Interference Control and Resource Allocation in Adults with Attention-Deficit/Hyperactivity Disorder: An Evaluation of Response Variability and Error Compensation

by

Kelly Wheaton

Submitted in Partial Fulfillment of the Requirements for the Degree Doctor of Philosophy

Supervised by

Professor Rafael Klorman

Department of Clinical and Social Sciences in Psychology
Arts, Sciences and Engineering
School of Arts and Sciences

University of Rochester
Rochester, New York

2012
Curriculum Vitae

Kelly Wheaton was born in Newton, Massachusetts on May 2, 1983. She attended Colby College from 2001 to 2005. In 2005, she graduated magna cum laude with Bachelor of Arts degrees in Biology and Psychology with a Concentration in Neuroscience. She came to the University of Rochester in the Fall of 2005 and began graduate studies in Clinical Psychology. Upon acceptance, she received the Robert L. and Mary L. Sproull University Fellowship for exceptional credentials and talent in research. In 2009, Kelly received the Helen and Vincent K. Nowlis Award for excellence in teaching and mentoring. She pursued her research in Attention-Deficit/Hyperactivity Disorder under the direction of Dr. Rafael Klorman and received the Master of Arts degree from the University of Rochester in 2008. Kelly’s two year project was on the effects of methylphenidate on response activation and selective response inhibition in a flanker task. Kelly completed clinical externships at Mt. Hope Family Center, the Department of Psychiatry at the University of Rochester Medical Center, and the Rochester Psychiatric Center, and a research assistantship at the VA Center for Integrated Healthcare. In July of 2012, Kelly will complete her predoctoral clinical internship at Dartmouth Medical School, where she has also been accepted for a postdoctoral fellowship.
Acknowledgments

First and foremost, I would like to express my deepest gratitude to my advisor, Rafael Klorman, Ph.D. Without his support and guidance throughout my graduate school career, the completion of this dissertation would not have been possible. In addition, I would like to thank my committee members, Mandi Burnette, Ph.D. and Tristram Smith, Ph.D., for providing their time and thoughtful comments throughout the dissertation process.

I would also like to acknowledge Thomas Gift, M.D. and Erin Gorman, M.A. for their significant contributions to this study. Arthur Loveland also deserves my thanks for providing crucial technical support, as does Maryann Gilbert for her administrative guidance and words of encouragement over the years. I would also like to express my gratitude to Larry Hawk’s laboratory at the State University of New York at Buffalo, especially Michelle Bubnik who provided me with programming necessary for the completion of this study.

This research was partly funded by Grant MH 068332-01 from the National Institute of Mental Health (Rafael Klorman, PI).

I would like to dedicate this dissertation to my parents, Mark and Diane Wheaton. Words cannot encapsulate how forever grateful I will be for their unwavering love, support, and faith. My brothers, Brian and Jeff, and late grandparents, Paul and Helene LeBlanc, also deserve my sincerest appreciation for providing me with the inspiration to persevere and never lose sight of my personal and professional dreams.
Abstract

This research investigated intrasubject variability in reaction time, interference control, and error compensation during a flanker task in 37 adults with Attention-Deficit/Hyperactivity Disorder (ADHD; 20 Combined subtype, 17 Predominantly Inattentive subtype) and 26 healthy controls. I hypothesized that, similar to children with ADHD, adults with the disorder would demonstrate: (a) greater interference control deficits than control subjects, as reflected in greater effects of incongruent flankers on accuracy, reaction time, and intrasubject variability; and (b) less post-error slowing than controls, indicating difficulties with error compensation associated with resource allocation deficits. Intrasubject variability was assessed using the ex-Gaussian distributional model and the deviation from the mode method. Across task conditions, similar to pediatric samples, adults with ADHD demonstrated greater intrasubject variability involving greater sigma, reflecting relatively faster reaction times in the normal portion of the curve, and greater tau, indicating greater variability in the positive skew of the distribution. These results suggest that the portion of the RT distribution affected in patients with ADHD is consistent across the lifespan. Variability in child and adult ADHD may be explained by the default-mode hypothesis, which emphasizes the role of attentional lapses in performance. In contrast to prediction, performance measures did not implicate a specific deficit in interference control among adults with ADHD. In fact, controls were more adversely affected by incongruent arrays with respect to the proportion of correct responses, directional errors, and nonresponses to targets. Only
for false alarms was there a greater interference effect among adults with ADHD. However, whereas previous studies have not found an elevated flanker effect on intrasubject variability of patients with ADHD, the present results indicated that adults with ADHD exhibited increased variability with greater demands for interference control. Intrasubject variability in adults with ADHD involved greater sigma during flanker incongruent compared to congruent trials, reflecting increased variability in the normal portion of the RT distribution. In addition, adults with ADHD exhibited diminished post-error slowing, a result consistent with previous findings for children with the disorder. This deficit in executive functioning is present in individuals with ADHD throughout development and can be explained by the resource allocation hypothesis.
<table>
<thead>
<tr>
<th>Chapter 1</th>
<th>Introduction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Overview of ADHD</td>
<td>2</td>
</tr>
<tr>
<td>Developmental course</td>
<td>2</td>
</tr>
<tr>
<td>Prevalence</td>
<td>4</td>
</tr>
<tr>
<td>Psychiatric comorbidity</td>
<td>5</td>
</tr>
<tr>
<td>Functional Impairment</td>
<td>7</td>
</tr>
<tr>
<td>Psychopharmacological Treatments</td>
<td>9</td>
</tr>
<tr>
<td>Etiology</td>
<td>11</td>
</tr>
<tr>
<td>Executive Functioning Deficits</td>
<td>13</td>
</tr>
<tr>
<td>Models of Executive Functioning in ADHD</td>
<td>15</td>
</tr>
<tr>
<td>Summary</td>
<td>16</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Chapter 2</th>
<th>Intrasubject Variability and Error Compensation in ADHD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flanker Task</td>
<td>17</td>
</tr>
<tr>
<td>ADHD and Intrasubject Variability in Reaction Time</td>
<td>18</td>
</tr>
<tr>
<td>Ex-Gaussian Distributional Model</td>
<td>21</td>
</tr>
<tr>
<td>Deviation from the Mode Method</td>
<td>25</td>
</tr>
<tr>
<td>Fast Fourier Transform Method</td>
<td>26</td>
</tr>
<tr>
<td>Intrasubject Variability and Methylphenidate</td>
<td>27</td>
</tr>
<tr>
<td>Intrasubject Variability and the Default-Mode Network</td>
<td>28</td>
</tr>
<tr>
<td>ADHD and Error Compensation</td>
<td>29</td>
</tr>
<tr>
<td>Chapter 3 Method</td>
<td></td>
</tr>
<tr>
<td>-----------------</td>
<td>---</td>
</tr>
<tr>
<td>Participants</td>
<td>34</td>
</tr>
<tr>
<td>Selection Criteria</td>
<td>34</td>
</tr>
<tr>
<td>Diagnosis of learning disorders</td>
<td>36</td>
</tr>
<tr>
<td>Diagnostic Procedures</td>
<td>37</td>
</tr>
<tr>
<td>ADHD participants</td>
<td>37</td>
</tr>
<tr>
<td>Control participants</td>
<td>37</td>
</tr>
<tr>
<td>Laboratory Sessions</td>
<td>38</td>
</tr>
<tr>
<td>Flanker Task</td>
<td>38</td>
</tr>
<tr>
<td>Physiological Recording</td>
<td>39</td>
</tr>
<tr>
<td>Performance Scoring</td>
<td>40</td>
</tr>
<tr>
<td>Intrasubject Variability Scoring</td>
<td>40</td>
</tr>
<tr>
<td>Ex-Gaussian Distributional Model</td>
<td>40</td>
</tr>
<tr>
<td>Deviation from the Mode Method</td>
<td>41</td>
</tr>
<tr>
<td>Post-Error Reaction Time Scoring</td>
<td>41</td>
</tr>
<tr>
<td>Power Analyses</td>
<td>43</td>
</tr>
<tr>
<td>A priori</td>
<td>43</td>
</tr>
<tr>
<td>Post hoc</td>
<td>43</td>
</tr>
</tbody>
</table>
Chapter 4  Results

Analyses of Background Variables  44
Demographic and Psychoeducational Variables  44
Psychiatric Diagnoses and Treatment History  46
Analyses of Dependent Variables  47
Accuracy Measures  48
  Proportion of correct responses to targets  48
  Proportion of directional errors  49
  Proportion of false alarms  50
  Proportion of nonresponses to targets  51
  Reaction Time for Correct Responses  52
  Standard Deviation for Correct Responses  53
Ex-Gaussian Parameters  54
  Prediction of group membership from ex-Gaussian measures  56
  Deviation from the Mode  58
  Reaction Time on Error and E+1 Trials  58
Subtype Differences  60
Confounding Variables  60

