Table 1 Continued

Theoretical Model	Components	Structure	Supported by Research/Factor Analysis
Gioia, Isquith, Guy, & Kenworthy (2000)	Cognitive, emotional, and behavioral: Guiding, Directing, Managing (Corresponding to factors on the BRIEF: Metacognition, Behavioral Regulation, Emotional Regulation)	Hierarchical	Egeland, Fallmyr, 2010; Gioia, Isquith, Retzlaff, & Espy 2002; Roth, Lance, Isquith, Fischer, & Giancola, 2013; Lyons Usher, Leon, Stanford, Holmbeck, & Bryant, 2015; Roth, Lnce, Isquith, Fischer, & Giancola 2013
Lezak (1982, 2004)	Volition; Planning; Purposive action; Evaluation of effective performance	Developmental	None Identified
McCloskey's Holarchical Model of Executive Function (2009)	32 EF processes based on self-regulation as the over-arching EF	Holarchical	None Identified
Miller & Cohen, (2001)	Cognitive control (encompasses additional constructs such as selective attention, response inhibition)	Biological/ Neurological	None Identified
Miyake et al. (2000)	Shifting, Inhibition, Updating of working memory	Developmental	Brydges, Fox, Reid, & Anderson, 2014; Rohlf et al., 2012; Smolker, Depue, Reineberg, Orr, & Banich, 2015; Wiebe et al., 2011; Wu et al., 2011
Norman & Shallice (1986) Supervisory Attentional System	Supervisory attentional system (later adapted to include a Contention scheduling function)	Hierarchical	None Identified

Table 1 Continued

Theoretical Model	Components	Structure	Supported by Research/Factor Analysis
Pennington & Ozonoff (1996) evolved from Welsh & Pennington (1988)	Two broad factors: 1- *Executive control* has four sub-processes: set shifting, planning, response inhibition, and working memory. 2- Output speed is conceptualized as *vigilance*.	Hierarchical	Murphy et al. 2001; Nigg et al., 2005; Willcutt et al., 2005
Rapport, Chung, Shore, & Isaacs Working memory model (2001)	Working memory	Single Construct	Kofler et al., 2014; Raiker, Rapport, Kofler , & Sarver, 2012
Stuss & Benson (1986) evolved to Stuss & Alexander (2000, 2007)	Anticipation, Goal Selection, Pre-Planning, and Monitoring govern Drive and Sequencing (1986)	Undifferentiated	Stuss & Alexander, 2000, 2007
	Energization, Task Setting, Monitoring; Central Executive Supervisory System with the three anatomically and functionally independent processes		
Zelazo et al. Cognitive Complexity and Control theory (1997)	Problem Representation, Planning, Maintenance of Strategies (Execution), Evaluation of Results	Hierarchical	Zelazo, Craik, & Booth, 2002; Zelazo & Müller, 2002

Some multi-factor models are based on a hierarchical structure, with a supervisory, integrating, or central function that supports and directs other subprocesses to accomplish a task, attend to a stimulus, or set a goal. For example, Rapport and colleagues (2001) emphasized the role of working memory to direct other functions, while Barkley (1997, 2011) suggested inhibition/self-regulation as the core EF process that directs others. Hughes (2011) noted a more unitary nature of EF early in

development, with research findings supporting a separation of processes throughout childhood and into early adulthood. Given that processes and their neurological correlates evolve with age, a one-dimensional model (e.g., Baddeley & Hitch, 1976; Brown, 2006; Rapport, et al, 2001) does not adequately capture the integrative role of EF (Miyake et al., 2000; Romine & Reynolds, 2005; Zelazo et al., 1997). Miyake and colleagues (2000) overcame the unity and diversity in EF with a model of separable processes connected by an underlying commonality termed EF.

EF and Neurodevelopment

Development of EF

Even young children demonstrate the beginnings of EF such as planning and attentional control (Wasserman & Wasserman, 2013). Beginning in infants as young as 9 months, the ability to maintain attention (e.g., attentional control) or remember an object's placement when it is hidden (e.g., working memory and visualization) develops and the infant learns to direct his/her attention and behavior to obtain a desired end (Jurado & Rosselli, 2007). Though there is some inconsistency in whether gender differences exist at the preschool age, EF appears to have a unitary structure in younger children, as individual processes are not evident in testing and factor analysis (Wiebe et al., 2011; Hughes et al., 2010). Hughes (2011) indicated that EF is a more global construct in young children, supported by neuroimaging research (e.g., Conklin et al., 2007; Lee, Wallace, Raznahan, Clasen, & Giedd, 2014; Tamm, Menon, & Reiss, 2002).

Welsh, Pennington, and Groisser (1991) concluded that between the ages of 2-12 years, children become able to cognitively process more complex tasks at certain

developmental stages. Despite some debate as to whether EF may manifest as a unitary construct prior to 11 years (Brydges et al., 2014), age 6 appears to be the first distinct age at which visual-motor search activity and simple planning becomes developmentally different (Hughes, 2011). At 10 years of age (or at the transition to adolescence), the ability emerges to maintain set, along with abilities for hypothesis testing, shift/cognitive flexibility, increased speed of processing, and inhibition (Boelema et al., 2014; Vink et al., 2014; Wang et al., 2013). Then in adolescence, more complex planning and increased verbal fluency is evident (Hughes, 2011). Late adolescence and early adulthood marks continued maturation of the frontal lobes and some functions, such as behavioral inhibition, impulse control and attentional shifting (Stuss & Alexander, 2007; Taylor, Barker, Heavey, & McHale, 2013). It is the end of adolescence when EF becomes more like that of an adult (Boelema et al., 2014). Each of the developmental changes and changes in EF seem to correlate with growth spurts in the frontal cortex, specifically the prefrontal cortex (PFC).

Developmental "leaps" appear to occur at these growth intervals, including the ability to cognitively negotiate when to use conflicting rules or inhibit an action with alternative action (Boelema et al., 2014; Romine & Reynolds, 2005). Tasks such as these are generally inaccessible to young children but become manageable for adolescents and young adults. This progression in ability appears concurrent to periods of synaptic pruning (i.e., removal of unnecessary/unused connections in the frontal lobes), myelination of the PFC—allowing increased signal integrity and speed, and

changes to the receptivity and production of neurotransmitters (e.g., dopamine and serotonin; Romine & Reynolds, 2005; Tau & Peterson, 2010).

Children and adolescents progress through the stages of cognitive development with associated changes in general brain activity; but most importantly, growth is associated with changes in activity and myelination in the PFC (Brydges et al., 2014; Stuss & Alexander, 2007). The PFC increasingly becomes the orchestrator of many EFs from late childhood through the young adult years (Jurado & Rosselli, 2007; Miller, Ho & Hinshaw, 2012; Romine & Reynolds, 2005). Alternatively, patterns of neural activation move from more generalized in children to more focused areas in adults. While researchers are uncertain whether activation patterns lead to improved EF or if improved EF leads to more specific activation patterns, activity in the PFC becomes further localized with each developmental jump (Hughes, 2011). Thus it is hypothesized that development across EF processes becomes co-dependent with activation patterns. As a result, increased ability to self-regulate yields increased complexity in task completion, problem solving, and cognition.

EF in Young Adults

Although middle childhood sees the greatest development in EF, the process continues into adulthood (Boelema et al., 2014; Maricle et al., 2010; Romine & Reynolds, 2005; Wasserman & Wasserman, 2013). Research has demonstrated that neuronal development continues via synaptogenesis, pruning and remodeling of connections (Tau & Peterson, 2010), with some lags in function in early adulthood associated with greater pruning after age 17 (Taylor et al 2013). As a result, there is

variability throughout adolescence and into young adulthood specifically related to working memory and set-shifting (Anderson, Anderson, Northam, Jacobs & Catroppa, 2001; Conklin, Luciana, Hooper & Yarger, 2007; Huizinga & van der Molen, 2007; Kalkut, Han, Lansing, Holdnak & Delis, 2009; Rueda et al., 2004; Welsh et al., 1991). Notably, gender differences seem to emerge in adolescence that may disappear in young adulthood (Giedd et al., 1999; Kalkut et al., 2009; Taylor, Barker, Heavey, & McHale, 2013). Kalkut et al. (2009) provide support for continued development of EF specific to set-shifting into early adolescence; while Conklin et al. (2007) found working memory to continue development into middle to late adolescence.

In young adulthood, EF processes become more differentiated anatomically as well (Albert & Steinberg, 2011). The PFC has a protracted maturational period, continuing through the early 20's, at which time the majority of EF processes reach their peak (Conklin et al., 2007; Hughes, 2011; Tau & Peterson, 2010). Thus, by the mid 20's, the connections between the PFC and other regions are mature (Albert & Steinberg, 2011). Functional imaging has provided views of the developmental differentiation within the frontal lobes, specifically the locations in the PFC subserving EF processes as they emerge.

EF in Young Adults with ADHD

Current research in EF and ADHD is increasing as more observed deficits in everyday function are measured and discussed (see Solsnes, Skranes, Brubakk, & Lohaugen, 2014; Woltering, Liu, Rokeach, & Tannock, 2013). Children with ADHD symptoms differ between subtypes (e.g., inattentive presentation, hyperactive-impulsive

presentation, or combined presentation); however, research with most young adults indicates the hyperactive symptoms tend to decrease (Faraone et al., 2000). Nevertheless, adults with ADHD continue to show deficits in attention, inhibition, reasoning, planning, and working memory (Faraone et al., 2000; Gray, Fettes, Woltering, Mawjee, & Tannock, 2016; Kim, Liu, Glizer, Tannock, & Woltering, 2014). As a subpopulation of adults with ADHD, college students with ADHD are presumed to be of at least of average intelligence and academic performance prior to college (e.g., they graduated from high school and gained admittance to college); however, research suggests these adults continue to display neurophysiological differences when compared to non-ADHD controls (Faraone et al., 2000; Nigg et al., 2005; Gray et al., 2014; Woltering et al., 2013). Similarly, EF assessment in those with ADHD has also yielded findings suggesting variable impairment in everyday functioning (Sibley et al., 2012). Of note however, a marked difference can be seen when comparing symptom severity to impairment on self-report measures relative to parent-report, emphasizing the importance of utilizing informant reports of functioning for diagnostic purposes and qualitative comparisons of function between age peers (Faraone et al., 2000; Sibley et al, 2012). Gray and colleagues (2016) point out, however, that direct assessment (e.g., neuropsychological measures of EF) often fails to find EF deficits in young adults with ADHD who report clinically significant deficits in function on self-reports.

Functional Imaging

To explore differences in processes, imaging and functional studies utilize an range of technology and assessment methodologies such as event-related potentials

(ERPs), functional magnetic resonance imaging (fMRI), single-photon emission computerized tomography (SPECT), or functional near-infrared spectroscopy (fNIRS) to list a few. Each of these methods has its advantages and disadvantages. While fMRI can show detailed images of cortical activation patterns, it is expensive and requires the subject to remain still for an extended period of time in order to generate images without artifacts (Yasumura et al., 2014). Not precisely a neuro*image*, ERPs measure cortical electrophysiological responses, providing high temporal resolution (typically measured in milliseconds; Luck, 2014). ERPs are cost efficient, portable, and have advantages with certain populations (e.g., infants, nonverbal subjects, subjects sensitive to closed spaces or loud noises, etc.), but have poor spatial resolution (Luck, 2014). Positron emission tomography (PET) can be used to measure glucose metabolism in the brain or regional areas of specific neurotransmitter density; however, it is quite cost prohibitive and requires medical personnel to administer radioactive isotopes into the bloodstream (Weyandt et al., 2013). More economical than other hemodynamic measures, fNIRS provides a middle ground for spatial and temporal resolution and portability (Strait & Scheutz, 2014).

Imaging With fNIRS

Both fMRI and fNIRS rely on the blood oxygenation level dependent (BOLD) effect to visualize areas of activation (Joanette et al., 2008) based on the degree of absorption of the light in the tissue (Ye, Tak, Jang, Jung, Jang, 2009). After a stimulus is presented, it takes approximately 4-8 seconds for any change in Hb concentration to reach its peak. Over the next several seconds, the brain reestablishes homeostasis

resulting in no further changes in hemodynamics until another stimulus event occurs (Strait & Scheutz, 2014). Movement artifacts, extremely problematic for fMRI, can be accounted for with fNIRS (Hoshi, 2011); however, the placement of the NIRS probes on top of the skin and muscles requires additional calculations to compensate for these tissues and accurately measure the absorption of light in these tissues (Strait & Scheutz, 2014). Originally designed to measure tissue oxygenation for clinical purposes, near-infrared spectroscopy (NIRS) was quickly adopted by neurophysiologists to measure oxygenation in the brain (Hoshi, 2011; Joanette et al., 2008).

Broadly described, fNIRS systems emit near-infrared light at specified wavelengths and then detect the amount reflected light via optical sensors placed on the skin to measure the absorption of light at those wavelengths. As all living tissues require oxygen to function, changes in the density of deoxygenated hemoglobin (deoxyHb) and oxygenated hemoglobin (oxyHb) indicate decreased/increased activity in the area, thus *functional* NIRS (Hoshi, 2011). Because deoxyHb and oxyHb absorb light at different rates (Duncan et al., 1996), the differential level of wavelength-specific signal can be calculated to derive changes in the levels of oxyHb and deoxyHb in the underlying tissue (Strait & Scheutz, 2014).

NIRS is based upon the principles of the Beer-Lambert law (See Equation 1) which measures absorption coefficients in non-scattering media, such as homogenous solutions (Sassaroli & Fantini, 2004). As human tissue is a heterogeneous combination of bone, skin, muscle, and fluids, the modified Beer-Lambert law uses the known absorption coefficients of the tissues, the distance between source and detector, and the

differential path length factor (DPF) which accounts for increases in distance the light travels due to scattering (Cope et al., 1988; Duncan et al., 1996; Ye et al, 2009; See Equation 2).

Equation 1

Beer-Lambert Law

$$E_o = E_i \exp(-\mu_a d)$$

Note. E_o= detected intensity; E_i= input intensity; μ_a= the absorption coefficient of *non*-scattering media; *d*=distance between emitter and detector

Equation 2

Modified Beer-Lambert Law

$$A(\mu_a) = \mu_a(\overline{L})(\mu_a) + A(\mu_a = 0)$$

where

$$(\overline{L})(\mu_a) = \frac{1}{\mu_a}\int_0^{\mu_a}(L)\mathrm{d}\mu'_a$$

Note. A is the absorbance of the medium, $A(\mu_a = 0)$ is the absorbance due to loss occurring due to scattering; $(\overline{L})$ = mean average path length of detected photons over the range of the absorption coefficient (0-μ_a)

Imaging EF

Analysis of studies investigating neural activation during EF tasks indicates that, irrespective of the type of imaging technique utilized, the regions of the cortex most often involved are found broadly in the PFC and the anterior cingulate cortex (see

Banich, 2009; Joanette et al., 2008; Jurado & Rosselli, 2007; Robinson et al., 2014; Romine & Reynolds, 2005; Stuss & Alexander, 2007; Wang et al, 2013), with interconnected regions throughout the cortex. EF processes such as cognitive flexibility/shift, inhibition, planning, and working memory, more often are associated with the dorsolateral PFC (DLPFC) during EF tasks (Robinson et al., 2014; Ehlis et al., 2005, 2008).

Despite observable changes in behavior, examination of a single EF component from a neuroanatomical vantage has been problematic due to overlapping processes and constructs within assessment measures utilized (Best, Miller & Jones, 2009; Stuss, 2011; Zelazo et al., 1997). Additionally, researchers disagree as to the number of EF processes that exist, the differentiation of these processes, and often describe them in terms unique to those in their study. Table 2 highlights studies utilizing a variety of methodologies to assess EF processes in the Miyake et al. (2000) model of EF, and those areas of the cortex that were found to likely subserve these functions. Utilizing a variety of methodologies, the majority of these studies found statistically significant activation in the PFC. It is important to recognize the highly interconnected nature of the PFC to the other regions of the cortex; however, the DLPFC, orbitofrontal cortex (OFC), and ventrolateral PFC (VLPFC) are most frequently implicated. While some differences between studies exist due to task and study design factors, these regions are the most frequently cited in the literature as the areas consistently found to activate during EF-associated tasks.

Table 2 Miyake et al. (2000) Model of EF Processes and Associated Cortical Structures with a Sample of Studies Finding Those Results.

Proposed EF	Associated Brain Structure(s)	Supporting Evidence
Shifting/Cognitive Flexibility	DLPFC, OFC, rostrodorsal PFC, left inferior frontal gyrus, left parietal, anterior cingulate, VLPFC, VMPFC	Hirshorn & Thompson-Schill, 2006; Müller et al., 2014; Nagahama et al. 2001; Nagahama et al. 2005; Picton, Alain, & McIntosh, 2002; Rolls, 2002; Stuss et al., 2002; Smolker et al., 2015
Inhibiting	OFC, middle and inferior frontal gyrus, left superior frontal cortex, caudate nucleus, basal ganglia, striatum	Aron, Fletcher, Bullmore, Sahakian, & Robbins, 2003; Picton et al., 2007; Tamm et al., 2002
Updating of Working Memory (including organizing, monitoring, manipulating, and correcting)	DLPFC, right lateral PFC; anterior cingulate	Ehlis et al., 2008; Herff et al., 2014; Lichter & Cummings, 2001; Picton, et al., 2002; Picton et al., 2007; Rodriguez Merzagora, Izzetoglu, Onaral, & Schultheis, 2014; Stuss et al., 2000; Rolls, 2002

Note: DLPFC = dorsolateral prefrontal cortex; OFC = orbitofrontal cortex; PFC = prefrontal cortex; VLPFC = ventrolateral prefrontal cortex; VMPFC = ventromedial prefrontal cortex

The Assessment of Executive Functions

Assessment of EF components can take make many forms. Clinicians and researchers utilize observation, rating scales, and performance-based measures to quantify EF processes across individuals (Anderson, 2002; Barkley & Murphy, 2010; Lezak et al., 2004; McCloskey et al., 2008; Reynolds & Horton, 2008; Toplak et al., 2009). Use of reaction time tasks, paper-pencil tasks, or computer-administered tasks are the primary techniques for performance-based assessment (Anderson, 2002; Reynolds & Horton, 2008; Weyandt et al., 2013), whereas rating scales, completed as self-reports or by informants (e.g., parents or teachers), provide information regarding daily functioning (Kamradt et al., 2014; Reynolds & Horton, 2008).

Rating Scales

Rating scales are a recommended component of an evaluation for ADHD, supplying necessary information regarding an individual's everyday functioning (Anderson, 2002; Barkley & Murphy, 2010; Duff & Sulla, 2015; Kamradt et al., 2014; Reynolds & Horton, 2008; Toplak et al., 2009), as diagnosis of any psychiatric condition is predicated by an *impairment* in daily function. A number of rating scales are available which assess a variety of EF processes, though they may or may not be based upon a research-supported model of EF (e.g., Behavior Rating Inventory of Executive Function [BRIEF], Gioia, Isquith, & Guy, 2000; Barkley Deficits in Executive Functioning Scale [B-DEFS], Barkley, 2006; Delis Rating of Executive Functions [D-REF], Delis, 2012). Interpretation of ratings and implications for areas of deficit are available in the test manuals or texts on assessment of EF (e.g., Lezak et al., 2004; McCloskey & Perkins, 2013). Ratings may be completed by the individual being assessed (i.e., self-report); however, collateral reports from a third party (i.e., parent, teacher, spouse) are particularly important for individuals who may lack the insight to self-report accurately (Anderson, 2002; Dvorsky, Langberg, Molitor, & Bourchtein, 2016; Kamradt et al., 2014).

Though providing necessary and useful information, irrespective of the rating scale used, most studies reveal self-reports made by those with ADHD tend to underreport symptoms and deficits in everyday function (Heinonen et al., 2013; Kooij et al., 2008). Data regarding the effects of medication status on self-report of symptoms is unknown; and, even though studies of adults providing self-report of symptoms are

available, no data regarding medication effects was found. While rating scales of everyday skills are necessary, direct observation and performance-based assessment of EF is also a necessity in clinical settings (Dvorsky et al., 2016).

Performance-Based Tasks and Tests

Performance-based measures include those measures in which the examinee is observed performing the EF task, usually in a laboratory or clinical setting, and include a variety of tasks. The more common ones include measures of EF processes such as inhibition/impulsivity, planning, problem solving, attention/vigilance (or inattention), set shifting/cognitive flexibility, and working memory. Tasks include sorting tasks, continuous performance tests, flanker tasks, and various tests of working memory (e.g., n-back, letter-number sequencing). Many EF assessments (e.g., Delis-Kaplan Executive Function System [D-KEFS], Delis, Kaplan, & Kramer, 2001; Conners Continuous Performance Test—Third Edition [Conners CPT-III], Conners, 2015) now utilize a computer-administered, game-like format (e.g., go/no-go tasks, continuous performance tests, set shifting or sorting tasks; Geburek et al., 2013). These assessment tools are intended to allow the clinician to analyze deficits in EF or other processes based on patterns of performance.

Problematically, performance-based tasks often require multiple EFs to complete the task correctly; therefore, unrelated processes can affect the results (Hale et al., 2009; Toplak et al., 2009). At the same time, some research has revealed that many children and adults with EF disorders such as ADHD have varying degrees of impairment in EF, or none at all (Kamradt et al., 2014; Nigg et al., 2005). As a result, these individuals

may perform adequately during neuropsychological evaluation, but deplete all their cognitive resources to do so (Lyons Usher et al., 2015).

Because many EF measures are administered in a clinical one-on-one environment (i.e., an optimal setting), the ecological validity of these measures is also questioned (Anderson, 2002; Barkley & Murphy, 2010; Mahone et al., 2002; Kamradt et al., 2014), thereby increasing the necessity of confirmatory measures (e.g., other-informant completed rating scales; Sibley et al., 2012). Unfortunately, several studies have demonstrated a lack of agreement between rating scales and performance-based measures with minimal to inconsistent correlations, or conversely, limited predictive power (e.g., Barkley & Murphy, 2010; Hale et al., 2009; Toplak et al., 2013).

Set Shifting Tasks

The class of tasks referred to as Set Shifting (or Cognitive Flexibility) tasks have been widely researched using such tests as the Wisconsin Card Sorting Test (WCST; Heaton, Chelune, Talley, Kay, & Curtis, 1993), the switching conditions of many D-KEFS tests (e.g., Sorting Test, Verbal Fluency Test, Set Shifting Test, Trail Making Test [TMT]), the original TMT Part B (Reitan & Wolfson, 1953) and the Stroop Color-Word Interference task (Stroop, 1935). In fact, the most widely utilized assessments of shifting/cognitive flexibility are the WCST and the TMT-Part B (Baldo, Delis, Wilkins, & Shimamura, 2004; Chan et al., 2015; Nyhus & Barceló, 2009; Sánchez-Cubillo et al., 2009). The difference or ratio in completion time for TMT-Part B (letter-number switching) over TMT-Part A (number sequencing) has been found to measure set-

shifting/cognitive flexibility in factor and meta-analytic studies (e.g., Müller et al., 2014; Pennington & Ozonoff, 1996; Sánchez-Cubillo et al., 2009; Willcutt et al., 2005).

Imaging with fNIRS revealed differences in hemispheric activation on the Stroop (Ehlis, Herrmann, Wagener, & Fallgatter, 2005) with greater activation in the left superior-frontal region; however, no consistent pattern of lateralization was evident on TMT-B (Shibuya-Tayoshi et al., 2007). Though some suggest set shifting tasks (e.g., TMT, Stroop, WCST) require multiple processes, adequate performance elicited increased activity in the DLPFC and VLPFC during inhibition tasks (Boecker et al., 2007), trail-making tasks (Nakahachi et al., 2010; Shibuya-Tayoshi et al., 2007), and on the Wisconsin Card Sorting Test (Sumitani et al., 2006).

Continuous Performance Tests

The CPT has been utilized since 1956 as a measure sensitive to brain damage or dysfunction, often utilized in the assessment of attention, ADHD, or other clinical disorders with implications for EF (Riccio et al., 2002). As vigilance and inhibition have been found to be areas of deficit in individuals with ADHD (e.g., Willcutt et al., 2005; Hale et al., 2009), variables such as reaction time and commission errors are indicative of attention and inhibition, respectively. Though it has been demonstrated to be highly sensitive to dysfunction, the results of the CPT generally do not provide sufficient, or specific, diagnostic clarification and should be used as part of a battery of assessment measures (Riccio et al., 2002). Standardized and computer-administered, a CPT can provide a norm-referenced assessment of response time, response time variability, commission errors, and/or omission errors based upon the individual's performance.

Several forms of CPT are available that require the examinee to respond to each signal except the target, or respond only when the signal is the target. Wang and colleagues (2013) indicated slower response speed (e.g., how long the examinee evaluated their response and acted), greater response variability and increased number of errors (e.g., commission and omission) are often exhibited by individuals with ADHD. Others have noted the relative frequency of commission errors generally indicates impulsive responding or disinhibition, identified as a core feature of ADHD (Geburek et al., 2013; Riccio et al., 2002).

Flanker Tasks

Flanker tasks are computer-based and vary in their overall length, but are sufficiently long enough to require an individual to sustain his or her attention to the task for greater than 10 to 14 minutes. This type of task requires speeded decision making and discrimination of the directionality of a given stimulus with accuracy, and the ability to inhibit responding inaccurately when presented conflicting visual information. Research conducted over the previous 10 years (see meta-analyses conducted by Geburek, Rist, Geiga, Stroux, & Petersen, 2013 and Mullane, Corkum, Klein, & McLaughlin, 2009) has evaluated the use of the Flanker task to assess EF in individuals with and without ADHD and found impulsive responding (commission errors) and high variability in reaction time in children, and inattention (difficulty with vigilance) in adults with ADHD.

Updating of Working Memory

A limited capacity system, working memory is tasked with temporary storage and manipulation information required for comprehension, learning, and reasoning (Baddeley & Hitch, 1974). In its current version, the BRIEF (Gioia et al., 2000) rating scale provides a measure of everyday working memory function as compared to age peers. Items in this cluster measure behaviors such as losing needed materials, forgetting to complete tasks, or having difficulty remember multi-step instructions. Performance-based tasks have been developed to assess visual and verbal modalities (e.g., n-back tasks, spatial span tasks, letter-number sequencing, sentence memory), and can be divided into maintenance tasks (e.g., hold onto information across a non-distracted delay) or maintenance-plus tasks (e.g., require information to be shuffled or processing additional stimuli while maintaining the information; Conklin et al., 2007).

Planning and Problem-Solving Tasks

The Tower of Hanoi (Simon, 1975), Tower of London (Shallice, 1982) and variations such as Tower test from the D-KEFS (Delis et al., 2001) are variations on a logic game intended to engage planning and problem solving. The task requires the examinee to move disks or beads from a starting point to a specified end result, following the rules for the game, and may have a bonus element for speeded completion. Though these tasks may also require abilities such as working memory and attention, they are generally considered to be tasks of planning and problem solving (Sullivan, Riccio, & Castillo, 2009; Wodka et al., 2008), often deficit in individuals with ADHD as well. For example, Wodka and colleagues found group differences between ADHD and

non-ADHD groups on the Tower test of the D-KEFS, with the ADHD group performing much lower than peers on this measure. In contrast, a meta-analysis of studies examining Tower tasks as a measure of EF found, however, that poor performance on Tower tasks is present across a number of neurological disorders and may be related to the other requisite skills for successful performance (i.e., attention and working memory; Sullivan et al., 2009). Other planning and problem solving tasks include mazes (e.g., Porteus maze; Porteus, 1950, 1959) and to some extent the Twenty Questions Test (20Q) on the D-KEFS (Delis et al., 2001).

Prefrontal Activation during EF Tasks

Research utilizing functional imaging has clearly demonstrated the PFC to be crucial to many EF-associated tasks (e.g., TMT-B, WCST, n-back, Tower of Hanoi) as was shown in Table 2. The degree of activation, however, is associated with age-related maturation, defined by pruning and myelination (Sheridan, Kharitonova, Martin, Chatterjee, & Gabrieli, 2014). As noted previously, EF processes have been studied utilizing a variety of tasks and methodologies. Based on the Miyake et al (2000) model of EF, imaging studies have revealed all three components to be subserved by the PFC, with associations to other aspects of the cortex (see Table 2 for detailed notation of cortical areas of activation). Table 3 lists a sample of imaging studies utilizing traditional EF tasks.

Table 3 EF Tasks, Processes and Evidence.

Type of Task	EF Components Assessed	Format	Sample of Imaging Studies
Continuous performance tests	Inhibition (commission errors) Vigilance (omission errors)	Digital	Tana, Montin, Cerutti, & Bianchi, 2010; Wang et al., 2013
Dimensional Set Shifting Tasks	Shifting/Cognitive flexibility Working memory	Digital, Physical	Hartberg et al., 2011; Nagahama et al., 2001, 2005
Flanker Tasks	Inhibition, Decision speed	Digital	Iannaccone et al., 2015; von der Gablentz, Tempelmann, Münte, & Heldmann, 2015; Żurawska vel Grajewska et al., 2011
Go/No-Go	Inhibition	Digital	Aron et al., 2003; Iannaccone et al., 2015; Inoue et al., 2012
N-back	Working memory	Digital	Fishbum, Norr, Medvedev, & Vaidya, 2014; Herff et al., 2014; León-Domínguez, Martín-Rodríguez, & León-Carrión, 2015; Molteni et al., 2012;
Stroop tasks	Inhibition Set shifting	Digital, Paper	Hartberg et al., 2011; Laguë-Beauvais, Brunet, Gagnon, Lesage, & Bherer, 2013
Tower Tasks (e.g., Tower of Hanoi, Tower of London)	Planning Working memory	Digital, Physical	Wagner, Koch, Reichenbach, Sauer, & Schlösser, 2006
Trail Making Test-B (Number-Letter)	Shifting/Cognitive flexibility	Paper-pencil	Allen, Owens, Fong, & Richards, 2011; Hartberg et al., 2011; Lee, Wallace, et al., 2014; Müller et al., 2014

Statement of the Problem

Examining EF proves to be a challenge for a myriad of reasons. The developmental and hierarchical nature of cognitive processes, the confounds of tests, tasks and processes, the overlapping EF components measured, and individual factors make generalizations regarding neural activity associated with EF difficult to say the least. Recently, an increasing number of measures are administered via computer or

tablet (i.e., digital format), adding yet another potential confound. There is limited research available to support or refute contentions that digital measures reflect activation of the frontal lobes differently than paper-pencil or physical measures. Furthermore, it remains unclear whether these measures are measuring the same construct based on their method of presentation (i.e., paper-pencil or computer-based).

This study examined potential interactions between neural activation patterns in the PFC, task performance, EF ratings, and ADHD status. It is not established that individuals with ADHD demonstrate differing patterns of activation from those without ADHD during EF tasks. It is believed that EF patterns are fairly stable by young adulthood (Hughes, 2011; Romine & Reynolds, 2005) however. Further, while there is a plethora of research on children with ADHD and typically developing children, there is considerably less research on older adolescents and young adults. The EXAMINER is a relatively new addition to the assessment of EF, with very little associated literature; this study added to the research regarding its utility. This study was the first to investigate hemodynamics utilizing EXAMINER tasks, comparing ADHD and non-ADHD groups. Looking at the relation between brain activation, task performance, and ADHD status will provide further insight on neurological correlates of young adults with ADHD. The methodology for this study is found in Chapter III.

CHAPTER III

METHODS

Participants

The larger study was approved by the University Institutional Review Board (IRB). A recruitment email was sent through the "Current Students" listserv that included details about the study, participant inclusion/exclusion criteria, and the Principal Investigator's contact information. Potential participants were English-speaking, 18- to 22-years-old, and who 1) self-reported previous diagnosis of ADHD or 2) had no previous diagnosis of ADHD. Two hundred four individuals responded to the initial email. Using a random list generator (available online at https://www.randomizer.org), 55 of the initial 204 respondents were subsequently contacted, pre-screened for inclusion/exclusion criteria, and scheduled for participation before the end of the Spring 2016 semester, when data collection ended.

Due to the confounding effects of other neurologic and/or other behavioral disorders, individuals with previous diagnoses of intellectual disability, seizure disorder, traumatic brain injury, or psychiatric diagnosis other than ADHD were excluded. Additionally, individuals taking any psychotropic medication other than a form of short-acting stimulant medication, such as methylphenidate (e.g., Ritalin or variant) or amphetamine salts (e.g., Adderall or variant), were excluded from participation, due to potential medication effects influencing the results. Also, participants taking stimulant medication were asked when they normally take their medication. Participants were

subsequently scheduled for testing, after self-selecting whether they would be medication-free, approximately 24 hours after their last dose, to attempt to minimize effects of medication on performance and measures of hemodynamics.

Prior diagnosis of ADHD was provided by self-report, with results of the CAARS ADHD Index used to document current levels of self-reported symptoms. Of the initial respondent group, 52 participants completed the study. Of these 52, two participants' data were excluded when it was determined they did not meet inclusion criteria (e.g., due to age or inability to complete the tasks). The final number of participants who completed the study was N = 50, 31 with no ADHD diagnosis and 19 diagnosed with ADHD, by self-report.

Characteristics of the sample included average age of 20.22 (1.38) years. Overall, participants were fairly evenly split on gender (52% male); were Caucasian (64%); spoke English in their home (94%); and were currently enrolled in an undergraduate program (96%). Of the 50 participants, 19 (38%) self-identified as having been diagnosed with ADHD with 15 of 19 currently taking medication. Statistical differences between groups (such as age, sex, gaming experience, educational level) were calculated using Chi-square analysis across groups (see Table 4). Homogeneity of variance (Levene statistic) tests were non-significant across sample demographic categories and rating scale results. As expected, statistically significant between group differences were found for number of ADHD symptoms (CAARS ADHD Index *T*-scores; $p<.001$) and medication status ($p<.001$). These results indicate a statistically significant difference between the ADHD and Non-ADHD groups based on

symptom report; furthermore, the individuals in the ADHD group were statistically more likely to be taking medication.

Table 4 Participant Demographics.

Variable	Non-ADHD *N*=31	ADHD *N*=19	Total *N*=50	X^2	*p*
Gender				0.26	.61
Male	17 (34.0%)	9 (18.0%)	26 (52.0%)		
Female	14 (28.0%)	10 (20.0%)	24 (48.0%)		
Race/Ethnicity				7.14	.07
African American	4 (8.0%)	0 (0.0%)	4 (8.0%)		
Hispanic	4 (8.0%)	5 (10.0%)	9 (18.0%)		
Caucasian	18 (36.0%)	14 (28.0%	32 (64.0%)		
Other	5 (10.0%)	0 (0.0%)	5 (10.0%)		
Class Standing				3.83	.57
Freshman	10 (20.0%)	4 (8.0%)	14 (28.0%)		
Sophomore	7 (14.0%)	4 (8.0%)	11 (22.0%)		
Junior	9 (18.0%)	6 (12.0%)	15 (30.0%)		
Senior	3 (6.0%)	5 (10.0%)	8 (16.0%)		
Other	2 (4.0%)	0 (0.0%)	2 (4.0%)		
Take Medication (yes, regularly)	5 (10.0%)	15 (30.0%)		19.37	**<.001****
Home Language – English	30 (60.0%)	16 (94.1%)		1.11	.29
Mean hours spent gaming per week (SD) [1]	7.1 (10.27)	5.08 (8.76)	6.34 (8.76)	11.68	.77
				F	*P*
Mean Age in Years (SD)	20.00 (1.32)	20.58 (1.43)	20.22 (1.38)	2.14	.15
BRIEF-A					
BRI	49.74 (9.13)	64.89 (11.95)	55.50 (12.60)	22.49[3]	**<.001****
MCI	57.32 (9.86)	67.79 (8.61)	61.30 (10.63)	14.58	**<.001****
CAARS ADHD Index[2]	49.61 (7.88)	61.68 (7.14)		29.62	**<.001****

Note. ADHD = Attention Deficit/Hyperactivity Disorder; BRIEF-A = Behavior Rating Inventory of Executive Function- Adult Version; CAARS = Conners Adult ADHD Rating Scale.
[1] N=48, data on hours/week spent gaming were not available for 2 participants; [2] Reported values are clinical T-Scores, [3] Welch's ANOVA *F* statistic.
**p<.01

Measures

Demographic Information

Demographic information (e.g., age, sex, current educational year, ethnicity, parents' education level, primary language in the home, medication use, other diagnosis/medical condition, and gaming experience) was obtained from all participants to assess and potentially control for possible confounding factors using a demographic information sheet completed by the participant (see Appendix A). Additionally, information regarding medications, time of last dose (if applicable) and level of ADHD symptoms was obtained from all participants, as described previously. Variables of interest are listed in Table 5.