Chapter 5  Discussion

Participant Characteristics  61
Interference Effects on Performance Measures  63
Effects of response hand 64
Interference Effects on Variability Measures 65
Overall Performance and Intrasubject Variability 67
in Adults with ADHD
Interference Control Deficits in Adults with ADHD 68
Error Compensation Deficits in Adults with ADHD 71
Subtype Effects 72
Significance of Research 73
Limitations 74
Directions for Future Research 75
References 77
### List of Figures

<table>
<thead>
<tr>
<th>Figure</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Figure 1</td>
<td>Description of selected response categories in E+1 analysis</td>
<td>109</td>
</tr>
</tbody>
</table>
# List of Tables

<table>
<thead>
<tr>
<th>Table</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Table 1</td>
<td>Proportion of responses for each response category in E+1 analysis</td>
<td>110</td>
</tr>
<tr>
<td>Table 2</td>
<td>Demographic and psychoeducational characteristics by group</td>
<td>112</td>
</tr>
<tr>
<td>Table 3</td>
<td>Percent of psychiatric diagnoses and treatment history by group</td>
<td>114</td>
</tr>
<tr>
<td>Table 4</td>
<td>Mean (SD) proportions of response categories, reaction time, and measures of reaction time variability by group</td>
<td>115</td>
</tr>
<tr>
<td>Table 5</td>
<td>Mean (SD) of proportion of response categories, reaction time, and measures of reaction time variability by flanker category and group</td>
<td>116</td>
</tr>
<tr>
<td>Table 6</td>
<td>Correlations of mean reaction time and measures of variability of reaction time</td>
<td>118</td>
</tr>
<tr>
<td>Table 7</td>
<td>Results of logistic regression of diagnostic status</td>
<td>119</td>
</tr>
<tr>
<td>Table 8</td>
<td>Results of analysis of variance by subtype for each dependent variable</td>
<td>120</td>
</tr>
</tbody>
</table>
Foreword

This study was conducted in collaboration with Rafael Klorman, Ph.D., Thomas Gift, M.D., and Erin Gorman, M.A. The study was designed by Drs. Gift and Klorman, who obtained extramural support, secured IRB approval for the study, and, with the assistance of Ms. Gorman, programmed the experimental task, and recruited participants. Drs. Gift and Klorman conducted clinical interviews of participants. I was involved in the recruitment, screening, psychoeducational assessment, and testing of a portion of the sample. Dr. Klorman and Ms. Gorman evaluated and tested the remainder of the sample. Dr. Klorman also wrote some programs for scoring results. I was responsible for reviewing the literature and developing the hypotheses regarding intrasubject variability and error compensation. I also edited and ran several programs to obtain intrasubject variability parameters, conducted statistical analyses, and interpreted the results.
Chapter 1

Introduction

Attention-Deficit/Hyperactivity Disorder (ADHD) is a neurodevelopmental disorder that is typically diagnosed in childhood. The fourth edition of the Diagnostic and Statistical Manual of Mental Disorders-Text Revision (DSM-IV-TR; American Psychiatric Association, 2000) defines three subtypes of ADHD: Predominantly Inattentive, Predominantly Hyperactive-Impulsive, and Combined. These subtypes represent single or combined elevations of the two dimensions of ADHD: hyperactivity/impulsivity and inattention. Individuals diagnosed with the Predominantly Hyperactive-Impulsive subtype are depicted as exhibiting such traits as developmentally inappropriate levels of energy, talkativeness, and restlessness, and acting “as if driven by a motor.” Those diagnosed with the Predominantly Inattentive subtype are ascribed descriptors like often engaging in daydreaming, being easily distracted, making careless mistakes, exhibiting organizational difficulties, and having difficulty focusing on and/or finishing a task. Individuals with the Combined subtype are those reported to exhibit symptoms of both of these subtypes. Diagnostic criteria require presence of signs of the disorder before the age of seven, persistence of symptoms for at least six months, and impairment across various settings (e.g., school, work, home).

Developmental course

Typically, by 3 or 4 years of age, children with ADHD can be identified as different from their peers (Conners, March, Frances, Wells, & Ross, 2001). These
children are often described by their parents as active, mischievous, and oppositional. During the start of elementary school, the symptoms of ADHD become more apparent to adult observers. Symptoms of ADHD typically evolve and improve at different rates as a child ages; these children often progress from meeting criteria for the Predominantly Hyperactive/Impulsive subtype to those for the Predominantly Inattentive subtype (Lahey et al., 1994).

Initially, ADHD was thought to be solely a childhood disorder that ended after puberty. However, research has shown that ADHD can continue throughout childhood into adolescence and adulthood. Whereas children may demonstrate an amelioration of symptoms during mid-adolescence, 35 to 80% of clinic-referred children with ADHD still meet criteria for the disorder as adolescents, and 35 to 60% of individuals diagnosed with ADHD as children still meet criteria for the diagnosis as adults (Barkley, Fischer, Smallish, & Fletcher, 2006; Cuffe et al., 2001; Kessler et al., 2006; Kessler, Berglund, Demler, Jin, & Walters, 2005). Whereas some adults with ADHD were initially diagnosed in childhood, a significant number were first diagnosed as adults, presumably because their impairment during childhood was not obvious to parents or caregivers.

Despite the continued evidence of the disorder in adulthood, the presentation of ADHD in adulthood differs from that in childhood, raising questions surrounding the appropriateness of current criteria for the diagnosis in adults. For example, adults demonstrate less pronounced symptoms of hyperactivity (Barkley, Murphy, & Fischer, 2008; Biederman, Mick, & Faraone, 2000) and, therefore, current criteria
may underestimate the prevalence of ADHD in adults. In addition, the difficulty of establishing the age of onset criterion from retrospective self-report may also make for underdiagnosis of the disorder in adulthood (McGough & Barkley, 2004). Therefore, when applied to adults, the DSM-IV-TR criteria have been criticized as overly restrictive and failing to lead to a diagnosis despite the presence of clinically meaningful symptoms and impairments consistent with the disorder (Barkley, Fischer, Smallish, & Fletcher, 2002a).

**Prevalence**

ADHD affects 8 to 12% of children worldwide (Faraone, Sergeant, Gillberg, & Biederman, 2003). Epidemiological studies by Kessler and colleagues (2005, 2006) yielded estimates of a point prevalence of 4.4% and a lifetime prevalence of 8.1% for ADHD in adulthood. Epidemiological studies conducted in different countries suggest similar prevalence rates for adult ADHD (Fayyad et al., 2007). Similarly, longitudinal studies of clinical samples report a prevalence of approximately 5% in adulthood (Barkley et al., 2006; Faraone & Biederman, 2005; Mannuzza, Klein, Bessler, Malloy, & LaPadula, 1993; Mannuzza, Klein, Bessler, Malloy, & LaPudala, 1998; Weiss & Hechtman, 1993).

ADHD is considered to be a predominately male disorder, with a male-to-female ratio averaging 6:1 to 10:1 in clinic-referred children (Biederman et al., 2002; Szatmari, Offord, & Boyle, 1989). This ratio is smaller in population-based studies, averaging 3:1 (Biederman et al., 2002). This difference may be related to the greater number of boys referred to mental health professionals, such that population studies
indicate a smaller gender difference in prevalence (Biederman et al., 1995c; Pastor & Reuben, 2008). The greater number of referrals for boys is thought to be a result of differential recognition by caretakers and teachers of disruptive symptoms, often involving aggressiveness (Barkley, 2006). Therefore, the caregivers of these boys are more likely to seek treatment, often at the urging of school staff. Whereas boys are more likely to be diagnosed with the Predominantly Hyperactive/Impulsive and Combined subtypes, girls are more likely to be diagnosed with the Predominantly Inattentive subtype and, therefore, are less likely to be referred for professional attention (Barkley et al., 2002a; Biederman et al., 2002). The diagnosis of ADHD in adulthood is also more common in males than females (2:1); however, this discrepancy is far smaller and is consistent with the reduction in hyperactive/impulsive symptoms with development (Kessler et al., 2006).

**Psychiatric comorbidities**

The rate of psychiatric comorbidity is high in children, adolescents, and adults with ADHD. There is a strong correlation between ADHD and disruptive behavior disorders, with studies reporting that between 50 and 75% of children with ADHD also meet criteria for Conduct Disorder (Kazdin, 1995) and over 50% meet criteria for Oppositional Defiant Disorder (Biederman et al., 1993). The rate of this comorbidity is higher for children with the Combined versus the Predominantly Inattentive subtype (Milich, Balentine, & Lynam, 2001). Adults with ADHD also show increased rates of Conduct Disorder and Oppositional Defiant Disorder (Barkley et al., 1996b; Biederman et al., 1993; Murphy, Barkley, & Bush, 2002; Spencer,
Comparison of longitudinal studies of clinic-referred children with ADHD and studies of individuals diagnosed as adults suggests that individuals who were diagnosed with ADHD as children demonstrate higher rates of disruptive behavior disorders when compared to individuals diagnosed as adults (Barkley, Fischer, Edelbrock, & Smallish, 1990; Fischer, Barkley, Smalley, & Fletcher, 2002; Weiss & Hechtman, 1993).