Table 5 Measures and Variables.

Measure	What Measuring	Variables to Consider
fNIRS	Cerebral activation in anterior PFC and DLPFC	ΔHb AF7 (left) ΔHb FP1 (midleft) ΔHb FP2 (midright) ΔHb AF8 (right)
BRIEF	Inhibition Updating/Working Memory	Behavioral Regulation Index Metacognition Index
D-KEFS—20Q	Updating/Working Memory	Total Questions Asked Total Weighted Achievement Score
EXAMINER-CPT	Inhibition	Non-target Errors
EXAMINER-Flanker	Inhibition	Error Difference (Congruent correct-incongruent correct)
EXAMINER-n-Back	Updating/Working Memory	Total Errors

Table 5 Continued

Measure	What Measuring	Variables to Consider
EXAMINER-Set Shifting	Cognitive Flexibility/Shift	Total Errors
TMT	Cognitive Flexibility/shift	TMT Sum (TMT A + TMT B)
		TMT Ratio (TMT B / TMT A)
		TMT Diff (TMT B – TMT A)

Note: ΔHb = Change in oxy/deoxy hemoglobin; 20Q = Twenty Questions; CPT = Continuous Performance Test; D-KEFS = Delis-Kaplan Executive Function System; fNIRS = functional Near-Infrared Spectroscopy; OxyHb = oxygenated hemoglobin; TMT = Trail Making Test; TMT Diff = Difference

Behavior Rating Inventory of Executive Function-Adult Version (BRIEF-A)

The Behavior Rating Inventory of Executive Function-Adult Version (BRIEF-A; Roth, Isquith, & Gioia, 2005), an upward extension of the original BRIEF rating scale, is an inventory completed by the adult or an informant in the assessment of a variety of learning, attention, or other neurocognitive conditions. The BRIEF-A is a 75-item scale in which the respondent indicates the frequency of listed behaviors on a 3-point Likert scale (never, sometimes, or often). The summed responses yield T-scores ($\bar{X}$=50, *SD*=10) on nine clinical scales, which can then be summed to yield broader index scores. The Metacognition Index (MCI) is derived from the Initiate, Working Memory, Plan/Organize, Task Monitor, and Organization of Materials scales. The Behavioral Regulation Index is derived from the Inhibit, Shift, Emotional Control, and Self-Monitor scales. For the purposes of this study, the BRIEF-A Self-Report Indices were utilized to provide an assessment everyday EF, or daily functioning. The index scores were utilized, rather than the scale scores, as the indices have reported reliability coefficients

ranging from .93 to .96, while individual scales are less reliable, with coefficients ranging from .73 to .90 (Roth et al., 2005). Roth, Lance, Isquith, Fischer, and Giancola (2013), in a study of the factor structure of the BRIEF-A, found a group of young adults with ADHD to report greater difficulty on the MCI (e.g., higher T-scores) and poorer scores on Behavioral Regulation in inhibitory control and self-monitoring of behavior.

Conners' Adult ADHD Rating Scales (CAARS)

The Conners' Adult ADHD Rating Scales (CAARS; Conners, Erhardt, & Sparrow, 1999) is a measure typically utilized in the diagnosis of ADHD in adults age 18 and older. The CAARS is completed as a self-report or observer report, with a short form having 26 items. The respondent indicates the frequency of the behavior described on a 4-point Likert scale (Not at all/Never, Just a little/Once in a while, Pretty much/Often, or Very much/Frequently). The ADHD Index provides a measure of the likelihood the individual being rated meets diagnostic criteria for a diagnosis of ADHD. Reliability and validity of the CAARS was found to be satisfactory with reliability coefficients ranging from .86 to .92 (Erhardt, Epstein, Conners, Parker, & Sitaremios, 1999). The ADHD Index was utilized in this study to provide an indicator of current ADHD symptoms to verify group membership and ensure the differences between ADHD and Non-ADHD groups were real.

EXecutive Abilities: Measures and Instruments for Neurobehavioral Evaluation and Research (EXAMINER)

The EXAMINER is a recently developed series of tasks designed to measure working memory, inhibition, set shifting, fluency, insight, planning, social cognition and

behavior (Kramer et al., 2014). Commissioned by the National Institute of Neurological Disorder and Stroke (within the National Institutes of Health [NIH]), the EXAMINER is an attempt to provide a more psychometrically sound tool for use in neurological clinical trials and in research investigations in individuals across the lifespan. Conceptually, the developers utilized the Miyake et al. (2000) model of EF for design of tasks measuring set shifting, updating and monitoring, and inhibition of responses. Utilizing expert opinion via consultation and literature review, tasks and the structure of the battery were developed; item response theory was utilized to generate scores for the four composite variables of Global Executive Function, Cognitive Control, Fluency, and Working Memory (Kramer et al., 2014). The EXAMINER is published for use using multiple platforms. For this study, the EXAMINER tasks were run on a PsychoPy platform, an open-source program for running experiments in Python, which allows integration of hardware and precise timing making it ideal for use in neuroscientific research (Peirce, 2009).

Proposed tasks for this study included four subtests: Flanker, Set Shifting, Continuous Performance Test (CPT), and n-Back tasks. These tasks selected were chosen based on recent research utilizing the EXAMINER with control and ADHD groups in children and adolescents and factor analysis of task results (e.g., Schreiber et al., 2014, Robinson et al., 2014). According to the authors, Flanker and CPT provide measures of inhibition; Set Shifting is purported to measure cognitive flexibility/shift; and the n-Back task is a measure of visuospatial working memory. With the exception

of the CPT, each task was modified to run (e.g., provide a stimulus) in six 30 second blocks, with a minimum 10 seconds of rest between blocks.

Flanker

The Flanker task requires the subject to direct their focus to the center of a computer screen, and lasts approximately 15 minutes. Using a variable duration of 1000 msec-3000msec, five arrows are presented in the central part of the screen either above or below the fixation point for 1000 msec. The examinee pushes the left arrow key if the *center* arrow is pointing to the left or the right arrow key if the *center* arrow is pointing to the right. The arrows alongside the center arrow may be pointing the same direction (congruent) or in an opposite direction from the center arrow (incongruent). The goal is to respond as quickly and as accurately as possible. As reported in the EXAMINER User Manual (Kramer, 2011), reliability (coefficient alpha) estimates for Accuracy for the Flanker task, in subjects aged 18+, in both congruent and incongruent conditions, and were .88 and .93, respectively. Errors of commission (e.g., false alarms) are frequently utilized as behavioral indicators of disinhibition in ADHD literature, as described previously (Riccio et al., 2002). Electrophysiological studies conducted during completion of the Flanker task indicate the orbitofrontal cortex, inferior frontal gyrus and other medial aspects of the cortex to subserve inhibition (Abundis-Gutierrez et al., 2014). In a meta-analysis of fMRI and PET imaging of performance during interference tasks, Nee, Wager, and Jonides (2007) found flanker tasks to activate the right DLPFC and the right insula.

Set Shifting

The Set Shifting task requires the participant to sort a stimulus image by shape (Task A) or color (Task B) based upon the instruction given on the computer screen (Kramer et al., 2014). There are task-homogeneous and task-heterogeneous blocks, and these blocks switch pseudo-randomly allowing measurement of the examinee's ability to switch sets. The given stimulus may be the same color as the target shape (task-homogeneous) or a different color from the target (task-heterogeneous), requiring the examinee to shift cognitive set to complete the task correctly. As this is a newer paradigm for a shifting task, very limited research is currently published on this task. This design is a rather untested conceptual method for a dimensional sorting task; therefore, limited research regarding its validity is currently available. This study adds to that literature. The coefficient alpha estimate provided in the EXAMINER manual for accuracy in Set Shifting was .91. It is suggested to be sensitive to those with impulsive responding tendencies and who have difficulty adapting to feedback (e.g., cognitive flexibility), a critical deficit in those with ADHD.

Continuous Performance Test (CPT)

The EXAMINER CPT is a computer-based assessment of inhibition, lasting approximately 10-15 minutes. When a 5-pointed star is displayed on the computer screen, the examinee is to respond by pressing the left arrow key as quickly as possible; the examinee is to withhold a response to any other stimulus. The CPT in the EXAMINER has been designed to elicit false alarm errors as 80% of the stimuli are the target. The total number of false alarm errors is the dependent variable in the CPT

scoring; however, additional scores are available on the software scoring program, including measures of accuracy and reaction time (response speed). Internal consistency reliability estimate on the CPT accuracy was .78 in adults, no other reliability estimates are provided. As with the Flanker task, the false alarms (commission errors) are generally viewed as indicators of impulsive responding or lack of inhibition (Kramer et al., 2014; Riccio et al., 2002). Individuals with ADHD have shown poorer performance concurrent with decreased activation in the DLPFC (Tamm et al., 2002). Imaging results and lesion maps have indicated sufficient activation of the DLPFC and anterior cingulate cortex are required for successful completion of the CPT (Robinson et al., 2014; Tamm et al., 2002; Tana et al., 2010).

N-Back

The N-Back consists of both 1-back and 2-back conditions which require the examinee to recall the spatial location of the stimulus, a white square on a black computer screen, either one screen previous (1-back) or two screens previous (2-back). Internal consistency (Cronbach's alpha) was reported to be .85 in the 2-back condition for d-prime, calculated as the difference between the z-transformed scores of the hit rate and the false positive rate in identifying the correct position two screens previous. The n-back task is consistently utilized in research as a measure of working memory in clinical research, and has been utilized during fNIRS monitoring in several studies (see Hoshi, 2011; Ehlis et al., 2008; Kearney-Ramos et al., 2014). Although the larger study will consider two modes of administration, only the standard administration will be considered in this study. Imaging evidence has consistently shown the DLPFC to

subserve this type of task; however, as the EXAMINER utilizes a visuospatial rather than a verbal paradigm, activation may occur in either the right or left hemispheres. Working memory deficits are found in a variety of neurological conditions (e.g., ADHD, learning disabilities; Barkley, 1997, 2011; Ehlis et al., 2008; Rapport et al., 2001; Rohlf et al., 2012; Schreiber et al., 2014), and tasks with increased workload are found to activate the DLPFC, VLPFC, and anterior cingulate in non-clinical populations compared to those with ADHD (Ehlis et al., 2008; Herff et al., 2014).

DKEFS-Twenty Questions Test

The 20Q Test was selected from the Delis-Kaplan Executive Function System (DKEFS; Delis, Kaplan, & Kramer, 2001). This task is designed to assess verbal abstract planning, monitoring of performance, and updating strategy based upon feedback (Baldo et al., 2004; Delis et al., 2001). The examinee is shown a card with an array of 30 pictured objects and is asked to, in the fewest questions possible (up to a maximum of 20), develop and use yes-no questions to determine a target item selected by the examiner. The task is estimated to take approximately 5-10 minutes. Internal consistency estimates range from .72 to .87 (Delis et al., 2001). Baldo and colleagues (2004) examined performance in a group of individuals with frontal lobe lesions. They found the use of strategy and abstraction was significantly impaired in the frontal group as compared to controls. Consistent with the literature, this pattern of performance suggests that those with impaired frontal lobe function have inefficient strategies, monitoring, and use of feedback to adjust behavior as measured by this task. As two potential measures of updating are available (i.e., total questions asked, total weighted

achievement score), both will be analyzed to answer the proposed research questions. There is also limited data regarding the use of 20Q in the assessment of EF deficits and/or those with ADHD, and this study adds to that literature as well.

Trail Making Test

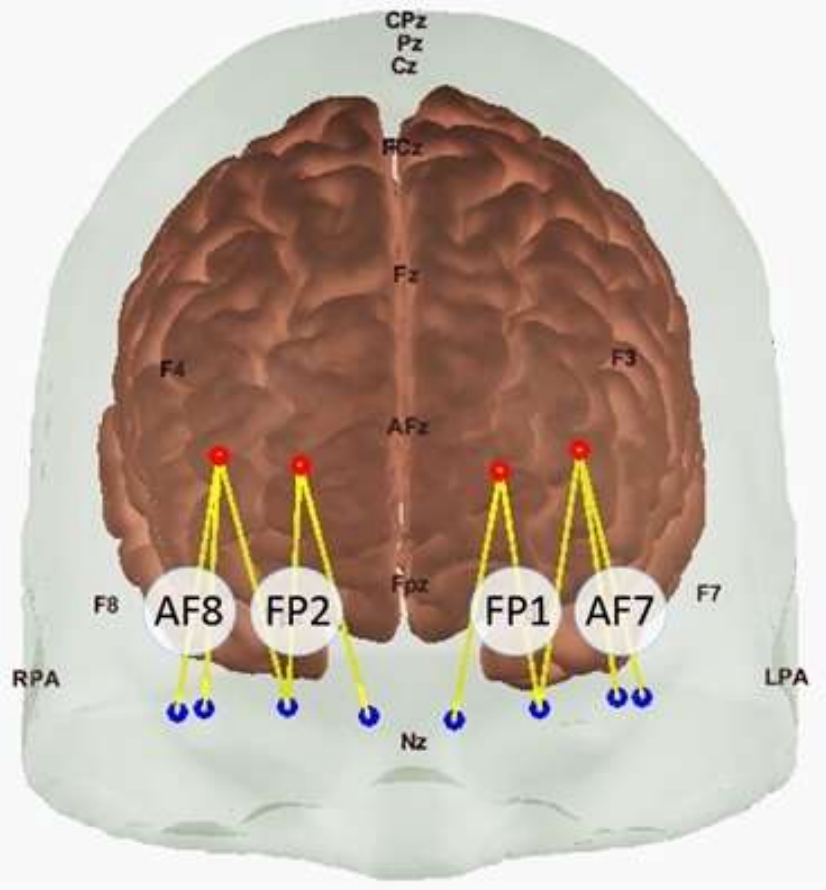
The Trail Making Test (TMT) is one component of the Halstead-Reitan Neuropsychological Test Battery (HRNB; Reitan & Wolfson, 1993). The TMT is traditionally comprised of two tasks, Part A (number sequencing) and Part B (letter-number sequencing/set shifting). The TMT Part B has an extensive record of use in the measurement of shift/cognitive flexibility and working memory (Allen et al., 2011; Kalkut et al., 2009; Müller, et al., 2014; Sanchez-Cubillo et al., 2009). Reliability reported in several studies is test-retest reliability for both Parts A and B are r=.79 and .89 respectively.

Imaging research conducted by Müller and colleagues (2014) utilizing the TMT found a lateralization of activation to the right hemisphere, with higher oxyHb measured in the ventral PFC followed by the lateral PFC. Further, individuals committing an increasing number of errors had reduced involvement of the DLPFC, substantiating its role in successful completion of the task. These findings were also in line with other studies finding regional increases in the PFC and specific increases in the DLPFC for successful TMT-B completion (e.g., Lee et al., 2014; Nakahachi et al., 2010; Shubuya-Tayoshi et al., 2007).

In order to parse out the motoric elements of performance, a variable of interest will be the difference in completion time between Part B and Part A, a procedure that

also accounts for errors in performing the required changes in set (e.g., switching from letter to number, to letter, and so on, see Lee et al., 2014 or Sanchez-Cubillo et al., 2009 for additional discussion of the use of TMT B-A). Additional evidence exists for the use of TMT B+A in those with ADHD, as global processing speed tends to be adversely affected in adults having ADHD. Thus, slower completion times overall may be seen in the ADHD group (Nigg et al., 2005). Interestingly, use of the TMT B/TMT A ratio score is also described in the literature. Use of the ratio of time to complete Part B to Part A is believed to yield an estimate of processing time for solely the cognitive shift, as the ratio removes time for needed for visual scanning and motoric elements (Nigg et al., 2005).

Figure 1 Diagram of NIRS probe



Note: The location of the optodes (red dots: sources, blue dots: detectors), channels created between optodes (yellow lines), and the 10-20 international EEG system labels. Areas of interest are highlighted and include AF7: Left, FP1: Midleft, FP2: Midright, AF8: Right). Figure adapted from C. Riccio, R. Mehta, S. Vidrine, J. Rhee, G. Garrett, & L. Herrera, 2016, unpublished manuscript.

Functional Near-Infrared Spectroscopy (fNIRS)

Hemodynamic responses (e.g., changes in oxyHb, deoxyHb and total Hb) were recorded by a continuous wave fNIRS system (Techen Inc. MA, USA, CW6 system) at 50 Hz sampling rate for the session. As the cortical area of interest was the bilateral anterior prefrontal cortex, a probe was created to align with Fp1/AF7 (left hemisphere)

and Fp2/AF8 (right hemisphere) according to The Ten Twenty Electrode System of the International Federation (see Report of the committee on methods of clinical examination in electroencephalography: 1957). The probe was designed with 4 source optode emitters at two wavelengths (690 and 830 nm) and 8 detectors to create 10 channels across the anterior frontal region (see Figure 1). The hemodynamic signals were pre-processed and analyzed using a continuous wave NIRS-specific processing and neuroimaging program, HomER2 (Center for Functional Neuroimaging Technologies, Massachusetts General Hospital East, MA).