Consistent with their higher rate of disruptive disorders, adolescents and adults diagnosed with ADHD are more likely to engage in antisocial behaviors and use of illicit substances (Barkley, Fischer, Smallish, & Fletcher, 2004; Biederman et al., 1995c). For example, adults with ADHD report higher rates of alcohol, tobacco, and recreational drug use as children and adolescents (Biederman, Wilens, Mick, Faraone, & Spencer, 1998; Biederman et al., 1992; Whalen, Jamner, Henker, Delfino, & Lozano, 2002). Twenty-one to 53% of individuals with ADHD meet criteria for alcohol abuse or dependence during their lifetime and 8 to 32% meet criteria for substance abuse or dependence (Biederman, 2004; Biederman et al., 1993; Murphy et al., 2002; Wilens, Biederman, Mick, Faraone, & Spencer, 1997; Wilens et al., 2008). Rates of substance abuse and dependence are even higher in adults with dual diagnoses of ADHD and Antisocial Personality Disorder (Barkley, 2006; Tercyak, Lerman, & Audrain, 2002); notably, this comorbidity is common (Biederman et al., 1993; Torgersen, Gjervan, & Rasmussen, 2006).

It could be argued that the higher rates of Antisocial Personality Disorder, Conduct Disorder, and Oppositional Defiant Disorder in individuals with ADHD may
help to explain the higher rates of involvement with police and courts, mostly involving traffic offenses and accidents, teen pregnancy, and sexually transmitted diseases in individuals with ADHD (Barkley, 2004; Barkley, Murphy, DuPaul, & Bush, 2002b; Barkley et al., 1996a; Murphy & Barkley, 1996). Otherwise put, the elevation of antisocial behaviors may be attributable, not to ADHD per se, but to its overlap with disruptive and antisocial disorders.

Both children and adults with ADHD also experience high rates of anxiety and mood disorders, such as Major Depressive Disorder and Dysthymic Disorder (Biederman, 2004; Biederman et al., 1992, 1993; 1995c). In line with the high rate of mood disorders, research indicates that a significantly greater percentage of children with ADHD attempt suicide in adulthood (10%) when compared to healthy peers, and 5% die from suicide or accidental injury (Weiss & Hechtman, 1993). Importantly, individuals with ADHD who are treated with stimulant medication make fewer suicide attempts (Paternite, Loney, Salisbury, & Whaley, 1999). Therefore, effective intervention is crucial to help reduce the effects of these comorbid conditions, as well as the functional impairments attributed to ADHD.

**Functional Impairments**

Children, adolescents, and adults with ADHD demonstrate significant impairment and persistent difficulties in several adaptive domains. With respect to academic and occupational performance, adolescents with ADHD are less likely to graduate from high school in comparison to their peers (Biederman et al., 1995c; Lambert, 1988; Mannuzza et al., 1993); relatedly, 80% of children diagnosed with
ADHD do not go on to attend college (Barkley et al., 2006). Adults with ADHD also demonstrate poorer occupational performance, including poor attention, concentration, and organization, factors which are associated with lower occupational status, more frequent changes in employment, and higher rates of quitting or being terminated from employment (Mannuzza, Klein, Bessler, Malloy, & Hynes, 1997; Murphy et al., 2002). A meta-analysis conducted by Frazier, Demaree, and Youngstrom (2004) indicated that cognitive deficits persist into adulthood. In fact, 46% of adults with ADHD surveyed reported that their ADHD symptoms contributed to their losing or leaving one or more jobs in the preceding 10 years (Biederman et al., 1993). Adults with ADHD also miss more days at work when compared to healthy coworkers (Seczik, Swenson, & Lage, 2005). These occupational problems can lead to financial difficulties, especially when combined with a higher frequency of problems related to money management overall (Barkley et al., 2008). Medical costs associated with prescription drugs and inpatient/outpatient services are also significantly higher for adults with ADHD (Secnik et al., 2005).

Social difficulties of individuals with ADHD include excessive talking, which may interfere with reciprocal conversations and the formation and maintenance of peer relationships. Overall, adults with ADHD have fewer friendships, and are more likely to be unpopular and rejected by peers (Biederman et al., 1993; Hechtman, Weiss, & Perlman, 1980). Rejection is more pronounced for children who are diagnosed with the Predominantly Hyperactive/Impulsive and Combined subtypes relative to those with the Predominantly Inattentive subtype (Erhardt & Hinshaw,
These problems have been reported to continue into adulthood, with the majority of adults with ADHD describing poor relationships with their parents, peers, significant others, colleagues, and workplace superiors, as well as an elevated frequency of marital separation and divorce (Barkley et al., 2006; Barkley et al., 1996b). This poor interpersonal functioning may be associated with the higher rate of pessimism and low self-esteem in adults with ADHD (Rucklidge, Brown, Crawford, & Kaplan, 2007; Shaw-Zirt, Popali-Lehane, & Chaplin, 2005).

The extent of these functional impairments related to ADHD and comorbid disorders and their impact on not only the individual with ADHD, but society as a whole, are troubling. Fortunately, psychopharmacological treatments, as described below, have been proven beneficial at decreasing symptoms of ADHD. Therefore, the proper diagnosis and treatment of this disorder is crucial to treat not only the symptoms of hyperactivity (i.e., impulsivity and inattention) but especially the associated impairments in daily functioning.

**Psychopharmacological Treatments**

Methylphenidate (brand name in the US: Ritalin®) is the most commonly prescribed medication for children with ADHD (Goldman, Genel, Bezman, & Slanetz, 1998). Methylphenidate increases catecholamines, namely dopamine and norepinephrine, in the synaptic cleft by blocking reuptake and facilitating release (Ruskin et al., 2001; Solanto, 1998; Spencer, 2004). Methylphenidate has an excitatory effect on structures related to attentional and inhibitory processing, including the reticular activating system, the limbic system, and the prefrontal cortex.
Although the exact mechanism by which methylphenidate works is unclear, its positive effect on ADHD is supported by behavioral observations and findings of neuropsychological studies.

Behavioral observations indicate that methylphenidate reduces inattention, hyperactivity, and impulsivity (Barkley, 1997; Heiser et al., 2004). Task performance is also enhanced, as indicated by improved accuracy and reaction time (Jonkman et al., 1999; Klorman, Brumaghim, Fitzpatrick, & Borgstedt, 1991). Overall, methylphenidate has been shown to reduce deficits in inhibition (Aron, Dowson, Sahakian, & Robbins, 2003), working memory (Bedard, Martinussen, Ickowicz, & Tannock, 2004), and sustained attention (Fitzpatrick, Klorman, Brumaghim, & Borgstedt, 1992) in children with ADHD. Methylphenidate also has a positive effect on risky behaviors, including substance abuse, which are common in ADHD. Specifically, longitudinal studies have shown that individuals treated with methylphenidate are less likely to use or abuse tobacco, stimulants, and opiates (Biederman et al., 1998; Wilens et al., 2008) and to be diagnosed with alcohol dependence as adults (Paternite, et al., 1999).

Although studied less intensively, the effectiveness of stimulants, including methylphenidate (Biederman et al., 2006; Kooij et al., 2004; Spencer et al., 1995), dextroamphetamine (brand name in the US: Dexedrine®; Weiss & Hechtman, 2006), and dexamethylphenidate (brand name in the US: Focalin®, McGough, Pataki, & Suddath, 2005; Spencer et al., 2007) in treating adults with ADHD has been supported. However, the beneficial effect of stimulant medications on accuracy and
reaction time is not specific to individuals with ADHD. Stimulant medications have
also been found to improve the psychomotor and cognitive performance of healthy
children and adults (Peloquin & Klorman, 1986; Rapoport et al., 1980; Schreiber,

Non-stimulant medications have also been proven effective at decreasing
ADHD symptoms. Among these medications studied in adults with ADHD are
atomoxetine, a norepinephrine reuptake inhibitor (Michelson, Adler, & Spencer,
2003), desipramine, a tricyclic antidepressant (Wilens et al., 1996), bupropion, a
norepinephrine and dopamine reuptake inhibitor (Kuperman et al., 2001), and
modafinil, which increases the release of norepinephrine and dopamine from synaptic
terminals (Greenhill et al., 2006).

Etiology

Whereas the exact pathophysiology is unclear, the interaction of several
biological, genetic, and environmental influences are thought to play a role in the
development and persistence of ADHD. Following evidence suggesting the role of
dopamine, norepinephrine, and serotonin in the treatment of ADHD, many genetic
studies have investigated genes involved in regulation of these neurotransmitters.
Candidate genes include the dopamine transporter (DAT) gene, which is involved in
the facilitation of the reuptake of dopamine into the presynaptic cleft, and the DRD4
dopamine receptor gene, which is associated with postsynaptic sensitivity in the
frontal-subcortical networks (Barr, 2001; Cook et al., 1995; Daly, Hawi, Fitzgerald, &
Gill, 1999; Van Tol et al., 1992). Research has also supported the possible role of
genes involved in the regulation of serotonin and norepinephrine in the etiology of ADHD (Comings et al., 2000).

Family and twin studies support the heritability of ADHD. On average, 30 to 35% of siblings of individuals with ADHD also meet criteria for the disorder (Faraone, Biederman, & Friedman, 2000). Parents of children with ADHD have a 57% prevalence rate of ADHD, compared to 5% in the general population (Biederman et al., 1995a). Genetic influences are also supported by large scale twin studies, which report an average heritability of 77% (Biederman et al., 1992; Coolidge, Thede, & Young, 2000; Nadder, Rutter, Silberg, Maes, & Eaves, 2002).

Certain adverse psychosocial factors have also been linked to the development of ADHD. Potential factors include lower socioeconomic status, larger family size, history of foster care placement, paternal criminality, and parental (especially maternal) psychopathology (Barkley, 2006; Biederman et al., 1995b). Several studies have highlighted the role of prenatal factors in brain abnormalities related to ADHD, including pregnancy complications, poor maternal health, maternal age, fetal distress, duration of labor, and low birth weight (Mick, Biederman, Prince, Fischer, & Faraone, 2002; Milberger, Biederman, Faraone, Chen, & Jones, 1996).

Imaging studies have revealed structural abnormalities, such as smaller cerebral volumes in the frontal cortex, cerebellum, and subcortex of children with ADHD (Castellanos & Tannock, 2002). Research also supports the role of the anterior cingulate cortex (ACC) in the psychopathology of this disorder (Bush, Luu, & Posner, 1999; Rubia et al., 1999). Overall, neuroimaging studies indicate
hypoactivity in the ACC of individuals with ADHD (Rubia et al., 1999; Schulz et al., 2004). Anomalies in cortical thickness in the ACC have also been reported (Makris et al., 2007) and the connectivity between the ACC and other brain regions has been found to be diminished in ADHD (Castellanos et al., 2008).

**Executive Functioning Deficits**

Findings from cognitive and neuropsychological tasks indicate pervasive and specific deficits of executive functioning in children, adolescents, and adults with ADHD (Barkley, 1997; Downey, Stelson, Pomerleau, & Giordiani, 1997; Wender, Wolf, & Wasserstein, 2001). These deficits are consistent with the neurological abnormalities found in ADHD, particularly abnormalities involving the prefrontal cortex, which is instrumental in executive functioning.

Executive functioning, as defined by Welsh and Pennington (1988), is “the ability to maintain an appropriate problem solving set for attainment of a future goal.” Executive functioning is controlled by the frontal-subcortical regions and, as put forth by Pennington and Ozonoff (1996), is made up of five domains: (1) fluency, (2) planning, (3) working memory, (4) inhibition, and (5) set shifting. Overall, studies utilizing neuropsychological tasks have supported similar executive functioning deficits in children and adults with ADHD. However, since executive functioning in adults with ADHD has been studied less intensively, several areas have yet to be investigated.

A meta-analysis conducted by Hervey and colleagues identified three executive functioning tasks on which adults with ADHD perform worse than their
peers without ADHD (Hervey, Epstein, & Curry, 2004). These tasks include the Trail-Making Test-B (Reitan, 1958), which taps motor function and set switching, the Tower of Hanoi task (Pennington, Groisser, & Welsh, 1993), which measures nonverbal working memory, planning, and set switching, and the Rey-Osterrieth Complex Figure test (Rey & Osterrieth, 1993), which reflects visual working memory.

Because of the importance of inhibition deficits in ADHD, much research has been conducted utilizing various inhibition tasks, including the Stop-Signal and Go/No go tasks, which are choice reaction time tasks used to study inhibition of a prepotent response (Nigg, 1999; Yong-Liang et al., 2000), flanker tasks, which require inhibition or suppression of interfering stimuli (Crone, Jennings, & van der Molen, 2003; Johnson et al., 2007; Jonkman, van Melis, Kemner, & Markus, 2007), and antisaccade tasks, which require inhibition of reflexive eye movements (Nigg, 2001; Nigg, Butler, Huang-Pollack, & Henderson, 2002).

Error monitoring, including detection and compensation, is also considered to be a primary executive function, which involves the anterior cingulate cortex (Holyrod et al., 2004). Whereas the ability of children with ADHD to correct errors is comparable to that of controls when instructed, they demonstrate difficulties in self-correction of errors (Sergeant & van der Meere, 1988). Performance and physiological evidence support deficits in both error detection and compensation in individuals with ADHD (Albrecht et al., 2008; Groen et al., 2008; Liotti, Pliszka, Perez, Kothmann, & Woldorff, 2005; McLoughlin et al., 2009; Schachar et al., 2004;
Despite consistent findings surrounding executive functioning deficits in ADHD, researchers differ in their views of the specific cognitive elements involved in this disorder. Although, as reviewed below, this study did not aim to find support for a particular model, a brief discussion of the existing models of executive functioning deficits in ADHD is warranted.

Douglas (1999) highlighted the importance of attentional as well as inhibitory deficits in ADHD. She argued that ADHD is an executive functioning problem, involving an integration of attentional functions, rather than the specific components of volition, planning, purposeful action, and effective performance. Douglas highlighted the deficient performance of children with ADHD on continuous performance tasks (CPTs; Sergeant & van der Meere, 1988). These tasks require the subject to monitor a series of changing stimuli while remaining prepared to respond to a target and inhibit responding to incorrect stimuli. In addition, Douglas emphasized the importance of findings with event-related potentials suggesting deficits in stimulus evaluation in ADHD (Klorman et al., 1991).

In contrast to Douglas’ emphasis on attentional along with executive deficits, Barkley’s (1997) Model of Executive Functioning highlighted deficits in behavioral inhibition and delayed response in children with ADHD. According to this model, children with ADHD have deficits in inhibiting prepotent responses, interrupting
ongoing response, and interference control. A deficit in inhibition is posited to lead to a delay of other executive functions, including verbal and nonverbal working memory, self-regulation, and reconstitution (i.e., the ability to break down and recombine behaviors to achieve a goal).

Sergeant and colleagues proposed the resource allocation hypothesis to explain deficits in ADHD (Sergeant & van der Meere, 1990; Sergeant, Oosterlaan, & van der Meere, 1999). In line with Sanders’ (1983) cognitive-energetic model, Sergeant et al. asserted that children with ADHD demonstrate deficits, not in attention, but in allocation and/or regulation of effort (Sergeant, Oosterlaan, & van der Meere, 1999). According to this theory, performance deficits, including deficits in error monitoring, are a result of differences between an individual’s state, or overall alertness, and the state required for optimal task performance.

Summary

Similarities exist between ADHD in childhood and adulthood, including symptoms, type and rate of psychiatric comorbidities, functional and executive functioning deficits, and response to psychopharmacological treatments. Insofar as the syndrome of ADHD was recognized in children several decades earlier than in adults, the majority of theoretical and experimental studies of this disorder have focused on children. Continued in depth investigation is necessary to better understand this disorder in adulthood. Because of the crucial role of behavioral inhibition in ADHD, further investigation of interference control deficits, especially with respect to performance and error compensation, is warranted.
Chapter 2

Intrasubject Variability and Error Compensation in ADHD

Flanker Task

The flanker task, devised by Eriksen & Eriksen (1974), is a classic paradigm used in cognitive psychology for investigating interference control. In this choice reaction time task, a centrally presented target stimulus (e.g., H or S, indicating a right or left hand response, respectively) is flanked on each side by non-target distractor stimuli (flankers). These distractors can be congruent (e.g., SSSSS) or incongruent (e.g., HHSHH) with the target. Response conflict occurs when subjects are unable to inhibit the automatic evaluation of the flankers. Although subjects are instructed to ignore distractor elements, the presence of incongruent flankers is associated with longer reaction times and higher error rates compared to congruent flanker arrays.

Children and adults with ADHD are slowed more in their reactions by the demands of interference control during the flanker task (Carter, Krener, Chaderjian, Northcutt, & Wolfe, 1995; Crone et al., 2003; Jonkman et al., 1999). A recent review (Mullane, Corkum, Klein, McLaughlin, & Lawrence, 2011) of seven studies indicated that the performance of children with ADHD was more adversely affected by incongruent flankers than was the case for typical peers. However, this finding did not reach significance or yielded a small effect size in several of these investigations. In addition, a more recent report (Johnstone et al., 2010) obtained negative findings.
Results on the effect of methylphenidate on interference control deficits have been mixed. For example, Scheres et al. (2003) did not find an effect of methylphenidate on flanker task performance, but Ridderinkhof and colleagues (2005) reanalyzed her results and reported that methylphenidate administration sped reaction time and reduced reaction time variability. Similar findings regarding the beneficial effect of methylphenidate on interference control deficits in children with ADHD were reported by Castellanos and colleagues (2005).