The EXAMINER tasks were adapted and administered using PsychoPy2 (Peirce, 2009) with stim marks to notate the beginnings and ends of each 30 second block, with the noted exception of a single 6 minute administration of the CPT. OxyHb, deoxyHb, and total Hb were measured and recorded concurrent to the administration of each digital task with baseline and event-related data. Changes in oxyHb/deoxyHb were calculated utilizing the difference in absorbance in accordance with current literature using the modified Beer-Lambert law (see Equation 2; Baker et al., 2014; Duncan et al., 1996; Hoshi, 2011; Sassaroli & Fantini, 2004; Strangman, Culver, Thompson, & Boas, 2002). Individual time courses of oxyHb and deoxyHb were corrected for baseline readings (described below). Each individual's event-related hemodynamic data was then computed and averaged for each position across the anterior PFC (e.g., left, midleft, midright, and right; computations by research team member, J. Rhee).

fNIRS Analyses

As mentioned previously, the recorded hemodynamic responses were processed and analyzed using HomER2 (Center for Functional Neuroimaging Technologies, Massachusetts General Hospital East, MA). Initially, raw NIRS signals were converted into measures of change in optical density by calculating the negative logarithm of the detected signal. To lessen the influence of high-frequency noise (Koenraadt, Roelofsen, Duysens, & Keijsers, 2014), the signals were low-pass filtered, a process used to smooth out the data by attenuating signals above the desired frequencies (e.g., using a 3 Hz cut-off).

During NIRS measurement, head movement often appears as abrupt changes in the amplitude of the signal (Molavi & Dumont, 2012). To correct for these motion artifacts, wavelet-based transformation of the data was used to calculate the distribution of the wavelet coefficients. A hard threshold was set to transform coefficients greater than 1.5 times the interquartile range to zero (Molavi & Dumont, 2012). After this correction of motion artifacts, each signal was again low-pass filtered using a 0.5 Hz frequency cut off to remove systemic heart beat signal responses. Signals were then high-pass filtered for signals below 0.016 Hz to reduce the influence slow wave drift caused by the NIRS system as it was operating (Koenraadt et al., 2014). The optimized signals (e.g., optical density changes after filtering) were then converted into oxyHb and deoxyHb concentrations based on calculations stemming from the modified Beer-Lambert law as described by Duncan et al., 1996 with a partial path length factor of 6.

For each task and within each stimulus block, mean oxyHb and deoxyHb values were obtained in a two second window prior to the stim in each block ($oxyHb_{baseline}$ and $deoxyHb_{baseline}$), and in the two second window around the peak oxyHb value within 20 seconds after the event stimulation of each block ($oxyHb_{event}$ and $deoxyHb_{event}$). Neural hemodynamic responses were calculated as [($oxyHb_{event} - deoxyHb_{event}$) – ($oxyHb_{baseline} - deoxyHb_{baseline}$)] (Hyodo et al., 2016; Yücel et al., 2015). The hemodynamic responses were combined/stacked by individual across each 30s block for each test; however, as the CPT is, by its nature a *continuous* task, the CPT only had one six minute block of measurement. Finally, the computed hemodynamic responses from the different channels (see Figure 1) were averaged to obtain an overall mean response for each task for each individual for each of the four sites: left lateral (Channels 1 and 2), left medial (Channels 3, 4, and 5), right medial (Channels 6, 7, and 8), and right lateral (Channels 9 and 10; computations and description provided by J. Rhee from Riccio et al., 2016).

Procedures

Following IRB approval, an email recruitment notice was sent to the general student body at the author's university. A random number sequence generator was utilized to select 50 participants from the 204 initial responses received. After receiving another brief description of the study and initial screening questions, participants were then scheduled for appointments when study personnel were available. When a participant changed his or her mind, or did not attend the session, an alternate participant was randomly selected and scheduled. For those who identified as having a prior diagnosis of ADHD, who were taking MPH (or variant), the appointment was set at a

time when study personnel were available and when he or she would not have taken medication for approximately 24 hours. Upon arrival, the purpose and procedure of the study and confidentiality were explained; they were shown all computer equipment and the head gear for the fNIRS. Once informed consent was obtained, the fNIRS headband was positioned.

For the study, the participant was seated in a quiet room. Measurements of the participants' head circumference, length of the center line from the Nasion (bridge of the nose) to the Inion (occipital protuberance), and distance between the preauricular points (over the crown) were taken by study personnel. The custom headband was placed on the participant's forehead. Once in position, the participant was asked to avoid excessive movement for 30 seconds to obtain three 10 second resting intervals for baseline measurements. They were then instructed to avoid any movement other than what was necessary for the experimental tasks, to the extent feasible (see standardized instructions, Appendix 4).

Each computerized task with fNIRS was separated by approximately 30 seconds of resting activity, conversation, or preparation for the next task to reduce interference from task to task. It was between digital tasks that participants completed the TMT and the 20Q subtest. Participants were allowed to take breaks as needed or if they appeared fatigued. Participants also completed the demographic information form, CAARS, and BRIEF-A rating scales. After finishing all tasks, the examinee was provided a gift card for their participation.

CHAPTER IV

RESULTS

For this study, data collected from a larger pilot study (e.g., Riccio et al., 2016) were analyzed. The study was a cross-sectional, two group design that integrated performance-based measures of EF with measured hemodynamic activity in the PFC and self-reported (rating scale) EF behavior in daily functioning. As the sample size was quite small, alpha was set at .05 to ensure small differences between groups could be identified and minimize the possibility of making a Type II error. G*Power v. 3.1.9.2 (Erdfelder, Faul, & Buchner, 1996; Faul, Erdfelder, Lang, & Buchner, 2007) was utilized for initial and post hoc power analyses. Based on an assumed moderate effect size of F=.25, and ANOVA modeling, it was believed having approximately 25-30 subjects per group would provide sufficient power (β=.80) to address the research questions. While rating and non-digital EF tasks were administered to all subjects, no fNIRS data were collected for one subject, yielding N=49 for NIRS data analysis. Additionally, one subject was unable to complete the N-Back task (N=48), and no data were collected during the CPT for another subject (N=48).

Overall, the sample was fairly evenly split on gender (52% male). Ethnicities were Caucasian (64%), Hispanic (18%), and African American (8%); Other (10%) included those who identified as biracial, Non-Hispanic Pacific Islander, or Asian. Participants spoke English in their home (94%) and were currently enrolled in an

undergraduate program (96%). Of the 50 participants, 19 (38%) self-identified as having been diagnosed with ADHD, and 15 of those were currently taking medication.

Chi-square test of independence revealed that identified ADHD/non-ADHD groups did not vary systematically on any one demographic characteristic (e.g., age, sex, gaming experience, educational level; see Table 6), with two noted exceptions: CAARS ADHD Index (e.g., ADHD symptom severity), X^2 (1, N=50 =29.62, $p < .001$) and medication status, X^2 (1, N=50 =19.37, $p < .001$) as noted in Table 4. Based on the Chi-square results of ADHD status, it is reasonable to separate the groups according to self-reported ADHD status, as these individuals' ratings of ADHD symptoms, as a group, are statistically higher (e.g., more severe) than the non-ADHD group. Additionally, ADHD and non-ADHD groups did not differ in the amount of time spent gaming per week.

Analysis

Hemodynamics and EF Performance

Research Question 1

To what extent are hemodynamic differences in oxyHb and deoxyHb in the PFC related to results of performance on the EXAMINER tasks (e.g., CPT, Flanker, N-Back, and Set Shifting), 20Q, and TMT and ratings of EF as found on the BRIEF-A self-report? It was hypothesized that oxy/deoxy differences found in the DLPFC (bilaterally in regions AF7 and AF8) would be directly and positively associated with results of performance-based tasks and negatively associated with rating measures of EF. In other words, greater oxygenation would be associated with better performance on digital and non-digital EF tasks and with lower scores on the BRIEF indices. To test this

hypothesis, the planned analysis included a two-tailed, Pearson-product moment correlational analysis. Upon visual examination, however, the data are heteroscedastic, despite attempts to apply a transformation, rendering Pearson's *r* an inappropriate measure of association. As a result, nonparametric (e.g., Spearman's rho) correlations were utilized to analyze the degree of association between BRIEF T-scores from the Behavioral Regulation Index (BRI), the Metacognition Index (MCI)), variables from the EXAMINER performance-based measures (e.g., CPT—non-target errors, Flanker—incongruent errors, N-back—total errors, and Set Shifting—Total errors), and hemodynamic findings as per the planned analysis (See Tables 6 and 7).

Table 6 Spearman's Rho Correlation Coefficients between Non-Digital EF Measures and Average Hemodynamic Responses by Task and Channel

	Flanker[a]				Set Shifting[a]			
EF Measure	Left	ML	MR	Right	Left	ML	MR	Right
BRI	-.15	.30	-.40	.07	-.**32***	-.07	-.20	-.18
MCI	-.10	.11	-.003	.06	-.26	.02	-.04	-.05
20Q-Total Questions	-.09	-.02	-.12	-.09	-.28	-.05	-.16	-.28
20Q-Achievement	-.21	.06	-.03	.09	-.**37****	-.06	-.06	-.**37****
TMT-Sum	.05	.13	-.01	-.02	-.15	-.23	-.**35***	-.02
TMT-Ratio	.08	-.11	.08	.29*	-.04	-.**38****	-.**34***	.03
TMT-Difference	.09	.04	.06	.20	-.08	-.**34***	-.**40****	.04
	CPT[b]				N-Back[b]			
EF Measure	Left	ML	MR	Right	Left	ML	MR	Right
BRI	-.19	-.12	-.11	-.29*	.14	.11	.09	.07
MCI	-.26	-.21	-.22	-.32*	.07	-.08	-.08	-.03
20Q-Total Questions	-.19	-.01	.05	-.15	-.13	-.14	-.10	-.15
20Q-Achievement	-.28	-.02	-.11	-.23	-.20	-.17	-.20	-.25
TMT-Sum	.10	.14	.09	.08	-.07	-.10	-.13	-.05
TMT-Ratio	.**40****	.19	.24	.18	.13	-.15	.14	.24
TMT-Difference	.**40****	.25	.22	.18	.15	-.09	.02	.14

Note. For 20Q, higher scores are associated with better performance; for all others, lower scores are associated with better performance. 20Q= Twenty Questions; BRI= Behavior Regulation Index; MCI= Metacognition Index; ML= Midleft; MR= Midright; TMT= Trail Making Test.
[a] N= 49; [b] N= 48
*p<.05; **p<.01.

For the BRIEF Indices, preliminary visual analysis revealed the relation between BRI and MCI with hemodynamics to be monotonic, with some outlying scores present on both rating scale and NIRS data. Statistically significant negative correlations were found between the BRI and Left during Set Shifting and Right/AF8 during CPT, between the MCI and Right channel during CPT, between 20Q Achievement score and Left and Right channels during Set Shifting. Moderate negative correlations were found between non-digital performance tasks, the TMT-Ratio and TMT-Difference scores, and the Midleft and Midright channels during Set Shifting, respectively. A moderate positive correlation was found between the TMT-Ratio and TMT-Difference and Left CPT channel.

The direction and strength of these correlations suggests a moderate association between inhibition (BRI) and decreased oxyHb in the left DLPFC during a task of cognitive flexibility—as BRI scores increased, indicating greater dysfunction, oxyHb decreased in the left DLPFC. Higher self-reported difficulty with updating of working memory (MCI) was moderately associated with decreased oxyHb in the left DLPFC during a task of inhibition and sustained attention, and improved performance on a task of updating of working memory (20Q) was moderately associated with increased oxyHb in bilateral DLPFC during Set Shifting. Difficulty on a task of cognitive flexibility (TMT) was moderately associated with decreased oxyHb in the bilateral OFC during a task of cognitive flexibility and with oxyHb in the left DLPFC during a task of inhibition.

Digital EF tasks included the EXAMINER tasks (e.g., CPT, Flanker, Set Shifting, and N-Back). Again, the data from NIRS and EXAMINER were heteroscedastic, making the Spearman rank-order correlation a more appropriate measure of association. Visual inspection of scatterplots of the data showed the relationships between EXAMINER performance variables and NIRS channels to be reasonably monotonic, with a few outlying datapoints. Spearman's rho (r_s) correlations between the EXAMINER tasks and the corresponding NIRS recorded responses are shown in Table 7.

Table 7 Spearman's Rho Correlation Coefficients between Digital EF Tasks and Average Hemodynamic Responses

	Flanker[a]				Set Shifting[a]			
EF Variable	Left	ML	MR	Right	Left	ML	MR	Right
Flanker Error Difference	-.**34***	-.28	-.10	-.17	--	--	--	--
Set Shifting Total Errors	--	--	--	--	-.28	-.25	-.26	-.27
	CPT[b]				N-Back[b]			
CPT Nontarget Errors	.16	.10	.08	.01	--	--	--	--
N-Back Total Errors	--	--	--	--	.22	-.13	.07	.12

Note. ML= Mid-Left; MR= Mid-Right.
[a] *N*= 49; [b] *N*= 48
**p*<.05

Of the EF variables and average hemodynamic responses, only one statistically significant correlation was obtained. A moderately strong, negative association was found between Flanker error difference (e.g., fewer differences in errors made in incongruent and congruent conditions) and increased oxyHB in the left DLPFC. As the

data were quite dispersed within these EF variables, no other correlations with the average hemodynamic responses were noted to be statistically significant. While not statistically significant, increased oxyHb during Flanker (across all channels) was weakly associated with decreased error differences or more consistent performance between incongruent and congruent task conditions. Also, decreased errors score in Set Shifting was weakly associated with increased oxyHb during the Set Shifting task across all channels. As the results indicate only weak associations, the null hypothesis cannot be rejected; increased oxygenation may or may not be associated with improved EF performance and everyday functioning.

Between Group Differences in Hemodynamics

Research Question 2

Do ADHD and non-ADHD groups differ in DLPFC activation as measured by hemodynamics? It was hypothesized the non-ADHD group would demonstrate greater oxygenation bilaterally in the DLPFC (Left/AF7 and Right/AF8) as compared to the ADHD group during EF tasks. To test this hypothesis, one-way ANOVA of the averaged hemodynamic responses during their respective digital EF tasks, across all four fNIRS channels, between ADHD and non-ADHD groups was conducted. Of note, no NIRS data was collected for one participant, as mentioned previously, and two additional participants' data were not available due to technical issues, one on the CPT and one on the N-Back, leaving N=48 for Flanker and Set Shifting, and N=47 for N-Back and CPT.

Group means for task and channel by ADHD status are shown in Appendix C. On Flanker Left, $\bar{X}$=2.64 (2.70), Midleft, $\bar{X}$=2.48 (1.93), and Right channels, $\bar{X}$=3.02 (2.23), the ADHD group data was widely dispersed. This finding was also true for the CPT Left channel, $\bar{X}$=2.23 (2.40); however, visual inspection of the Q-Q Plots for each task/channel combination revealed the values to be normally distributed (e.g., near to the line representing the regression of theoretical to empirical data points), with minimal (0-2) outlying values.

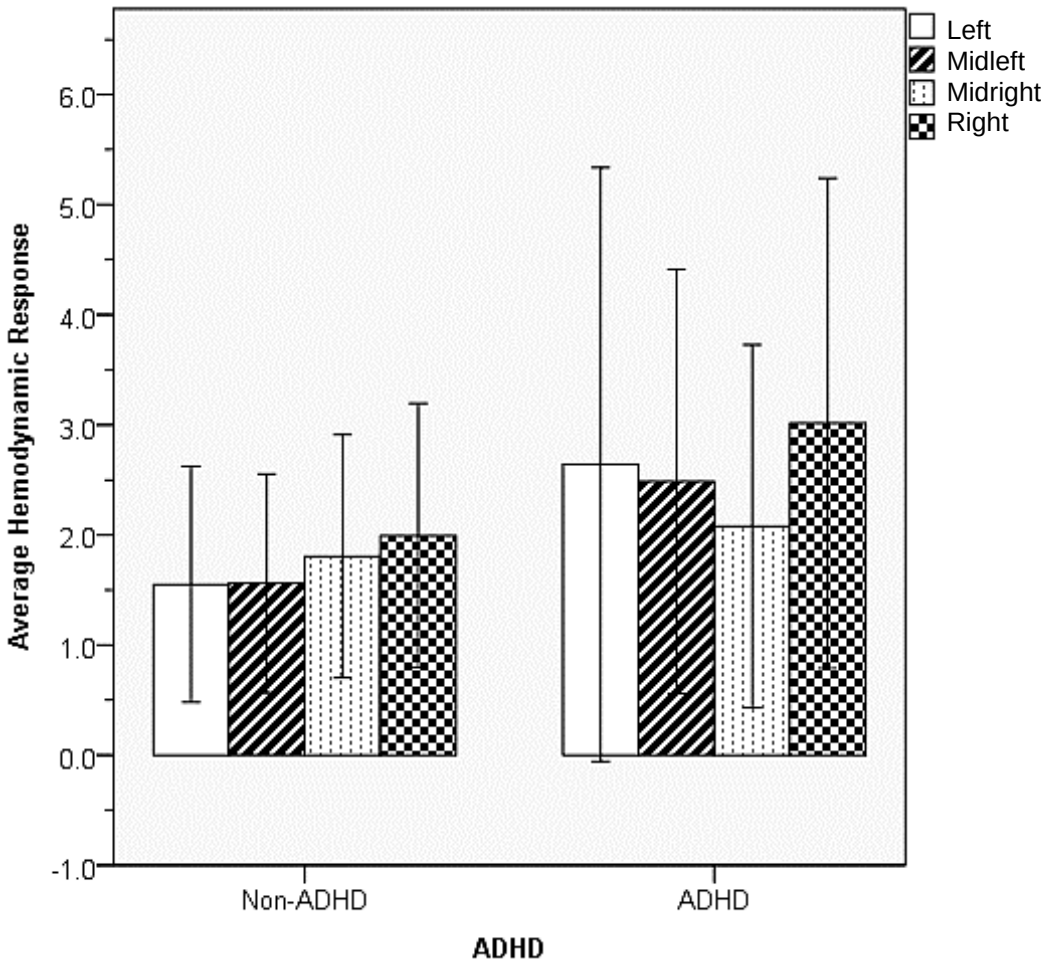
Test for homogeneity of variance was violated on three Flanker channels and on the N-Back Left channel, as measured by the Levene's *F* shown in Table 8. For task/channel combinations violating the assumption of homogeneity, Welch's *F* was calculated. No task/channel combinations were found to reveal a statistically significant difference between ADHD/non-ADHD groups in degree of activation in the DLPFC on digital EF tasks. Visual inspection of the bar graphs representing the average neural hemodynamic responses during the digital EF tasks reveals small to minimal group differences (See Figures 2-5). For these reasons, the null hypothesis was not rejected.