**ADHD and Intrasubject Variability in Reaction Time**

As previously reviewed, both children and adults with ADHD demonstrate impaired task performance, including higher error rates and slower reaction times, when compared to healthy controls (Epstein, Conners, Sitarenios, & Ehrhardt, 1998; Epstein, Johnson, Varia, & Conners, 2001; Gansler et al., 1998; Johnson et al., 2001, 2007; Nigg, 1999; Oosterlaan & Sergeant, 1996; Teicher, Ito, Glod, & Barber, 1996). However, other studies did not find significant performance deficits in reaction time (Castellanos et al., 2005; Di Martino et al., 2008; Van Meel et al., 2005), accuracy (Ridderinkhof et al., 2005), or both reaction time and accuracy (McLoughlin et al., 2009). A more consistent finding is that individuals with ADHD exhibit greater reaction time variability on a variety of tasks, (Castellanos & Tannock, 2002; de Zeeuw et al., 2008; Di Martino et al., 2008; Karatekin, 2004; Klorman, Brumaghim, Fitzpatrick, & Borgstedt, 1992; Kuntsi, Oosterlaan, & Stevenson, 2001; Leth-Steens, Elbaz, & Douglas, 2000; Sergeant & van der Meere, 1990; van de Voorde, Roeyers, & Wiersema, 2010; Williams, Strauss, Hultsch, Hunter, & Tannock, 2007).
However, a common problem in the reaction time literature is that global measures, such as the mean and standard deviation, used to describe reaction time distributions inherently assume that reaction times fit a normal Gaussian distribution. It is well known that typical reaction time distributions are positively skewed. Although this positive skew is found across studies involving reaction time, it is more pronounced in distributions of children with ADHD (Leth-Steensen et al., 2000). This increased skew is a result of the larger number of abnormally slow responses, which leads to the positive skew and influences the calculation of measures of central tendency and dispersion of response time.

Nesselroade (1991) emphasized the importance of focusing on intrasubject variability, rather than the traditional perspective that subjects’ performance is stable. Nesselroade identified random fluctuation in reaction time as an example of intrasubject variability. Over the past decade, researchers have focused on intrasubject variability to account for the effect of skew on variability measures of reaction time in ADHD. Intrasubject variability is calculated using mathematically sophisticated scoring schemes that take into account the degree of skew in the reaction time distribution. Greater intrasubject variability has been found in individuals with traumatic brain injury, anxiety, and schizophrenia (Bresin, Robinson, Ode, & Leth-Steensen, 2011; Kaiser et al., 2008; Stuss, Pogue, Buckle, & Bondar, 1994).

Leth-Steensen and colleagues (2000), who conducted the seminal research on intrasubject variability in ADHD, reported that the reaction time distributions of
children with ADHD were distinguished by a greater positive skew when compared to controls. When children with ADHD responded quickly, their reaction time did not differ from that of controls; however, when responding slowly, the reaction time was significantly slower. Therefore, researchers suggest that the reported slower reaction time for children with ADHD is not a result of overall slowing of response time, but rather a result of a greater number of slower responses (Leth-Steensen et al., 2000).

Increased intrasubject variability has been found in ADHD subjects utilizing a variety of tasks including: flanker (Di Martino et al., 2008), choice reaction time (MacDonald, Nyberg, & Backman, 2006; Leth-Steensen et al., 2000), continued performance (Douglas, 1999; Epstein et al., 2006; Kollins, McClernon, & Epstein, 2009), ocular motor (Mahone, Mostofsky, Lasker, Zee, & Denckla, 2009), stop-signal (Klein, Wendling, Huettner, Ruder, & Peper, 2006), sustained attention (Bellgrove, Hawi, Kirley, Gill, & Robertson, 2005), and working memory (Buzy, Medoff, & Schweitzer, 2009; Karatekin, 2004) tasks.

Factors including event rate, incentives, and comorbidity have been found to influence variability in children with ADHD. Studies have reported that children with ADHD do not demonstrate differences in intrasubject variability compared to controls when the paradigms involve faster event rates and incentives (Andreou et al., 2007; Kuntsi, Wood, van der Meere, & Asherson, 2009). Geurts and colleagues (2008) found increased intrasubject variability for children with comorbid ADHD and
Autism Spectrum Disorder when compared to children with pure ADHD, suggesting that comorbidity may be a factor to consider when interpreting the results of studies.

Whereas several studies on children with ADHD found differences in intrasubject variability in the absence of differences on performance measures, these studies failed to find specific task effects on intrasubject variability measures. Specifically, Di Martino and colleagues (2008), who conducted the only study comparing intrasubject variability on a flanker task in children with and without ADHD, reported greater variability in children with ADHD. However, they reported that group differences in intrasubject variability were not affected by flanker incongruence.

**Ex-Gaussian Distributional Model**

To account for the skewness of reaction time data, alternative methods to the standard deviation, including the ex-Gaussian model, have been suggested. Application of the ex-Gaussian distributional model to reaction times can provide quantitative measures of properties of the reaction time distribution (Heathcote, Popiel, & Mewhort, 1991; Luce, 1986; Ratcliff, 1979). The assumption of this model is that response time can be characterized as a convolution of the normal distribution and an independent exponential distribution that accounts for extreme, slow reaction times.

The ex-Gaussian distribution is made up of three elements: mu (μ) and sigma (σ), which describe the mean and standard deviation of the normal component,
respectively, and tau (τ), which describes the mean and standard deviation of the exponential component (Ratcliff, 1979).

When the response time distributions are fit with the ex-Gaussian model, mu and sigma describe the location of the fastest reaction times, whereas tau describes the degree of positive skew in the distribution. Greater tau differs from general reaction time slowing. Whereas general slowing may suggest a number of cognitive deficits, researchers suggest that periodic exceptionally long reaction times are a result of poor attention (Hervey et al., 2006).

The ex-Gaussian approach in the study of ADHD has been employed with tasks including Conners’ Continuous Performance task (Epstein et al., 2006; Hervey et al., 2006; Kollins et al., 2009), choice reaction time tasks (Geurts et al., 2008; Leth-Steensen et al., 2000; Williams et al., 2007), go/no-go tasks (Epstein et al., 2011; Vaurio, Simmonds, & Mostofsky, 2009), and a working memory task (Buzy et al., 2009). With the exception of Geurts et al.’s study (2008), which utilized a task of very brief duration (i.e., the task consisted of 64 trials and lasted a total of 182 seconds), studies have identified greater intrasubject variability for ADHD than control subjects and for unmedicated compared to medicated children with ADHD.

In contrast to studies reporting that children with ADHD respond slower than controls, several researchers utilizing the ex-Gaussian parameter (mu) did not find a significant difference between ADHD and control participants on reaction time (Buzy et al., 2009; Geurts et al., 2000; Leth-Steensen et al., 2000; Vaurio et al., 2009). Researchers have attributed this finding to the fact that subjects with ADHD
demonstrate frequent excessively slow responses and that the ex-Gaussian approach
examines the mean reaction time in the normally distributed portion of the curve (mu)
separately from the positive skew (tau). According to this position, individuals with
ADHD do not differ from their peers in the distribution of their fast, as opposed to
their slower, reactions.

Studies have reported that children and adolescents with ADHD demonstrate
greater sigma, indicating greater variability in the normal part of the curve, and
greater tau, denoting greater variability in the exponential distribution (Buzy et al.,
2009; Hervey et al., 2006; & Vaurio et al., 2009).

As mentioned earlier, Geurts et al. (2008) found no significant differences
between ADHD and control children on sigma or tau. However, they reported a
greater sigma for children with comorbid Autism Spectrum Disorder and ADHD
compared to controls and pure ADHD groups, indicating that this comorbid group
demonstrated variable responses in the normal component of the reaction time
distribution. These results highlight the importance of examining the effect of
comorbidity on intrasubject variability.

Leth-Steensen and colleagues (2000) reported that the effect of ADHD on
response variability differed based on the age of the control group to which the
ADHD group was compared. Specifically, when children with ADHD were
compared to age matched controls, ADHD subjects demonstrated greater tau, but no
differences in sigma. However, when the ADHD group was compared to younger
controls, the ADHD group demonstrated greater sigma, but no differences in tau.
This study highlights the importance of taking into account potential age differences in ex-Gaussian parameters.

Kollins, McClernon, and Epstein (2009) conducted the only known study on reaction time variability in adults with ADHD. These researchers investigated the performance of smokers with and without ADHD during a continuous performance task with two smoking conditions: satiated and abstinent. The researchers found that, in comparison with controls, subjects with ADHD did not differ on sigma, but they exhibited a trend towards a greater tau. There was also a significant Group by Drug condition interaction, suggesting that tau was greater for ADHD subjects when tested under the abstinent condition, results indicating an effect of nicotine withdrawal on reaction time variability.

Whereas the ex-Gaussian model is a significant improvement over global distributional measures, it presents some difficulties. Specifically, this model does not adequately fit some subjects’ distributions. For example, Sabol and colleagues found that the ex-Gaussian distribution was a poor fit to the distributions obtained from their rats (Sabol, Richards, Broom, Roach, & Hausknecht, 2003). When the stimulus was more salient, thus easier to detect, no positive skew was found in the distribution. In addition, even when the data were positively skewed, the ex-Gaussian distribution did not fit well. Another example of this problem was Leth-Steensen and colleagues’ (2000) report that the reaction time distributions of 13% of their subjects could not be fit to the ex-Gaussian distribution.
Deviation from the Mode Method

Certain researchers have recommended mode-based approaches over the ex-Gaussian model because mode-methods focus specifically on the positive skew of reaction time data, rather than a convolution of normal and exponential distributions (Bickel 2002, 2003). When a distribution is positively skewed, the mean is larger than the mode. Since the mean increases as the positive skew increases, the greater the degree of the skew, the greater the difference between the mode and mean of a distribution.

Deviation from the mode is computed by subtracting the modal reaction time from the mean reaction time, and provides information about the variability of responses (Acheson & de Wit, 2008; Hausknecht et al., 2005; Sabol et al., 2003; Spencer et al., 2009). The sign of the deviation from the mode and its size reflect the direction and the degree of the skew, respectively.

Whereas the mode of discrete data with a limited number of values and a large number of data points is easily calculated, computing the mode of continuous data, such as reaction time, is more complicated. In this case, the mode is typically calculated by identifying the bin with the most data points (Acheson & de Wit, 2008; Hausknecht et al., 2005; Sabol et al., 2003). A limitation of this method is that the mode varies depending on the size of the time interval used (e.g., 10 vs. 50 ms). In an attempt to ameliorate this problem, additional methods of mode estimation, including the Half-Range Mode method described by Bickel (2002, 2003), have been utilized to score reaction time data (Hedges & Shah, 2003). When calculating the Half-Range
Mode, the distribution is divided into two halves and the half with the most data points is selected. This half is further divided and the denser half is chosen again. This process is repeated until less than three data points make up the final half selected. The mean of these points is taken as the mode and the difference between the mode and mean is taken as the measure of intrasubject variability.

Hausknecht et al. (2005) utilized both the ex-Gaussian method and the deviation from the mode to score reaction time variability when investigating the effects of prenatal alcohol exposure on attention deficits in rats. Despite the differences in the two approaches, both methods led to the same result concerning the variability of reaction time.

**Fast Fourier Transformation**

Spectrum analysis based on fast Fourier transformation (FFT; Bracewell, 1989) is often utilized to evaluate fluctuations in intrasubject variability. In this method, the frequencies of response times sampled during a certain interval are analyzed. A pattern of responses in the periodogram is reflected by a peak in power, or relative strength, at certain frequencies; this result reflects the occurrence of exceptionally slow reaction times. Using FFT, Castellanos and colleagues (2005) evaluated fluctuations in reaction time in children with ADHD during a flanker task. They concluded that, compared with controls, boys with ADHD demonstrated low frequency oscillations (.05 - .10 Hz) in their reaction time distributions, reflecting the occurrence of aberrantly long responses approximately every 10-20 seconds. However, these researchers failed to find a flanker effect on group differences in
frequency of oscillations. Similarly, Di Martino et al. (2008) utilized the FFT approach during a flanker task and found that children with ADHD could be distinguished from healthy controls on the basis of this low frequency oscillation. However, as noted earlier, these researchers did not find an effect of flanker congruence on the variability demonstrated by children with ADHD.

**Intrasubject Variability and Methylphenidate**

Most research supporting the beneficial effects of methylphenidate on speed and variability of response (Bedard et al., 2004; Klorman, et al., 1991; Strauss et al., 1984) utilized mean and standard deviation indices. More recent studies have investigated the effect of methylphenidate on contemporary measures of intrasubject variability. Epstein and colleagues (2006) found that reaction time variability, as measured by the ex-Gaussian method, was reduced in children with ADHD treated with stimulant medication compared to those who were unmedicated. Sigma and tau measures indicated that the reaction times of children with ADHD on stimulant medication were less variable and less positively skewed compared to children with ADHD not on medication. Epstein et al. highlighted the importance of considering tau in the variability of children with ADHD, and they pointed to findings indicating that children with ADHD treated with stimulant medication demonstrated faster reaction times as measured by mean reaction time and slower reaction times when ex-Gaussian parameters were utilized.

Spencer and colleagues (2009) improved on Epstein’s design by conducting a randomized, double-blind study. Utilizing the deviation from the mode method,
Spencer et al. reported that methylphenidate led to a significant reduction in the skew and peak of reaction time distributions. Both laboratories attributed this improvement in variability to beneficial effects of stimulants related to reduction of frequency and severity of lapses in attention. In addition, Castellanos and colleagues (2005) found that methylphenidate reduced reaction time variability, indicating fewer aberrantly slow responses and providing further support to ADHD-related default-mode interference, which is defined in the next section.

**Intrasubject Variability and the Default-Mode Network**

Whereas researchers attribute reaction time variability to many different factors, most agree that this variability reflects the allocation of resources necessary to sustain attention (Bellgrove, Hester, & Garavan, 2004; Cao et al., 2008; Douglas, 1999; Leth-Steensen et al., 2000; Stuss, Murphy, Binns, & Alexander, 2003). Researchers hypothesize that the greater number of excessively long reaction times seen in ADHD reflects intermittent lapses in attention related to a deficit in cognitive control rather than a general inability to execute fast responses (Douglas, 1999; Leth-Steensen et al., 2000).

Successful performance in cognitive tasks not only requires brain activation, but also selective deactivation. Neuroimaging studies have found that a group of brain regions, including the ventromedial prefrontal cortex, posterior cingulate cortex, precuneus, and the middle temporal gyrus, are “deactive” during task performance (Binder et al., 1999; Raichle et al., 2001). Raichle and colleagues (2001) termed these regions the default-mode network because of this region’s activation during conscious
rest and task-irrelevant processes, including monitoring environment and internal thought processes, such as “mind wandering.” Spontaneous low frequency oscillations (< 0.1 Hz) of resting state fMRI have been found to reflect default-mode network activation (De Luca, Beckmann, De Stefano, Matthews, & Smith, 2006).

Lapses in attention and performance errors of healthy individuals have been linked to a failure in the deactivation of the default-mode network (Weissman, Roberts, Visscher, & Woldorff, 2006). Conversely, the ability to sustain attention is associated with an increase in the deactivation of network brain regions (Daselaar, Prince, & Cabeza, 2004; Hahn, Ross, & Stein, 2007; Hester et al., 2004; McKiernan, Kaufman, Kucera-Thompson, & Binder, 2003). Abnormalities in this network are found in adolescents with ADHD (Tian et al., 2006), as well as in individuals with autism (Kennedy et al., 2006) and schizophrenia (Liang et al., 2006), two other disorders associated with intrasubject variability.

The default-mode interference hypothesis addresses intrasubject variability in ADHD. This hypothesis posits that task-irrelevant default-mode network processes intrude into task-relevant processes and cause attentional lapses that interfere with effective performance (Sonuga-Barke & Castellanos, 2007). Mason and colleagues (2007) utilized fMRI and linked subjective reports of task-irrelevant thoughts or “mind-wandering” to activation of the default-mode network.

**ADHD and Error Compensation**

In addition to anomalies present in the reaction time distributions of individuals with ADHD during correct trials, differences also exist on error trials.
Research consistently shows that subjects with ADHD commit more errors when compared to control subjects (Epstein, Conners, Sitarenios, & Ehrhardt, 1998; Epstein et al., 2001; Gansler et al., 1998; Johnson et al., 2001; Nigg, 1999; Oosterlaan & Sergeant, 1996; Teicher et al., 1996). However, how and why this occurs is less understood.