Table 8 Test of Homogeneity of Variance and ANOVA or Welch's F for each Digital EF Task and Channel Based on ADHD Status.

		Levene's Test		ANOVA		Welch's ANOVA	
EF Task	NIRS Channel	*F*	*p*	*F*	*p*	*F*	*p*
Flanker	Left	7.93**	<.01	n/a	--	2.82	.11
	Midleft	8.28**	<.01	n/a	--	3.75	.07
	Midright	2.16	.15	0.48	.49		
	Right	6.12*	.02	n/a	--	3.37	.08
Set Shifting	Left	0.79	.38	1.97	.17		
	Midleft	1.62	.21	0.56	.46		
	Midright	0.08	.78	0.92	.34		
	Right	2.36	.13	0.12	.73		
N-back	Left	7.50**	<.01	n/a	--	.90	.35
	Midleft	0.67	.42	0.22	.64		
	Midright	0.24	.62	0.16	.69		
	Right	1.22	.28	0.35	.56		
CPT	Left	1.46	.23	1.07	.31		
	Midleft	0.72	.40	0.54	.47		
	Midright	0.56	.46	0.40	.53		
	Right	0.98	.33	0.12	.74		

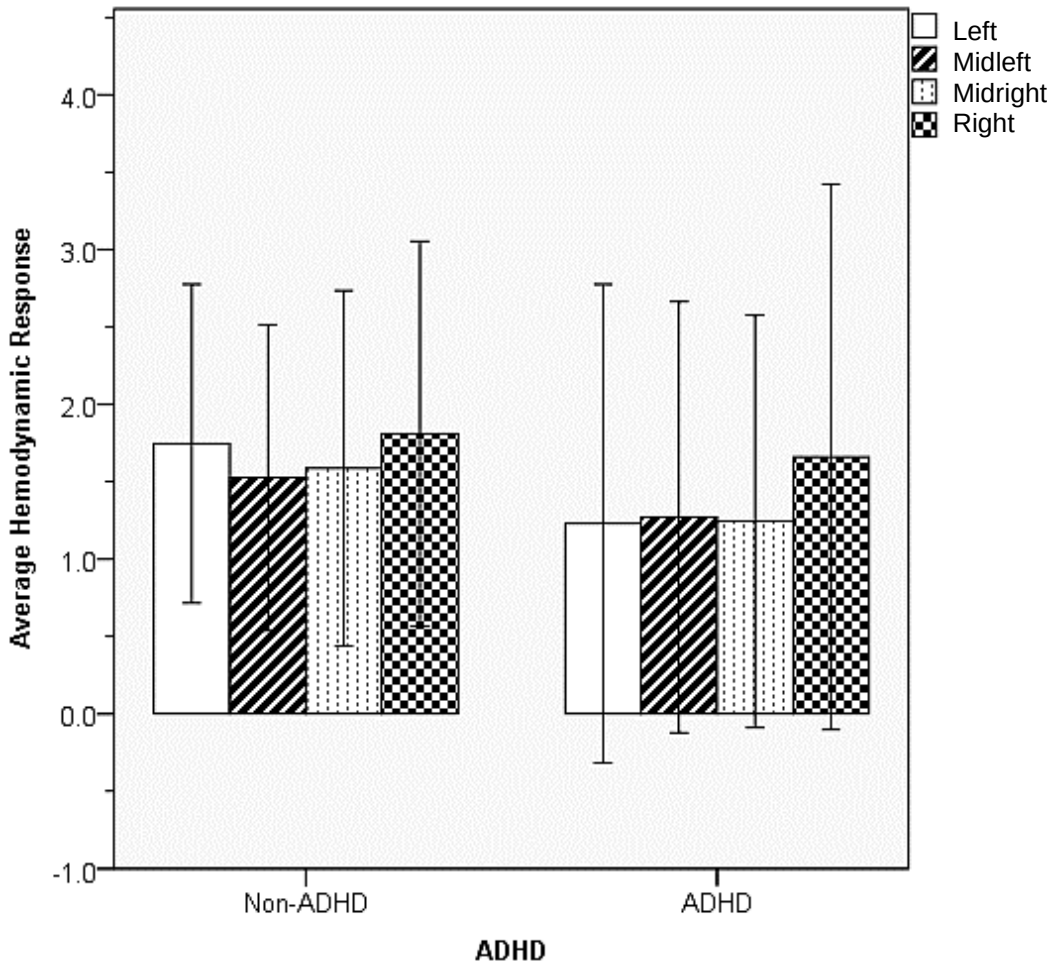
Note. CPT= Continuous Performance Test; n/a= not appropriate as homogeneity of variance assumption was not met. Use *Welch's F* instead of the *F* ratio.
[a]N= 48; [b]N= 47.
* p <.05; ** p<.01

Figure 2 Average neural hemodynamic response during Flanker task by ADHD status.



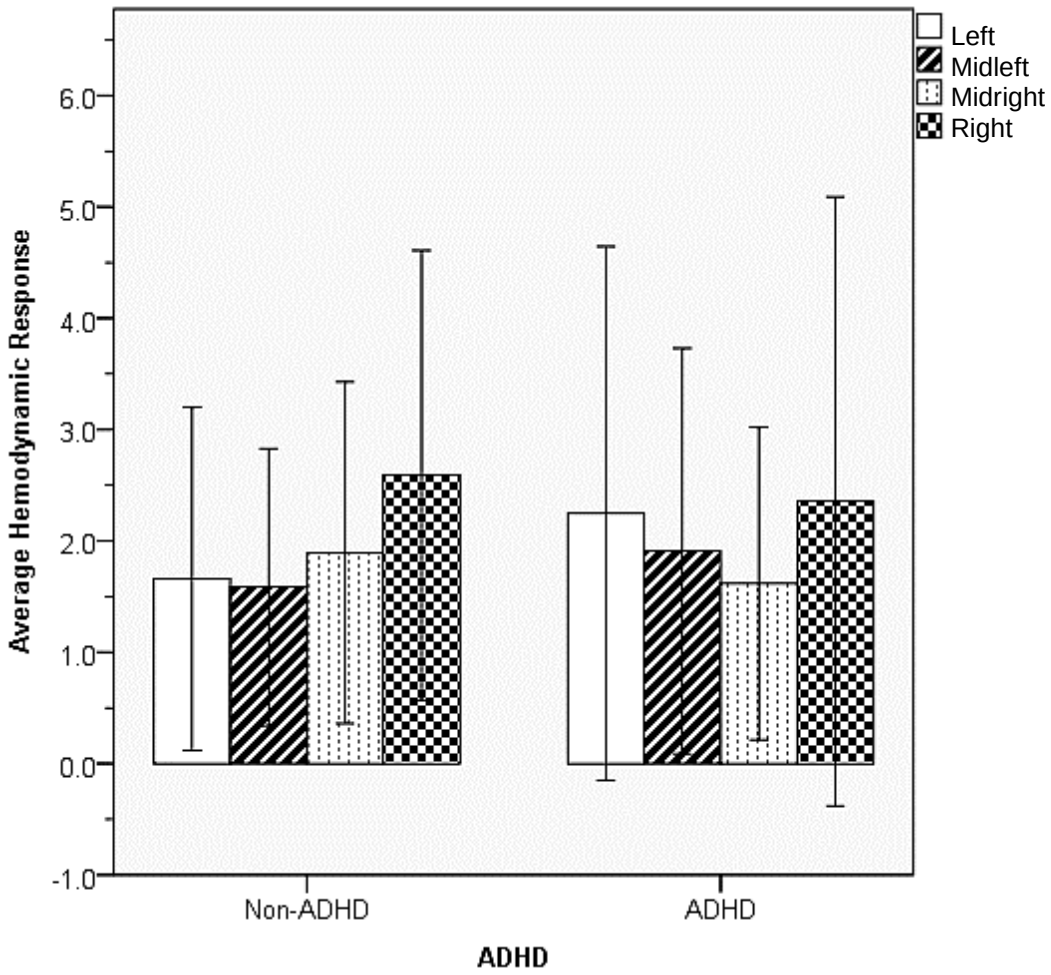
Note. Error bars represent 1 SD.

Figure 3 Average neural hemodynamic response during Set Shifting by ADHD status.



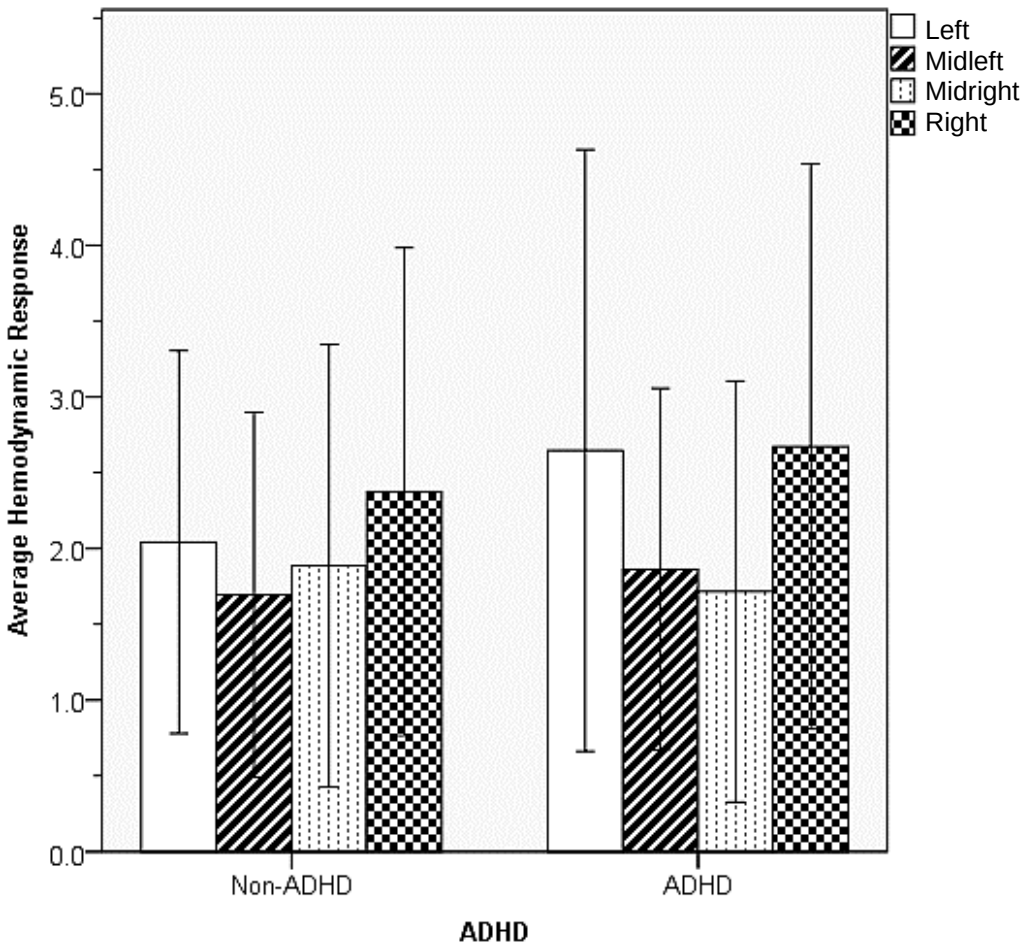
Note. Error bars represent 1 SD.

Figure 4 Average neural hemodynamic response during CPT by ADHD status.



Note. Error bars represent 1 SD.

Figure 5 Average neural hemodynamic response during N-Back by ADHD status.



Note. Error bars represent 1 SD.

Research Question 2a

Does gaming experience affect between group variances on hemodynamics? Based on available research, it was hypothesized that higher rates of gaming were associated with decreased oxyHb. Analysis of group means of gaming frequency per week (Non-ADHD: M=7.10; SD=10.3; ADHD: M=5.08, SD=5.42) revealed the amount of time spent gaming did not vary systematically by group (X^2=0.88, N=30, 18).

Additional analysis of the interaction of gaming frequency with ADHD status was considered by utilizing gaming frequency as an ordinally-scaled independent variable in a two-way ANCOVA. A two-way ANCOVA requires additional consideration of the homogeneity of error variance, normality of the error distributions of the grouped data, and any outliers in the cells generated.

Table 9 Levene's Test of Equality of Error Variances[a]

EF Task	NIRS Channel	F[b]	p
Flanker	Left	2.19	**.04***
	Midleft	2.34	**.03***
	Midright	1.00	.50
	Right	4.63	<**.001****
Set Shift	Left	2.82	**.01***
	Midleft	2.54	**.02***
	Midright	1.23	.32
	Right	1.72	.11
CPT	Left	1.49	.19
	Midleft	1.73	.11
	Midright	2.23	**.04***
	Right	1.14	.39
N-Back	Left	1.30	.28
	Midleft	1.34	.26
	Midright	1.29	.28
	Right	0.97	.54

Note. In this case, Levene's F tests the null hypothesis that the error variances of task-specific hemodynamic responses were equal across groups. Statistically significant results violate the assumption of equality of error variances in ANOVA.
[a] Design: Intercept + ADHD + Freq_wk + (ADHD * Freq_wk) where Freq_wk= number of hours per week spent gaming as self-reported by participants. [b] Levene's statistics reflect df_1= 24 and df_2= 20.
* = p< .05; ** = p< *.01*

Analysis of Levene's test for equality of error variances across EF task and NIRS channels revealed several statistically significant results (see Table 9), and examination of Shapiro-Wilk's test of normality revealed that most of the NIRS channels, when grouped on ADHD status, were non-normal (see Table 10). Visual analysis of boxplots of the residuals revealed several outliers across NIRS channels. In fact, the distribution of gaming frequency per week was non-normally distributed within both the non-ADHD group, with skewness of 2.66 (*SE*=0.43) and kurtosis of 8.99 (*SE*=0.83), and the ADHD group, with skewness of 1.29 (*SE*=0.54) and kurtosis of 1.90 (*SE*=1.04).

Estimated means and descriptive statistics were calculated for the hemodynamic responses using gaming frequency per week as the covariate (see Appendix C). Visual examination of scatterplots of the standardized residuals plotted against predicted values were heteroscedastic with numerous outliers in the hemodynamic data skewing the distributions. Levene's test of equality of error variances revealed further statistically significant differences between the error variances of the hemodynamic data across groups. Supporting this observation, Box's test of equality of covariance matrices revealed a statistically significant difference between the covariance matrices of the hemodynamic responses based solely on ADHD status. Shapiro-Wilk's test of normality revealed the hemodynamic responses in several channels to be non-normal statistical distributions with statistically significant ($p<.05$) results in all four EF tasks within the non-ADHD group hemodynamic response data and in two EF tasks within the ADHD group hemodynamic data (see Table 10).

Table 10 Shapiro-Wilk Test of Normality for EF Task Variables and Impairment Indices.

EF Variable	Group[a]	*W*	*p*
20Q-Total Questions Asked	Non-ADHD	.94	.07
	ADHD	.87	**.01***
20Q-Achievement Score	Non-ADHD	.95	.13
	ADHD	.93	.18
TMT-Sum	Non-ADHD	.92	**.02***
	ADHD	.92	.14
TMT-Ratio Score	Non-ADHD	.97	.44
	ADHD	.88	**.02***
TMT-Difference Score	Non-ADHD	.95	.14
	ADHD	.90	.05
CPT Nontarget Errors	Non-ADHD	.83	**<.001****
	ADHD	.86	.01*
Flanker Error Difference	Non-ADHD	.77	**<.001****
	ADHD	.86	**.01****
N-Back Total Errors	Non-ADHD	.89	**.01****
	ADHD	.91	.08
Shift Total Errors	Non-ADHD	.92	**.03***
	ADHD	.91	.08
BRI	Non-ADHD	.94	.08
	ADHD	.91	.07
MCI	Non-ADHD	.96	.37
	ADHD	.94	.28

Note. 20Q=Twenty Questions; BRI=Behavior Regulation Index; CPT=Continuous Performance Test; MCI=Metacognition Index; TMT=Trail Making Test

[a] Non-ADHD group N=31; ADHD group N=19

* $p < .05$; ** $p < .01$

The data violate several assumptions of ANCOVA, and the shapes and constitutions of the distributions did not lend themselves to transformation. As the sample size was too small to trim, ANCOVA could not be completed. A measure of the degree of association between gaming and hemodynamics, was considered for ADHD and non-ADHD groups and gaming. Correlations between the hemodynamic data and hours gaming per week were calculated for ADHD and non-ADHD groups. No statistically significant correlations were found, with the strongest associations found in the ADHD group during the N-Back in the Left and Right channels, respectively, [Pearson's $r(18) = -.39$, $p = .11$; $r(18) = -.38$, $p = .12$]. In this case, the null is not rejected, as amount of time spent gaming was not found to have a statistically significant linear relationship with hemodynamics in ADHD or non-ADHD groups.