Error detection and compensation processes can be inferred from observations of overt behaviors, such as post-error slowing. Rabbitt (1966), who conducted the seminal research on this topic, reported that when healthy adults make an error, their reaction time on the ensuing correct trial is slowed. This slowing has also been demonstrated in healthy children (Sergeant & van der Meere, 1988; Shallice et al., 2002). Researchers have termed this reaction time after an error (E+1 reaction time), or the reaction time for the first correct trial following an error. This extra time is thought to reflect allocation of effort in order to execute a correct response (Kahneman, 1973). Whereas responding slower on the trial following an error is the normative pattern, post-error slowing of reaction time has been found to be smaller for children with ADHD when compared to controls (Schachar et al., 2004; Wiersema, van der Meere, & Roeyers, 2005). In addition, methylphenidate increases E+1 reaction time in children with ADHD, suggesting that stimulants act to improve error monitoring (Groen et al., 2008; Jonkman et al., 2007; Krusch et al., 1996). Sergeant and van der Meere (1988) reported that whereas E+1 reaction time of healthy children was slowed linearly by increasing cognitive load, children with ADHD demonstrated a smaller post-error slowing when cognitive load was higher.
This finding was interpreted as reflecting deficits in the ability to adjust performance after an error when processing demands are high.

In contrast to these reports of a reduced E+1 effect in children with ADHD, both Jonkman et al. (2007) and Yordanova et al. (2011) found that boys with ADHD did not differ from controls on E+1 slowing during a flanker task. However, Yordanova et al. reported that after committing an error, the responses of subjects with ADHD were less accurate and more variable compared to controls. Other researchers also did not find differences between ADHD and control children on E+1 slowing (Groom et al., 2010; van de Voorde, Roeyers, & Wiersema, 2010; Wild-Wall, Oades, Schmidt-Wessels, Christiansen, & Falkenstein, 2009).

E+1 reaction time has not been extensively examined in adults with ADHD. In the single report available, there was no difference in E+1 reaction time between adults with and without ADHD in a Go/No Go task (Wiersema, van der Meere, & Roeyers, 2009). However, this negative finding might be attributed to the relatively low difficulty of this version of the Go/No Go task, which was initially developed for children with ADHD. Therefore, further investigation of E+1 reaction time in adults with ADHD in a more challenging task is indicated.

**Rationale for the Present Study**

The current literature supports several similarities between children and adults with ADHD, including symptoms, comorbidities, and executive functioning deficits. Whereas ADHD is now recognized in adults, this disorder was identified decades earlier in children. The present study was intended to help fill the gaps in the current
research by studying interference control and resource allocation deficits in adults with ADHD. This study was aimed at investigating intrasubject variability and error compensation in adults with ADHD during a flanker task. Since published studies examining contemporary measures of intrasubject variability and E+1 reaction time in ADHD focused primarily on children, these processes warrant further investigation. In addition, no known studies have utilized the ex-Gaussian or deviation from the mode approach to investigate the effect of flanker incongruence in ADHD. There is one published study on intrasubject variability and one on error compensation in adults with ADHD. Neither of these studies utilized the flanker task. The results of the current study were intended to lend further support to the similarities between children and adults with ADHD, or highlight important differences in the expression of this disorder in adulthood.

**Hypotheses**

The major focus of the analyses was on measures of accuracy, speed, intrasubject variability, and E+1 slowing. The overall hypothesis was that ADHD subjects would demonstrate deficits in interference control, as evidenced by lower accuracy and speed, coupled with more variable response to flanker incongruence. Another prediction was that subjects with ADHD would exhibit reduced E+1 slowing, a result interpretable as deficient error compensation. Based on recent findings from other tasks tested on the present sample, I hypothesized that, when compared to controls and subjects with the Predominantly Inattentive subtype,
individuals with the Combined subtype would be less accurate and demonstrate
greater variability in reaction time.

It was possible that subjects with ADHD, compared to controls, would exhibit
worse overall performance or greater variability, but that they would not be more
impacted by incongruent flankers. Such findings would suggest that interference
control deficits are not prominent in adults with ADHD. Even so, main effects of
ADHD on reaction time variability would be of interest because of theoretical
formulations about biological processes underlying the rhythms of aberrantly slow
reactions (Castellanos et al., 2005). In turn, such overall deficits of speed or accuracy
by subjects with ADHD could be due to lower arousal or motivation.

Findings that individuals with ADHD are deficient in interference control or
in error compensation but not both would point to a difference between deficits
present in children and adults with ADHD. It was also possible that adults with
ADHD might be deficient on only some measures of intrasubject variability (i.e.,
deviation from the mode versus the ex-Gaussian measures). This outcome might
indicate that the two measures tap different aspects of variability.

Finally, results supporting neither overall nor differential deficits in variability
or error compensation in the ADHD sample could be attributed to such factors as (1)
insufficient power, despite efforts to the contrary outlined below; (2)
unrepresentativeness of the current sample; or (3) differences in cognitive deficits
between children and adults with ADHD.
Chapter 3

Method

Participants

This study was approved by the University of Rochester’s Research Subject Review Board. Strategies for the recruitment of participants with ADHD involved referrals from health care and mental health professionals, including community, medical, and private practices, as well as university health and counseling centers. Control participants were recruited via advertisements posted around the campus of the University of Rochester. Participation involved approximately 6 hours for control subjects and 12 hours for participants with ADHD, as a result of the more extensive assessment the latter required (see below). Participants received compensation of $15 per hour and a $25 bonus upon completion of the study.

The most common reason for referral of participants with ADHD was their consideration of stimulant treatment or need for a full diagnostic evaluation in order to receive accommodations from the college.

Selection Criteria

Demographic background was assessed by asking the participant to identify his/her ethnicity (Hispanic/Not Hispanic) and to select one or more racial categories (Caucasian, African American, Asian, American Indian/Alaska native, Native Hawaiian/Pacific Islander). In addition, the participant reported his/her own and his/her parents’ education and occupation, which permitted scoring of the
Hollingshead four-point socioeconomic (SES) estimate of social status (Hollingshead, 1975). For participants who were students, SES was scored based on parents’ status.

Eligible participants were between 18 and 50 years of age. Exclusion criteria included: (1) poor physical health as ascertained by a review of medical history; (2) uncorrected sensory disabilities; (3) a prorated IQ score less than 90 on the Matrix Reasoning and Vocabulary subtests of the Wechsler Adult Intelligence Scale 3rd Edition (WAIS-III; Wechsler, 1997). The choice of this dyad of tests was based on Sattler’s (2001) recommendation. The fourth edition of the Wechsler Adult Intelligence Scale was not employed because the protocol began before this version of the test was available. Participants with ADHD received the entire WAIS-III in order to meet the requirement of the protocol required by colleges for granting accommodations; (4) Autism Spectrum Disorder, central nervous system (CNS) disorder, head injury, or psychosis; (5) history of Major Depressive Disorder, Bipolar Disorder, Panic Disorder, Generalized Anxiety Disorder, Post-Traumatic Stress Disorder, Obsessive-Compulsive Disorder, or substance or alcohol dependence or abuse in the preceding six months; (6) orthopedic, neurological, or medical disorders that impeded motor responses in the present task; (7) unwillingness or inability to abstain from any medication that affects the CNS, excluding birth control or estrogen-replacement medication, antibiotics, aspirin or similar analgesic or nonsteroidal anti-inflammatory agents, insulin or oral hypoglycemics, statins, topical preparations, vitamins, and health supplements. Participants with ADHD were not excluded for current stimulant therapy, and no participants were excluded for use of tobacco or
moderate use of alcohol (≤ 2 drinks per day). However, participants were requested to discontinue use of these substances as follows: caffeine/nicotine no later than 1 hour prior to testing, alcohol a minimum of 24 hours prior to testing, and stimulant therapy a minimum of 48 hours prior to testing.

Psychiatric diagnoses were made by a psychiatrist (Thomas E. Gift, M.D.) or clinical psychologist (Rafael Klorman, Ph.D.) via the *Structured Clinical Interview for DSM-IV-TR Axis I Disorders-Clinical Version* (SCID-I; First, Gibson, Spitzer, & Williams, 2001) for adult disorders and the *Schedule for Affective Disorders and Schizophrenia for School-Age Children-Present and Lifetime Version* (K-SADS-PL; Kaufman et al., 1997) for disruptive disorders of childhood and adolescence. The K-SADS was supplemented by locally developed probes for ADHD in adulthood and Antisocial Personality Disorder. The two interviewers reviewed each case in order to reach a consensus regarding DSM-IV diagnoses.

**Diagnosis of learning disorders**

Participants were not excluded from the study based on a diagnosis of a learning disorder (LD). LD status was diagnosed based on scores on the Basic Reading cluster (Letter-Word Identification and Word Attack) and Calculation subtests of the Woodcock-Johnson III Tests of Achievement (Woodcock, McGrew, & Mather, 2001). The Woodcock-Johnson III Normative Update Tests of Achievement was not employed because the protocol began before this update was available. Consistent with Fletcher et al.’s (1998) criteria, a diagnosis of reading or math LD, respectively, was made if: (1) the subject’s Basic Reading cluster or
Calculation scores were in the lowest 25 percent of the distribution (standard score < 80); or (2) a regression-based discrepancy score between the WAIS-III IQ and either of the above Woodcock-Johnson III scores was greater than 1.5 standard errors.