Between Group Differences in Impairment and EF Task Performance

Research Question 3

Do ADHD and non-ADHD groups differ in performance on EF tasks (EXAMINER, TMT, 20Q) and impairment as measured by the BRIEF-A self-report? It was hypothesized the ADHD group would demonstrate greater impairment than the non-ADHD group. To test this hypothesis, ANOVA for group differences between the EF ratings (e.g., BRIEF-A Indices) and EF tasks by ADHD groups was conducted.

Table 11 Descriptive Statistics for EF Variables by Group.

Performance Variable	Group	M	SD	Skewness	Kurtosis
20Q Total Questions	Non-ADHD	54.2	5.32	0.62[a]	1.62[d]
	ADHD	53.4	7.35	-1.32[b]	1.91[e]
20Q Achievement Score	Non-ADHD	53.0	5.98	-0.06[a]	-0.71[d]
	ADHD	55.0	10.1	-0.89[b]	0.57[e]
TMT-Sum	Non-ADHD	62.1	16.7	1.04[a]	1.10[d]
	ADHD	67.4	16.2	0.76[b]	-0.28[e]
TMT-Ratio Score	Non-ADHD	2.45	0.72	0.19[a]	-0.74[d]
	ADHD	2.51	0.77	0.93[b]	-0.19[e]
TMT-Difference Score	Non-ADHD	24.8	12.2	0.76[a]	0.29[d]
	ADHD	27.7	11.4	0.79[b]	-0.44[e]
CPT Nontarget Errors	Non-ADHD	1.13	1.15	0.58[a]	-0.52[d]
	ADHD	1.42	1.50	0.94[b]	0.23[e]
Flanker Error Difference	Non-ADHD	0.84	1.10	1.31[a]	1.12[d]
	ADHD	1.26	1.76	1.26[b]	1.50[e]
N-Back Total Errors	Non-ADHD	3.50	2.50	1.28[c]	1.79[d]
	ADHD	4.37	1.92	-0.80[b]	0.15[e]
Set Shifting Total Errors	Non-ADHD	4.36	3.47	0.66[a]	-0.53[d]
	ADHD	3.53	3.10	0.54[b]	-0.63[e]

Note. 20Q=Twenty Questions; TMT=Trail Making Test; CPT=Continuous Performance Test
[a] *SE*=0.421; [b] *SE*=0.524; ; [c] *SE*=0.427 [d] *SE*=0.821; [e] *SE*=1.014

Descriptive statistics for the EF Performance variables are provided in Table 11. Shapiro-Wilk test of normality revealed non-normal distributions across all but two of the grouped EF performance variables with normal distributions within the measures of impairment on the BRIEF BRI and MCI indices (see Table 12). Visual examination of scatterplots, Q-Q plots, and boxplots of these data suggested the distributions demonstrated fair to good homoscedasticity, with some variables having one to two outlying data points. Statistical analysis using Levene's test of homogeneity of variances (see Table 12) revealed only three variables' variance to be statistically significantly different across ADHD/non-ADHD groups, including the 20Q

Achievement Score (F(1, 48)=6.79; p=.01), the Flanker Error Difference Score (F(1, 48)=4.74; p=.03), and the BRI (F(1, 48)=6.11; p=.02).

Table 12 Levene's Test of Homogeneity of Variances for EF and Impairment Variables.

Variable	Levene's F[a]	p
20Q Total Questions	2.38	.13
20Q Achievement Score	6.79	**.01***
TMT-Sum	0.05	.82
TMT-Ratio Score	0.09	.76
TMT-Difference Score	0.01	.92
CPT Nontarget Errors	1.47	.23
Flanker Error Difference	4.74	**.03***
N-Back Total Errors	0.77[b]	.38
Set Shifting Total Errors	0.34	.56
BRI	6.11	**.02***
MCI	0.29	.59

Note. [a] Levene's F(1, 48); [b] Levene's F(1, 47)
* $p < .05$; ** $p < .01$

One-way ANOVA was conducted on EF variables demonstrating homogeneity of variances with Welch's ANOVA utilized for the remaining variables (see Tables 12 and 13). Of the variables tested, the BRI and MCI scores were statistically significantly different across ADHD and non-ADHD groups, with Welch's F(1, 48)=22.5, $p < .001$ and F(1, 48)=14.6, $p < .001$, respectively. Analysis of mean differences revealed the ADHD group to evince statistically more impairment on self-ratings of EF than the non-ADHD group. In this result, the null hypothesis is rejected; however, as none of the EF

performance variables tested revealed any statistically significant mean differences across groups ($p>.05$), the null hypothesis for the performance element is not rejected.

Table 13 ANOVA or Welch's F for EF Performance and Impairment Variables.

EF Variable	F^a	p	Welch's F	P	Partial η^2
20Q Total Questions	0.17	.68			<.01
20Q Achievement Score	n/a	--	0.64	.43	.01
TMT-Sum	1.18	.28			.02
TMT-Ratio Score	0.07	.79			<.01
TMT-Difference Score	0.68	.42			.01
CPT Nontarget Errors	0.60	.44			.02
Flanker Error Difference	n/a	--	0.89	.35	.02
N-Back Total Errors	1.66^b	.20			.03
Set Shifting Total Errors	0.73	.40			.01
BRI	n/a	--	22.49	**< .001****	.38
MCI	14.58	**< .001****			.23

Note. 20Q=Twenty Questions; BRI=Behavior Regulation Index; CPT= Continuous Performance Test; MCI=Metacognition Index; n/a= not appropriate as homogeneity of variance assumption was not met. Use *Welch's F* instead of the *F* ratio.
[a] df= 1, 48; [b] df= 1, 47 only for N-Back task
* $p < .05$; ** $p < .01$

Digital and Non-Digital Performance-Based Tasks

Research Question 4

What is the level of association for results of computerized EF and non-computerized tasks? As there was no available research that considered computerized assessment of EF in relation to non-computerized tasks, the hypothesis was that there was no relation. To test this hypothesis, two-tailed correlational analysis (Pearson's product moment correlation) was proposed to evaluate the degree of association between

performance on the variables of the CPT, Flanker, N-Back, and Set Shifting relative to TMT and 20Q variables. Overall descriptive statistics for the digital and non-digital EF performance variables were calculated, and variables were then parsed by ADHD group to examine their degree of association within groups as well (see Appendix C).

Table 14 Spearman's (r_s) Correlation Coefficients Between Non-Digital and Digital Tasks for the Entire Sample.

			Non-Digital					Digital			
Task Type		EF Variable	1	2	3	4	5	6	7	8	9
Non-Digital	1	20Q Total	--	**.52****	-.07	-.06	-.06	.15	.21	.07	-.03
	2	20Q Achieve		--	-.13	-.10	-.09	.22	.17	-.03	-.03
	3	TMT-Sum			--	.23	**.66****	.26	-.09	-.02	.09
	4	TMT-Ratio				--	**.84****	-.09	.07	.10	.24
	5	TMT-Diff					--	.05	.05	<.01	.22
Digital	6	CPT NTErr						--	.23	.10	-.03
	7	Flanker Err Diff							--	.21	**.39****
	8	NB Total Err								--	.22
	9	Shift Total Err									--

Note. For 20Q, higher scores are associated with better performance; for all others, lower scores are associated with better performance. 20Q Total=Twenty Questions Total Questions Score; 20Q Achieve=Twenty Questions Achievement Score; TMT=Trail Making Test; TMT-Diff=Trail Making Test Difference Score; CPT NTErr=Continuous Performance Test Nontarget Errors; Flanker Err Diff=Flanker Error Difference; NB Total Err=N-Back Total Errors; Shift Total Err=Shift Total Errors.
*$p < .05$; **$p < .01$

Visual examination of the scatterplots revealed the data to have linearity and monotonicity. The distributions, however, were widely dispersed, and several outlying scores across the variables were found. As the data met the basic assumptions for

Spearman's r_s, rather than Pearson's *r*, correlations were calculated for each non-digital and digital pair combination and results analyzed for the complete sample (*N*=50; see Table 14). No statistically significant correlations between digital and non-digital tasks were present. Correlations within tasks (e.g., 20Q, TMT variables) and between Set Shifting and Flanker indicated the measures were more correlated to themselves than to other tasks or tasks of opposing media.

Table 15 Summary of Spearman's Correlations (r_s) by Task Type and ADHD Group.

		Non-Digital					Digital			
Task Type	EF Variable	1	2	3	4	5	6	7	8	9
Non-Digital	1 20Q Total	--	.40	-.29	-.14	-.32	.10	.01	<-.01	.04
	2 20Q Achieve	**.58****	--	-.24	-.36	-.38	-.07	.13	-.08	.40
	3 TMT-Sum	.06	-.15	--	.24	**.72****	-.20	.34	-.09	-.24
	4 TMT-Ratio	-.01	.12	.18	--	**.83****	-.12	<.001	.18	-.26
	5 TMT-Diff	.08	.06	**.54****	**.87****	--	-.21	.16	.12	-.28
Digital	6 CPT NTErr	.07	-.04	.07	.24	.10	--	.24	.07	.17
	7 Flanker Err Diff	.28	.23	.20	-.18	-.07	-.04	--	.18	**.52***
	8 NB Total Err	-.01	-.13	.06	**.37***	.26	.35	-.20	--	**.48***
	9 Shift Total Err	.35	.03	.02	.27	.27	.24	.04	**.39***	--

Note. Intercorrelations for ADHD participants (*N*=19) are presented above the diagonal. Intercorrelations for Non-ADHD participants (*N*=31) are presented below the diagonal. For 20Q, higher scores are associated with better performance; for all others, lower scores are associated with better performance. 20Q Total=Twenty Questions Total Questions Score; 20Q Achieve=Twenty Questions Achievement Score; TMT=Trail Making Test; TMT-Diff=Trail Making Test Difference Score; CPT NTErr=Continuous Performance Test Nontarget Errors; Flanker Err Diff=Flanker Error Difference; NB Total Err=N-Back Total Errors; Shift Total Err=Shift Total Errors.
*$p < .05$; **$p < .01$

When parsed by ADHD status, no statistically significant associations were found in the ADHD group between digital and non-digital tasks, and one statistically

significant moderate correlation was found between the N-Back Total Errors and TMT Ratio, $r_s(31)=.37$, $p=.04$ in the non-ADHD group (see Table 15). Additional correlation coefficients within the TMT task scores (Ratio and Difference) and between N-Back, Flanker, and Set Shifting were noted to be statistically significant; however, the coefficients indicated the scores were associated with each other or within the digital tasks themselves. No other correlations between digital and non-digital tasks were statistically significant. The null hypothesis in this case is not rejected; the variables selected from the digital and non-digital tasks were largely not associated with each other.

Performance Based Tasks and Self-Report

Research Question 5

To what extent are results of the BRIEF Self-Report consistent with results of computer-based and non-computerized tasks? It was hypothesized there would be minimal to low correlations between rating scales and performance-based tasks. To test this hypothesis, one-tailed Pearson-product moment correlational analysis was the proposed method of analysis of association between results of the computerized measures from the EXAMINER and TMT with the BRI and MCI. One-tailed intraclass correlations (ICC) were also calculated between the 20Q and BRIEF Indices to determine the degree of association between subjects' observations of EF impairment (or strength), as these were transformed to share the same metric.

As noted previously, the data were sufficiently linear and monotonic, but widely dispersed with a number of outlying points rendering Pearson's *r* an inappropriate

measure of association. As a result, one-tailed Spearman's r_s coefficients were utilized to assess the degree of association between self-report of everyday function and EF performance data as shown in Table 16. Statistically significant, but weak, positive correlations were present between the MCI and N-Back Total Errors, $r_s(49)=.24$, $p=.04$, and MCI and 20Q Achievement Score, $r_s(50)=.27$, $p=.03$. More difficulty with the N-Back task was weakly associated with poorer metacognitive functioning; however, the MCI and 20Q Achievement Score are metrics of opposing directions, as better functioning is indicated by lower MCI and higher 20Q Achievement Score. In this case, the association is positive and indicates better functioning was associated with lower scores on this task.

Table 16 One-Tailed Spearman's Correlations (r_s) Between EF Performance and Self-Report of Everyday Function.

EF Performance Measure	BRI[a]	MCI[a]
20Q Total Questions[b]	.10	.14
20Q Achievement Score[b]	.23	**.27***
TMT-Sum	.10	.12
TMT-Ratio Score	-.18	-.23
TMT-Difference Score	-.04	-.07
CPT Nontarget Errors	-.01	-.03
Flanker Error Difference	.16	.10
N-Back Total Errors[c]	.22	**.24***
Shift Total Errors	-.09	.12

Note. 20Q=Twenty Questions; BRI=Behavior Regulation Index; MCI=Metacognition Index; TMT=Trail Making Test; CPT=Continuous Performance Test.
[a] $N=50$ for all measures except N-Back. [b] For 20Q, higher scores are associated with better performance; for all others, lower scores are associated with better performance.
[c] $N=49$
* $p< .05$ (1-tailed).

The ICC was calculated using a two-way random effects model, to evaluate the consistency of observations of EF performance within each of the subjects. Results of the ICC, as shown in Table 17, reveal that observations of the participants of their own functioning are not associated with the results of EF performance measures. The means of the observations (BRI, MCI, and 20Q scores) were not significantly related for individuals in this model when random effects and consistency/reproducibility of the observations were considered. This is likely a function of the significant dispersement of the participant results across measures used to assess EF for this sample.

Table 17 Intraclass Correlation Coefficient.

	Intraclass	95% CI		*F* Test with True Value 0			
	Correlation[a]	LL	UL	Value	df1	df2	*p*
Single Measures	.25[b]	.12	.41	2.34	49	147	<.001
Average Measures	.57	.34	.74	2.34	49	147	<.001

Note. Two-way random effects model where both people effects and measures effects are random. LL=Lower Limit; UL=Upper Limit

[a] Type C intraclass correlation coefficients using a consistency definition. The between-measure variance is excluded from the denominator variance. [b] The estimator is the same, whether the interaction effect is present or not.

CHAPTER V

DISCUSSION AND CONCLUSIONS

This study examined hemodynamics of the PFC and the potential interactions between neural activation patterns in the PFC, task performance, EF ratings, and ADHD status. It is not established that individuals with ADHD demonstrate differing patterns of activation from those without ADHD during EF tasks, but this was considered in this study. This study also examined the associations between performance-based assessment of EF and everyday EF in individuals with and without ADHD. A number of factors related to assessment were examined, including differences in performance and hemodynamics, type of media used in assessment, and the association and differences in assessment media and self-reports.

It was hypothesized that greater oxygenation in the DLPFC would be associated with better performance on measures of EF and lower impairment. Weak associations were found suggesting decreased oxyHb with greater errors in performance on the Flanker task and the Set Shifting tasks; however, increased errors on the CPT and N-Back tasks were not accompanied by a decrease in oxyHb during those tasks. Moreover, the results yielded only one statistically significant result on the Flanker task in the AF7 channel (left lateral). Additionally, the results of self-report and performance across EF tasks did not yield results suggesting associations in EF performance and oxygenation. These results are inconsistent with current literature regarding hemodynamic function in the PFC during EF tasks (see Ehlis et al., 2005, 2008; Hirshorn & Thompson-Schill,

2006; Jacola, et al., 2014; Laguë-Beauvais, Brunet, Gagnon, Lesage, & Bherer, 2013; Robinson et al., 2014; Weyandt et al., 2013). Differences found in this study's results from the current literature may be due to a number of factors, including the relative homogeneity of the sample (e.g., young adults who gained acceptance to a large university—suggesting relative academic success and limited intellectual/functional variance among the sample), as well as the measures of EF utilized.

It was further proposed that individuals without ADHD would exhibit greater oxygenation bilaterally in the DLPFC (Left/AF7 and Right/AF8) as compared to the ADHD group during EF tasks. Results indicated no statistically significant differences in hemodynamic responses between ADHD and Non-ADHD participants across any NIRS channel during any of the EF tasks. These results are inconsistent with findings from Faraone et al., 2000, Nigg et al., 2005, Gray et al., 2014, and Woltering et al., 2013 who found neurophysiological differences (across the cortex but especially in the PFC) for ADHD compared to non-ADHD individuals during EF tasks. As this sample of ADHD individuals was small, the lack of power to detect differences may have resulted in this deviation from the findings in current literature.

As an added consideration of current increases in digital media use and gaming among young adults, the current literature in NIRS and gaming experience has suggested that those with more gaming experience have decreased oxygenation in the PFC (Bavelier, Achtman, Mani, & Föcker, 2012). As a result, this study considered amount of time currently spent gaming in relation to hemodynamic responses in those with and

without ADHD. The sample, however, did not differ in amount of time spent gaming within ADHD/Non-ADHD group membership.

It was hypothesized the ADHD group would demonstrate greater impairment than the non-ADHD group on EF task performance variables and self-report of everyday function. Results of self-report (e.g., measures of impairment as shown on the BRIEF) on the BRI and MCI indices did reflect group differences in self-reported impairment, with statistically significant between group variances. EF task performance variables, however, did not reflect the same between group differences. This is consistent with current literature indicating EF rating scales are generally good predictors of ADHD diagnostic status and that results of EF ratings are generally uncorrelated to performance on EF tasks (Kamradt et al., 2014; Toplak et al., 2009, 2013).

The level of association between results of computerized (e.g., digital) and non-digital EF tasks was theorized as a null association, as there was currently no available research considering this relationship. Overall results found no association between type of task and performance on that task. Additional consideration of the association of results within the ADHD and Non-ADHD groups was conducted, however, and a moderate association was found between error rate on the N-Back and the TMT B/A ratio score in the Non-ADHD group. As N-Back performance is considered related to visual working memory ability, it is possible that difficulty switching on TMT B and losing one's place in the sequence may be modestly associated with difficulty in visual working memory in this group. Additional consideration of other performance variables,

however, would need to be conducted, as performance on the Set Shifting task was not similarly associated (e.g., a task purported to require the same ability).

Overall, and irrespective of group membership, it was hypothesized there would be minimal to low correlations between rating scales and performance-based tasks. Consistent with the current literature, (e.g., Toplak et al., 2009, 2013), a weak correlation was found between the MCI and N-Back Total Error score, with no other statistically significant results suggesting impaired performance to be associated with impairment on self-report. In fact several of the correlation coefficients indicated an inverse relation/association between EF performance and ratings of impairment (e.g., good performance with poor ratings). These results are consistent with the literature regarding measurement of EF relative to rating of EF (Kamradt et al., 2014; Toplak et al., 2009, 2013).

Implications

The ability to visualize cortical activity via hemodynamic responses during EF tasks provides additional insight into the connection between cognition and neurophysiology. Improved understanding of EF and neurophysiological EF dysfunction could improve mental health professionals' ability to diagnose and treat a variety of clinical conditions. Findings of this study did confirm a deficit in the measurement of EF performance. The continued use of digital tasks to assess EF constructs and use those results for diagnostic purposes is not consistently supported by results in the literature as yet. Results found in this study continue to question the

efficacy of EF tests in measurement of ADHD symptomology, particularly in young adults.

What is supported in these findings is the use of self-report of EF in examining ADHD and its implications for daily functioning with young adults. Though hemodynamic results from a variety of imaging studies have found significant differences between individuals with and without ADHD during tasks requiring EF processes, these results did not align with those findings. Additional research into the associations of EF self-report and hemodynamic functioning during daily EF tasks may be of greater import.

Limitations

With a limited sample size from a homogenous group of individuals, relatively low power was a significant limitation in this study. As the developmental trajectory of EF processes continues into the mid 20's, but is more fine-tuning and pruning, it is possible that the developmental level (young adult) in participants confounded the findings here. Given that development of EF attenuates in the 20s, it is possible that the measures used were not sufficiently sensitive to group differences. Unfortunately, there is no age-based normative or clinical data for the EXAMINER tasks for comparison. Using a novel measure of EF, without confirmatory or contextual validity measures may have compromised the findings here as well. The EXAMINER is as yet a new set of measures of EF, and having confirmatory data from well-established digital measures (e.g., WCST, Conners CPT) may have provided more insight into the construct validity of the tasks utilized here. Furthermore, as only 19 participants with ADHD were

assessed, the results were not likely to yield statistically significant between group data; however, that some analyses found evidence for differences between groups in the data was encouraging.

In considering whether gaming frequency affected performance and hemodynamics, group sizes reduced when adding gaming frequency per week to the model. Also frequency data were unavailable for two participants, and hemodynamic data were not collected for two additional participants further limiting the power of that analysis. Addition of diagnostic procedures for determining group membership (e.g., diagnosis of ADHD) such as informant report or direct assessment of other cognitive processes, may have provided clearer definition and group membership data, yielding data with greater linearity, homoscedasticity and normality.

Given that the areas of interest and measured with NIRS were limited to the PFC, measuring additional cortical areas (e.g., temporal-parietal areas) may have yielded additional insights or differences in findings of cortical activation. Given current data on imaging of EF, what is known is that EF processes are not limited to the PFC, and incorporating greater areas of the cortex may have yielded different findings.

Future Research

Future research should consider obtaining a larger sample of young adults from multiple settings (e.g. university, community colleges, vocational programs, general public). The sample should include better representation of diverse groups as a result. Confirmatory measures or informant reports of ADHD symptoms and everyday functioning (e.g., rating scales completed by multiple informants) would improve

analysis of EF performance relative to everyday function. Additionally, hemodynamic assessment of the temporal and parietal lobes with expanded assessment during both digital and non-digital tasks would provide comparisons between media concurrent to task performance. Supplemental measures of EF performance should be considered to yield confirmation of EF processing deficits as well. To examine the developmental trajectory of brain activation during EF tasks, participants from various age groups (9-12 years, 13-17 years, 18-22 years) are needed. As stated, the EXAMINER is a newly developed measure and additional research is needed with the tasks included.

Conclusion

Results of this study suggest assessment of EF remains a difficult task, complicated by tasks having multiple underlying processing requirements, diversity in definition of the construct, and a lack of convergence between ratings and performance data. Hemodynamic data from NIRS, and other imaging methodologies, yield generally consistent findings showing the PFC to consistently subserve EF processes; however, these data do not reflect the degree of activation typically seen in the PFC during EF tasks suggesting less of a reliance on frontal functioning for this sample. Moreover, differences in EF ratings of everyday function in those with ADHD do not align with performance data on these measures of EF; this is consistent with prior research (Barkley & Murphy, 2010; Duff & Sulla, 2015; Kamradt, Ullsperger, & Nikolas, 2014; Lezak et al., 2004; Toplak et al., 2009). Individual differences and the age range selected, as a function of the sample characteristics, may explain the lack of statistically significant findings. Additional information regarding use of, and neurocognitive processes utilized

in, EF tasks in those with and without ADHD may provide additional insight into the connection between neurophysiology and everyday function.

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APPENDIX A

Computer/Video Games, Hemodynamics, and ADHD
Participant Consent Form

You are invited to take part in a research study being conducted by Dr. Cynthia Riccio and Dr. Ranjana Mehta, researchers at Texas A&M University. The information on this form is provided to help you decide whether or not to take part. If you decide to take part in the study, you will be asked to sign this consent form. If you decide you do not want to participate, there will be no penalty to you, and you will not lose any benefits you normally would have.

Why is this study being done?
The purpose of this study is to identify brain activity while playing internet games and completing other tasks in typical young adults and young adults with Attention Deficit Hyperactivity Disorder (ADHD).

Why am I being asked to be in this study?
You are being asked to be in the study because you expressed interest in participating in the study, you are 18-22 years of age, and either have a prior diagnosis of ADHD or have no identified disability. You also speak Englishfluently.

How many people will be asked to be in this study?
Approximately 100 people will be invited to participate in this study.

What are the alternatives to being in this study?
The alternative to being in the study is to not participate. There will be no penalty to you if you choose not to participate, and you will not lose any benefits you normally would receive.

What will I be asked to do in this study?
You will participate in 1 session. It will last about 3 hours in this laboratory at the School of Public Health. You will have the opportunity to see the fNIRS equipment before you decide to participate. Once we get your consent to participate, we will collect some demographic information including some information about your health and medical history, as well as your height. During this visit you will be attached with various sensors to monitor your brain activity from your forehead and scalp using a head band. You will be asked to complete some paper-pencil tasks, as well as to play some computer games and some computer based assessments of attention and memory and a task of problem-solving. Participants also will be asked to answer questions about their own behaviors. For most tasks you will be sitting at a computer; you will complete one task twice, once sitting, once standing.

Are there any risks to me?
The tasks you are asked to complete carry no more risk than you would come across on a daily basis as you complete coursework or other daily activities. The sensors do not carry any additional risks, other than that the headband may become uncomfortable toward the end of the study time. You will be reminded that you can terminate your participation at any time, with partial compensation after the first 1.5 hours. Each participant will be run individually, with only you and the investigators involved in the project present, decreasing the risks to privacy of your participation and data. You will be assigned a code upon entering the study and the study code will be the only identifying information used for the study documents. Only the investigators will have access to the information. Although the researchers have tried to avoid risks, you may feel that some questions/procedures that are asked of you will be stressful or upsetting. You do not have to answer anything you do not want to.

Will there be any costs to me?
The only cost will be your time to complete the study.

Will I be paid for participating in this study?
You will receive a $25 card for participation in this study on completion of your participation in the study. If you choose to discontinue after 1.5 hours, without completing the study, you will receive a partial payment in the form of a $10 giftcard. You will be asked to sign a receipt indicating that you received the giftcard.

Will information from this study be kept private?
The records of this study will be kept private and no report will contain information that could identify you. All information is coded and any personal identifying information removed from the research records. Results will be aggregated and reported for the group of participants, not for individual participants. All research records will be stored securely. Written records will be stored in a locked cabinet; electronic data will be encrypted and stored on a computer that is protected by a password. Information about you and related to this study will be kept confidential to the extent permitted or required by law. People who have access to your information include Drs. Riccio and Mehta and research study personnel. Representatives of regulatory agencies such as the Office of Human Research Protections (OHRP) and entities such as the Texas A&M University Human Subjects Protection Program (HSPP) may access your records to make sure the study is being run correctly and that information is collected properly.

Who may I contact for more information?
You may contact either Dr. Cynthia Riccio at 979 862-4906 or criccio@tamu.edu or Dr. Ranjana Mehta at 979-436-9327 or rmehta@tamu.edu. For questions about your rights as a research participant, to provide input regarding research, or if you have questions, complaints, or concerns about the research, you may call the Texas A&M University Human Subjects Protection Program office by phone at 1-979-458-4067, toll free at 1-855-795-8636, or by email at irb@tamu.edu.

What if I Change My Mind About Participating?
This research is voluntary and you have the choice whether or not to be in this research study. You may decide to not begin or to stop participating at any time. If you choose not to be in this study or stop being in the study, there will be no effect on your student status, medical care, employment, or relationship with Texas A&M University or other entity. If you do not complete the study, however, the compensation will be reduced to $10 rather than $25 in the form of a gift card.

STATEMENT OF CONSENT
I agree to be in this study and know that I am not giving up any legal rights by signing this form. The procedures, risks, and benefits have been explained to me, and my questions have been answered. I had the opportunity to see the fNIRS and heart rate monitoring equipment and ask questions about that process. I know that new information about this research study will be provided to me as it becomes available and that the researcher will tell me if I must be removed from the study. I can ask more questions if I want. A copy of this entire consent form will be given to me.

_____ _____
Participant's Signature Date

_____
Printed Name

INVESTIGATOR'S AFFIDAVIT:
Either I have or my agent has carefully explained to the participant the nature of the above project. I hereby certify that to the best of my knowledge the person who signed this consent form was informed of the nature, demands, benefits, and risks involved in his/her participation.

_____ _____
Investigator Signature Date

Demographic Information Sheet

Case # _____

Age: ____years … mos. Sex: Male_____ Female _

Race/Ethnicity: African American_ Asian/Pacific Islander _____ Hispanic/Latino ____

Native American _____White non-Hispanic _____ Biracial ____

Other: _____

Mother's Highest Educational Level: 9th-11th grade _____High School Diploma/GED _____

_____

Community College or Technical School ___ Some College _____

Completed 4 year degree _ Completed Graduate Degree _____

_____

Father's Highest Educational Level: 9th-11th grade _____High School Diploma/GED _____

_____

Community College or Technical School ___ Some College _____

Completed 4 year degree _ Completed Graduate Degree _____

What is the primary language in your home? English _____ Spanish _____ Other: _____

_____

Educational History:

Class standing: Freshman ____ Sophomore ____ Junior ____ Senior ____ Not in School _____

Did you receive Special Education services during K= 12? Yes_____ No _____

If yes, for what reason(s)? _____

Are you currently receiving support through the Office of Disability Services? Yes_____ No ___

_____ If yes, for what reason(s)? _____

Medical History:

What is your current height? _____ What is your current weight? _____

Which hand do you write with? Right _____ Left _____

Have you had any of the following or been diagnosed with any of the following: (check all that apply)

Loss of consciousness or coma _____ Asthma _ Head Injury _____

Seizure or Epilepsy _____ Concussion _____ Cancer _____

Cystic Fibrosis _____ Diabetes _____ ADHD/ADD ___

_____

Sickle Cell Anemia _____ Cerebral Palsy _____ Learning Disability

_____

Down Syndrome _____ Autism _____ Asperger Syndrome _____

_____

Intellectual Disability _____ Stroke _____

Other Disorder: _____

Are you currently taking any medications? Yes_____ No _____

If yes, please specify? _____

_____

_____

Have you taken your medication today? Yes_____ No _____

The next set of questions relate to online or video games and online training programs for attention or memory:

Have you ever used the Cogmed program? ___ Yes ___No BrainTrain ___ Yes ___No
Lumosity ___ Yes ___No CogniFit ___ Yes ___No Other: (please specify): _____

Do you currently, or have you in the past played online or videogames? _____ Yes _____ No
…..If Yes, please continue:
On average, currently, how many hours per week do you play any type of online or video games?
_____/per week
Do you play every day? ____ Yes ____No
Has your frequency of playing changed in the past 6 months? ___ No change __ Increased __Decreased
Currently what is your favorite online or videogame? _____
Which of the following types of games do you play or have you played?

Action games

Please indicate the games you play or played that you would consider "action games":

Strategy games

Please indicate the games you play or played that you would consider "strategy games":

Memory games

Please indicate the games you play or played that you would consider "memory games":

Simulation games

Please indicate the games you play or played that you would consider "simulation games":

Puzzle games

Please indicate the games you play or played that you would consider "puzzle games":

Please check any of the following games you play or have played (any edition):
_____ Tetris _____ Portal _____ Age of Empires _____ Candy Crush Saga
_____ Space Fortress _____ Call of Duty _____ Minecraft _____ Brain Safari
_____ Medal of Honor _____ Civilization _____ Starwars _____ Age of Wonders
_____ Company of Heroes _____ World in Conflict _____ Middle Earth

Task Checklist

CASE ID _____ Date: _____

(Odd # - sit first / Even # - stand first)

Examiner Tasks	Complete?
Consent explained and signed	
Copy of signed consent given to participant	
Checked fit / position of headband	
Height of desk recorded: seated	_____ in.
Height of desk recorded: standing	_____ in.
Participant hand used is recorded below	
Reminders given for movement	
All instructions read verbatim	
Gift card given to participant	
Receipt of gift card signed by participant	

Administered Measures / Forms	Complete / Score	Hand Used
20 Questions (scores)		N/A
**N-back #1 (*indicate*: sit / stand)		R L B
CPT		R L B
Flanker		R L B
Dimensional Card Sort		R L B
Trail Making Test A—seconds to complete		R L B
Trail Making Test B—seconds to complete		R L B
Tetris		R L B
Portal (Level / # of portals entered)		R L B
**N-back #2 (*indicate*: stand / sit)		R L B
Demographic Sheet		R L B
CAARS-Self: Short Form		R L B
BRIEF-A		R L B

Tetris Score Tabulation

Record "Lines Cleared" and "Total Score" at the ***end*** of ***each*** 30" interval (during the 10" pause).

End of Interval	Lines Cleared	Total Score	Difference
1			--
2			
3			
4			
5			
6			

When complete, calculate "Difference" score.

Highest Level Reached: _____

Portal Tabulation

Number of portals the participant *entered* during 6 minutes of gameplay:

_____

Highest Level Reached: _____

Seat subject, and set table height to a comfortable height, close to 90º-90º-90º (elbow, hips, knees) postural position. Record "Height of desk: seated" on "Checklist."

Consent Form

Read through consent form and explain study (measuring with fNIRS, executive function, etc.) and answer any questions. Have subject sign and date, examiner signs and dates and a *copy of the signed form is given to the participant –this may be done at the end of the session*.

NOTE: if the subject is to be standing for N-Back #1, have him/her stand and record "Height of desk: standing" on checklist.

NIRS Headband & Baseline

After double-checking for proper placement and fit of the NIRS headband-- **Please remain still for a few moments while we collect some baseline information.**

---

20 Questions

Use the D-KEFS instructions and picture card. Read the instructions *verbatim*. For each item, record the participant's *exact* questions on the Record Form.

N-Back (#1)—note if *seated* or *standing*! If CASE ID is an *even #*, STANDING first N-Back

Now, we will begin with a task on this computer. Please ensure you are (*seated / standing*) comfortably at this time, as we will ask you to refrain from making *any* additional movement while you are engaged in the task. Read verbatim the displayed instructions for the N-Back. BEFORE beginning the practice trial, read the following:

Movement Reminder:

Please place your hands in the position you feel would be most comfortable for responding during this task, and refrain from making *any additional* movement, such as shaking your head, raising your eyebrows, moving your arms, talking and so on. Do you have any questions?

The *examiner* presses the <SPACEBAR> to begin the practice trial. After the practice ends, read the *displayed* instructions for the test. Ask, "**Ready?**" and

NOTE: Discreetly watch the subject's face and eyes throughout the task to ensure they are responding to the stimuli on the screen and are not responding randomly or distracted. If needed, you may remind the subject it is important he/she does their best or to refrain from moving during the task.

press the <SPACEBAR> to begin each interval. **Record which hand the participant used to complete the task on the "Checklist."**

Continuous Performance Test (CPT)

Say: **We have another task on the computer in front of you.** Read the displayed instructions for the CPT. The *examiner* presses the <SPACEBAR> to begin the practice trial. After the practice trial ends, read the *displayed* instructions for the test. Paraphrase *Movement Reminder* (as needed). Press the <SPACEBAR> to begin. **Record which hand the participant used to complete the task on the "Checklist."**

Flanker

Now we will continue with different task on the computer in front of you. Read the displayed instructions for Flanker. The *examiner* presses the <SPACEBAR> to begin the practice trial. After the practice trial ends, read the *displayed* instructions for the test. Paraphrase *Movement Reminder* (as needed). Ask, "**Ready?**" and press the <SPACEBAR> to begin the test and each interval.

Dimensional Card Sort

Say: **We have another task for you on the computer in front of you.** Read the displayed instructions for the Dimensional Card Sort. The *examiner* presses the <SPACEBAR> to begin the practice trial. After the practice trial ends, read the *displayed* instructions for the test. Repeat/Paraphrase *Movement Reminder* as needed. Ask, "**Ready?**" and press the <SPACEBAR> to begin each interval.

Trail Making Test A

Place the protocol in front of the examinee with a pen (or pencil *without* eraser) and say: **Now we are going to do something different. On this page are some numbers. Begin at number 1** (point to 1) **and draw a line from 1 to 2** (point to 2)**, 2 to 3** (point to 3)**, 3 to 4** (point to 4)**, and so on in order until you reach the end** (point to "End")**. Draw the line as fast as you can. Ready—Begin!** Allow the participant to complete the Sample items. **Good! Let's try the next one.** Turn the page over and say: **On this page are more numbers. Do this the same way. Begin at number 1** (point to 1) **and draw a line from 1 to 2, 2 to 3, 3 to 4 and so on until you reach the end. Remember to work as fast as you can. Ready—Begin!**

Start timing as soon as the instruction "begin" is given. Watch the subject's performance closely in order to catch any errors as soon as they are made. If the subject makes an error, call it to his/her attention immediately, return the subject's pencil to the

last correct circle, and continue the test from that point. *Do not stop timing while correcting the error*. Record the completion time in seconds.

Trail Making Test B ⏱

Place the protocol in front of the examinee with a pen (or pencil *without* eraser) and say: **On this page are some numbers and letters. Begin at 1** (point to 1) **and draw a line from 1 to A** (point to A)**, A to 2** (point to 2)**, 2 to B** (point to B)**, B to 3** (point to 3)**, 3 to C** (point to C)**, and so on, in order until you reach the end** (point to "End")**. Remember, first you have a number then a letter, then a number, then a letter, and so on. Draw the lines as fast as you can. Do you have any questions? Ready—Begin!** Allow the participant to complete the Sample items. **Good! Let's try the next one.** Turn the page over and say: **On this page are both numbers and letters. Do this the same way. Begin at number 1** (point to 1) **and draw a line from 1 to A** (point to A)**, A to 2** (point to 2)**, 2 to B** (point to B)**, B to 3** (point to 3)**, 3 to C** (point to C)**, and so on, in order until you reach the end** (point to "End")**. Remember, first you have a number then a letter, then a number, then a letter, and so on. Do not skip around, but go from one circle to the next in the proper order. Draw the lines as fast as you can. Do you have any questions? Ready—Begin!**

Start timing as soon as the instruction "begin" is given. Watch the subject's performance closely in order to catch any errors as soon as they are made. If the subject makes an error, call it to his/her attention immediately, return the subject's pencil to the last correct circle, and continue the test from that point. *Do not stop timing while correcting the error*. Record the completion time in seconds.

Tetris—*(timer is required!)* ⏱

Minimize any other windows and pull up the previously loaded "TETRIS" game in Google Chrome.

Say: **We have a game for you to do on the computer in front of you. Again, please ensure you are comfortable in order to refrain from any extra movement while you are engaged in the task. This time you will play Tetris. You may have played Tetris previously; the object is to eliminate as many lines as possible accumulating as many points as you can. The controls for this version are as follows: "left arrow" to shift the piece left, "right arrow" to shift right, "up arrow" to rotate the piece to the right, and "down arrow" to 'soft drop' the piece into place.** ***As you play, I will briefly pause and unpause the game allowing you to pick up exactly where you left off. Ready?***

Provide the *Movement Reminder* and allow the subject to place his/her hands on the keyboard before beginning the game. When the participant indicates he/she is ready, begin the game.

Place the cursor over "Pause" in preparation for 30"/10" sequences. Using a stopwatch/interval timer, allow the subject to play for ***30*** seconds, then press "Pause" for ***10*** seconds. At each transition, indicate (discreetly) **Pause** and **Play** for making stim marks on NIRS recording. At each interval, record the number of lines cleared and current score.

Portal

Say: **We have another game for you to play. You may have played this game previously, it is called Portal. **Let me ask you, do you have a history of motion sickness?** ******If the participant has a history of motion sickness**: While playing this game, please let me know if you feel dizzy or nauseous.** Stop the game immediately if the participant reports feeling ill; alternatively, you may skip this game if the participant indicates a wish to do so.

In this game, the goal is to navigate your way through each level as efficiently as possible. The screen shows you what you would see if you were standing in the game. Click on "NEW GAME" and press the "SPACEBAR." Use the keyboard to demonstrate the following as the game opens and say: **You will use the following keys on the keyboard to move your "person" through the game. "W" to walk forward, "A" to strafe left, "D" to strafe right, "S" to walk backward, and the "SPACEBAR" to jump. You rotate your head/look around by moving the mouse in the direction you wish to look: left and right, slide the mouse forward to look up and toward you to look down. Additional instructions for movement and equipment use will be provided to you in the bottom right corner of the screen as needed. You are to try to exit each level as quickly and efficiently as possible *using the strategies and other things you have learned along the way*. *Interdimensional 'portals' will appear between the blue lines on this* (point) *wall and other walls in later levels to allow you to navigate through each level* Do you have any questions right now?** When the subject enters the room with the cube point out the exit door and indicate: **The arrow above the door indicates where you need to go.**

Beginning when the subject exits the elevator to begin ***Level 2***, start timing and record the *number of portals* the participant *ENTERS* regardless of correctness. Allow the participant to play for a total of 6 minutes. Indicate (discreetly) for NIRS stim marks

(Pause) when the participant enters "the elevator" between each level and again when the next level begins (Play).

N-Back (#2)—note if *seated* or *standing*!

Now, we have another task on this computer. Briefly review the instructions for the N-Back.

The *examiner* presses the <SPACEBAR> to begin the practice trial. Paraphrase the *Movement Reminder* (above). Press the <SPACEBAR> to begin the test. **Record which hand the participant used to complete the task on the "Checklist."**

Demographics Sheet

Hand the participant the demographic sheet, a pen, and say: **If you would, please complete the following information to tell us a little bit more about yourself as it relates to our study. Feel free to ask me if you have any questions.** **Record which hand the participant used to complete the task on the "Checklist."**

Conner's Adult ADHD Rating Scale (CAARS) & BRIEF-A

To be completed after computerized tasks. Hand subject the form and a pen and say: **If you would, please complete the following scale to tell us a little bit more about yourself as it relates to our study.** Read the instructions on the forms to the subject and say: **Feel free to ask me if you have any questions.** **Record which hand the participant used to complete the task on the "Checklist."**

Ending the Session

Thank the participant for their time and provide the "Receipt of Gift Card" form. Have the participant sign the form and hand them their gift card. Provide a copy of the signed consent form.

APPENDIX C

Table C-1 Descriptive Statistics for Hemodynamic Data by Task, Channel, and Group.

					95% CI	
EF Task	Channel	Group	M	SD	Lower	Upper
Flanker	Left	Non-ADHD[a]	1.551	1.071	1.151	1.951
		ADHD[b]	2.640	2.697	1.340	3.940
	Midleft	Non-ADHD[a]	1.560	0.993	1.189	1.931
		ADHD[b]	2.485	1.928	1.556	3.414
	Midright	Non-ADHD[a]	1.807	1.105	1.394	2.219
		ADHD[b]	2.079	1.648	1.284	2.873
	Right	Non-ADHD[a]	1.994	1.202	1.545	2.443
		ADHD[b]	3.015	2.226	1.941	4.088
Set Shifting	Left	Non-ADHD[a]	1.746	1.030	1.361	2.131
		ADHD[b]	1.230	1.546	0.485	1.975
	Midleft	Non-ADHD[a]	1.525	0.989	1.156	1.894
		ADHD[b]	1.270	1.393	0.599	1.942
	Midright	Non-ADHD[a]	1.587	1.149	1.158	2.016
		ADHD[b]	1.244	1.332	0.601	1.886
	Right	Non-ADHD[a]	1.810	1.245	1.345	2.275
		ADHD[b]	1.660	1.762	0.810	2.509
CPT	Left	Non-ADHD[c]	1.659	1.541	1.072	2.245
		ADHD[b]	2.246	2.399	1.090	3.403
	Midleft	Non-ADHD[c]	1.585	1.245	1.112	2.059
		ADHD[b]	1.909	1.820	1.031	2.786
	Midright	Non-ADHD[c]	1.894	1.534	1.310	2.477
		ADHD[b]	1.616	1.403	0.940	2.293
	Right	Non-ADHD[c]	2.589	2.019	1.821	3.357
		ADHD[b]	2.356	2.735	1.037	3.674
NBack	Left	Non-ADHD[c]	2.042	1.263	1.562	2.523
		ADHD[b]	2.647	1.985	1.691	3.604
	Midleft	Non-ADHD[c]	1.694	1.204	1.237	2.152
		ADHD[b]	1.862	1.194	1.287	2.438
	Midright	Non-ADHD[c]	1.887	1.458	1.333	2.442
		ADHD[b]	1.716	1.388	1.047	2.385
	Right	Non-ADHD[c]	2.375	1.609	1.763	2.987
		ADHD[b]	2.672	1.865	1.773	3.571

Note: CI= Confidence Interval; CPT=Continuous Performance Test

[a] $N = 30$; [b] $N = 19$; [c] $N = 29$

Table C-2 Descriptive Statistics for Hemodynamic Data by Task, Channel, and Gender.

					95% CI	
EF Task	Channel	Group	M	SD	Lower	Upper
Flanker	Left	Male[a]	1.46	0.94	-0.26	4.28
		Female[b]	2.51	2.49	0.10	9.63
	Midleft	Male[a]	1.72	1.00	0.32	4.34
		Female[b]	2.13	1.86	0.16	7.14
	Midright	Male[a]	1.70	1.00	-0.22	3.86
		Female[b]	2.13	1.60	0.06	5.91
	Right	Male[a]	1.98	1.15	-0.26	4.28
		Female[b]	2.82	2.11	0.20	9.21
Set Shifting	Left	Male[a]	1.26	1.06	-0.43	4.74
		Female[b]	1.84	1.42	-0.15	6.38
	Midleft	Male[a]	1.35	1.04	-0.16	4.06
		Female[b]	1.51	1.28	-0.83	4.93
	Midright	Male[a]	1.22	0.85	-0.10	3.74
		Female[b]	1.70	1.50	-0.68	4.89
	Right	Male[a]	1.43	0.93	0.19	4.12
		Female[b]	2.08	1.81	-0.64	5.31
CPT	Left	Male[a]	1.47	1.49	-1.01	5.82
		Female[c]	2.35	2.25	-0.72	10.15
	Midleft	Male[a]	1.40	1.14	-0.09	4.59
		Female[c]	2.06	1.75	-0.14	7.63
	Midright	Male[a]	1.40	1.06	0.10	3.96
		Female[c]	2.21	1.75	0.24	6.63
	Right	Male[a]	1.86	1.51	-0.36	6.05
		Female[c]	3.19	2.18	0.13	10.89
NBack	Left	Male[a]	1.97	1.44	-0.62	6.33
		Female[c]	2.62	1.72	0.03	6.38
	Midleft	Male[a]	1.79	1.26	0.34	6.34
		Female[c]	1.73	1.13	0.11	4.17
	Midright	Male[a]	1.54	1.25	0.01	5.92
		Female[c]	2.12	1.56	-0.08	6.41
	Right	Male[a]	1.83	1.16	0.16	4.56
		Female[c]	3.21	1.92	0.13	7.42

Note: CI= Confidence Interval; CPT=Continuous Performance Test

[a] $N = 25$; [b] $N = 24$; [c] $N = 23$

Table C-3 Estimated Means for Hemodynamic data by EF Task, NIRS Channel, and Group

				95% CI	
EF Task	Channel	Group	Estimated Means[a] (SE)	Lower	Upper
Flanker	Left	Non-ADHD[b]	1.62 (.363)	0.89	2.35
		ADHD[c]	2.73 (.446)	1.83	3.63
	Midleft	Non-ADHD[b]	1.61 (.285)	1.04	2.19
		ADHD[c]	2.42 (.349)	1.71	3.12
	Midright	Non-ADHD[b]	1.86 (.259)	1.34	2.38
		ADHD[c]	2.19 (.317)	1.55	2.83
	Right	Non-ADHD[b]	2.05 (.329)	1.39	2.72
		ADHD[c]	3.07 (.404)	2.26	3.88
Set Shifting	Left	Non-ADHD[b]	1.79 (.247)	1.29	2.28
		ADHD[c]	1.23 (.303)	0.62	1.84
	Midleft	Non-ADHD[b]	1.54 (.227)	1.08	2.00
		ADHD[c]	1.16 (.279)	0.60	1.72
	Midright	Non-ADHD[b]	1.68 (.239)	1.20	2.16
		ADHD[c]	1.24 (.293)	0.65	1.84
	Right	Non-ADHD[b]	1.85 (.289)	1.26	2.43
		ADHD[c]	1.67 (.354)	0.95	2.38
CPT	Left	Non-ADHD[b]	1.70 (.380)	0.93	2.46
		ADHD[c]	2.31 (.466)	1.37	3.25
	Midleft	Non-ADHD[b]	1.68 (.285)	1.10	2.25
		ADHD[c]	1.73 (.349)	1.03	2.44
	Midright	Non-ADHD[b]	1.96 (.295)	1.37	2.56
		ADHD[c]	1.67 (.362)	0.94	2.40
	Right	Non-ADHD[b]	2.62 (.468)	1.68	3.56
		ADHD[c]	2.39 (.574)	1.23	3.55
N-Back	Left	Non-ADHD[b]	1.96 (.295)	1.36	2.55
		ADHD[c]	2.82 (.362)	2.09	3.55
	Midleft	Non-ADHD[b]	1.70 (.240)	1.21	2.18
		ADHD[c]	1.83 (.295)	1.24	2.42
	Midright	Non-ADHD[b]	1.91 (.281)	1.34	2.48
		ADHD[c]	1.79 (.345)	1.10	2.49
	Right	Non-ADHD[b]	2.38 (.330)	1.72	3.05
		ADHD[c]	2.72 (.405)	1.90	3.54

Note: [a] Covariates appearing in the model were evaluated at gaming frequency hours/week = 6.344; [b] $N = 30$; [c] $N = 18$.

Table C-4 Overall Descriptive Statistics for Digital and Non-Digital EF Performance Variables.

Task Type	EF Variable	*M (SD)*	Skewness	Kurtosis
Digital Tasks	CPT Nontarget Errors	1.240 (1.287)	0.847[a]	0.227[b]
	Flanker Error Difference	1.000 (1.385)	1.488[a]	2.436[b]
	N-Back Total Errors[c]	3.840 (2.313)	0.660[d]	0.682[b]
	Set Shifting Total Errors	4.040 (3.326)	0.640[a]	-0.484[b]
Non-Digital Tasks	20Q Total Questions	53.88 (6.110)	-0.599[a]	2.166[b]
	20Q Achievement Score	53.78 (7.781)	-0.484[a]	0.519[b]
	TMT-Sum	64.12 (16.55)	0.866[a]	0.342[b]
	TMT-Ratio Score	2.471 (0.731)	0.486[a]	-0.513[b]
	TMT-Difference Score	25.92 (11.85)	0.713[a]	-0.068[b]

Note. 20Q=Twenty Questions; TMT=Trail Making Test; CPT=Continuous Performance Test
[a] *SE*=0.337; [b] *SE*=0.662; [c] *N*=49 on N-Back; *N*=50 for all other tasks and variables; [d] *SE*=0.340

Table C-5 Descriptive Statistics for Digital and Non-Digital EF Variables by ADHD Group.

Task Type	EF Variable	Group	*M (SD)*[a]	Skewness	Kurtosis
Digital	CPT Nontarget Errors	Non-ADHD	1.130 (1.15)	0.582[b]	-0.520[e]
		ADHD	1.420 (1.50)	0.938[c]	0.232[f]
	Flanker Error Difference	Non-ADHD	0.840 (1.10)	1.310[b]	1.115[e]
		ADHD	1.260 (1.76)	1.263[c]	1.497[f]
	N-Back Total Errors	Non-ADHD	3.500 (2.50)	1.280[d]	1.788[e]
		ADHD	4.370 (1.92)	-0.800[c]	0.150[f]
	Set Shifting Total Errors	Non-ADHD	4.355 (3.47)	0.663[b]	-0.533[e]
		ADHD	3.526 (3.10)	0.536[c]	-0.633[f]
Non-Digital	20Q Total Questions	Non-ADHD	54.16 (5.32)	0.620[b]	1.624[e]
		ADHD	53.42 (7.35)	-1.320[c]	1.906[f]
	20Q Achievement Score	Non-ADHD	53.00 (5.98)	-0.063[b]	-0.713[e]
		ADHD	55.05 (10.1)	-0.892[c]	0.569[f]
	TMT-Sum	Non-ADHD	62.12 (16.7)	1.040[b]	1.105[e]
		ADHD	67.37 (16.2)	0.762[c]	-0.278[f]
	TMT-Ratio Score	Non-ADHD	2.449 (0.72)	0.189[b]	-0.735[e]
		ADHD	2.507 (0.77)	0.931[c]	-0.189[f]
	TMT-Difference Score	Non-ADHD	24.84 (12.2)	0.765[b]	0.289[e]
		ADHD	27.68 (11.4)	0.793[c]	-0.439[f]

Note. 20Q=Twenty Questions; TMT=Trail Making Test; CPT=Continuous Performance Test
[a] N_{ADHD} = 19; $N_{Non\text{-}ADHD}$=31 [b] *SE*=0.421; [c] *SE*=0.524; [d] *SE*=0.427; [e] *SE*=0.821; [f] *SE*=1.014

Table C-6 Descriptive Statistics for Digital and Non-Digital EF Variables by Gender.

Task Type	EF Variable	Group	*M (SD)*[a]
Digital	CPT Nontarget Errors	Female	1.33 (1.31)
		Male	1.15 (1.29)
	Flanker Error Difference	Female	0.83 (1.24)
		Male	1.15 (1.52)
	N-Back Total Errors	Female	4.09 (2.25)
		Male	3.62 (2.38)
	Set Shifting Total Errors	Female	3.75 (2.89)
		Male	4.31 (3.72)
Non-Digital	20Q Total Questions	Female	54.38 (6.01)
		Male	53.42 (6.28)
	20Q Achievement Score	Female	53.04 (6.01)
		Male	54.46 (7.40)
	TMT-Sum	Female	58.13 (10.54)
		Male	69.65 (19.20)
	TMT-Ratio Score	Female	2.38 (0.69)
		Male	2.56 (0.77)
	TMT-Difference Score	Female	22.29 (9.35)
		Male	29.27 (13.05)

Note. 20Q=Twenty Questions; TMT=Trail Making Test; CPT=Continuous Performance Test
[a] $N_{Female} = 24$; $N_{Male} = 26$