**Diagnostic Procedures**

**ADHD participants**

Adults meeting criteria for a diagnosis of ADHD for both childhood and adulthood, as assessed from semi-structured interviews on the K-SADS, were eligible to participate in this study. If participants granted permission, the K-SADS was also administered to at least one collateral informant (e.g., parent, spouse, partner, childhood friend). In forming diagnoses, symptoms evaluated on the K-SADS were counted as present if they were endorsed by either the participant or his/her collateral informant. The majority of informants (81.1%) were parent(s), and the remainder included other family member(s) (13.5%) and other individuals in the participants’ lives (e.g., friends, roommates) (2.7%). No informant was available for one ADHD subject (2.7%).

**Control participants**

Control participants were asked to give permission for the investigators to contact an informant. Informants for controls were parent(s) (80.8%), family member(s) (3.8%), significant others (3.8%), or friends (3.8%). No informant was available for two controls (7.7%). Informants were requested to complete the Barkley and Murphy scales for ADHD and Oppositional Defiant Disorder (Murphy et al., 2001) for both current and past behavior. Symptoms on this questionnaire were
counted as present if the informant selected either “Often” or “Very Often.” Similar to the procedure followed for subjects with ADHD, a symptom was counted as present for control participants if it was positive for either the K-SADS or Barkley-Murphy questionnaire.

**Laboratory Sessions**

Testing consisted of two sessions. The first laboratory session involved a 1-hour eye tracking session, which is not part of this study. The second laboratory session began with attachment of EEG electrodes, followed by a Go/No Go discrimination task (Osman, Bashore, Coles, Donchin, & Meyer, 1992), which also will not be included in this dissertation. This task was followed by two flanker tasks described below. All testing occurred in a dimly lit booth. Stimuli were presented on a monitor positioned at eye level, 1 m in front of the subject.

**Flanker Task**

The first task was an arrow version of Eriksen and Eriksen’s (1974) flanker task. Because this task was not expected to elicit enough errors to calculate E+1 reaction time, it will not be discussed further. The second flanker task was a close replication of Hall, Bernat, and Patrick’s (2007) version of the Eriksen flanker task. Two congruent (HHHHH and SSSSS) and two incongruent (HSHHH and SSHSS) target arrays were presented with equal frequency. Subjects were instructed to respond as quickly and accurately as possible to the central target H with the index finger from one hand and to S with the other hand by pressing the two middle buttons.
on a response pad. Assignment of right versus left hands to a particular target (S vs. H) was reversed for each trial block.

Two manipulations were implemented to promote errors. First, the target (S or H) was alternated over trial blocks. Second, 14% of trials involved stimulus arrays with a nontarget central stimulus (X). Half of these No Go trials involved a congruent array (XXXX) and the remainder an incongruent display (HHXHH or SSXSS). Subjects were instructed to refrain from responding during these trials.

To summarize, the task consisted of 600 trials administered over six blocks of 100 trials and included the following displays (1) HHHHH \( (p = .215) \); (2) SSSSS \( (p = .215) \); (3) HHSHH \( (p = .215) \); (4) SSHSS \( (p = .215) \); (5) XXXXX \( (p = .07) \); (6) HHXHH \( (p = .035) \); and (7) SSXSS \( (p = .035) \). Trial types were randomized over the session.

Each trial began with a 150 ms display of the flanker array, followed by a 1,000 ms response window that was terminated by a fixation point, which remained on the screen until the start of the next trial. The intertrial interval ranged from 2,500 to 3,500 ms \( (M = 3,000 \text{ ms}) \) onset to onset. The task proper was administered following the completion of 40 practice trials. Brief breaks were offered between blocks. Assignment of hand/letter response was announced over an intercom before each trial block, and the subject was asked to repeat this information.

**Physiological Recording**

Neuroscan STIM and SCAN software in combination with locally written FORTRAN programs were used for experiment control, processing motor and
electrophysiological responses at a rate of 200 Hz in conjunction a Keithley Instruments DAS-1802-HC A/D board, and scoring performance off-line. Although EEG was collected for this research, these data were not used for this dissertation.

**Performance Scoring**

Responses faster than 200 ms and later than 2,500 ms were not considered, as they were likely to represent premature and late reactions, respectively. Although it was intended that subjects would respond within 1,000 ms, reactions beyond this time limit were scored so as to not curtail reaction time variability. However, as detailed below, the reaction time results were reanalyzed while eliminating responses over 1,000 ms. After excluding the first trial of each block, the following performance measures were calculated: (1) proportion of correct responses to S/H; (2) proportion of directional errors; (3) proportion of false alarms (presses to X displays); (4) proportion of nonresponses; (5) mean reaction time for correct responses; and (6) within-subject standard deviation of correct reaction time responses. Other errors involving premature and late reactions were also scored, but they were too infrequent for statistical analysis.

**Intrasubject Variability Scoring**

**Ex-Gaussian Distributional Method**

These and other variability measures were based on correct responses for trials involving presentations of displays of H and S (n = 504 - errors). A freeshare program (QMPE 2.18; Brown & Heathcote, 2003) was utilized to score reaction time data for correct responses (Cousineau, Brown, & Heathcote, 2004; Heathcote, Brown,
& Mewhort, 2002). This program used all valid reaction times during the task to calculate, separately for each flanker congruence x response hand condition: (1) mu (the mean of the normally distributed component); (2) sigma (the standard deviation of the normally distributed component); and (3) tau (the value that describes both the mean and standard deviation of the exponential component) for each subject. The continuous maximum likelihood (CML) method was used because it utilizes raw reaction time data and, unlike the quantile maximum likelihood (QML), this method does not base computations on quantiles. Heathcote and colleagues’ (2002) recommendation to use QML rather than CML was not followed because QML analyses would have resulted in subsets of trials based on too few observations.

Deviation from the Mode Method

To calculate the deviation from the mode, a Statistical Analysis System (SAS) program (M. Bubnik, personal communication, September 27, 2011) was used to implement the Half-Range Mode method (Bickel, 2002), separately for each flanker congruence x response hand condition. As described earlier, the difference between the mode and mean (deviation from the mode) is a measure of intrasubject variability.

Post-Error Reaction Time Scoring

Error analyses were conducted for participants with three or more error trials, as defined below. This criterion was applied in order to capture as many subjects as possible. Analyses requiring a greater number of minimum trials yielded similar results.

As described in Figure 1 and Table 1, an error (E) was defined as an incorrect
press to S/H (directional error) that was preceded by a correct reaction to either an S/H or an X display; in other words, errors that were part of a string of errors were not included. An E+1 trial was defined as a correct response to S/H preceded by an E trial. As illustrated in Figure 1, an E trial could be followed by a correct reaction to either S/H or X, whereas only those E trials followed by a correct press to S/H qualified as E+1. As a result, the proportion of E trials (.0205) exceeded that for E+1 trials (.0133).

A C+1 trial was defined as a correct response to S/H preceded by a correct press to S/H. As shown in Table 1, C+1 trials accounted for the largest proportion of S/H trials (.6657), far more than either errors or E+1 trials. Similarly, the overwhelming proportion of X trials (.9608) evoked appropriate responses, that is, correct rejections. On the whole, the distribution of response types was quite similar to that reported by Krusch et al. (1996).

The low number of E and E+1 trials precluded averaging reaction times for these response categories separately for each Flanker x Hand condition, and, therefore, an average reaction time for each response category was obtained by pooling over the entire session. As a result, it was necessary to compute, separately for E and E+1 trials, an estimate of matching C+1 trials that accounted for the varying number of trials in the condition that made up the mean reaction times for these response categories.

Matching C+1 trials for error and E+1 trials were calculated by weighting the mean C+1 reaction time for each Flanker x Hand condition, respectively, by the
proportion of error and E+1 trials in the same condition. E trials were matched with C+1 trials from the same flanker condition but with the opposite hand assignment. This scheme took into account the fact that E trials were directional errors involving responses with the opposite hand to assignment, and it was desirable to match error trials with C+1 for the hand employed by the subject in both E and C+1 responses. This issue did not arise for E+1 trials, which involved correct responses.

**Power Analyses**

**A priori**

Power estimates for interactions of Flanker x Diagnosis (Reaction time categories x Diagnosis) were computed a priori via the G*POWER program (Faul, Erdfelder, Buchner, & Lang, 2009). For $\alpha = .05$, power = .80, a medium effect size, and a correlation of .5 over conditions, and three groups (Controls, Combined subtype, and Predominantly Inattentive subtype), the program estimated that a sample of 17 subjects per group was needed. For comparisons of the aggregated ADHD group versus controls, the program estimated that 16 subjects per group were needed.

**Post hoc**

Similar to a priori analysis, power analyses were computed post hoc to determine the estimated power for each subtype analysis. For each dependent variable the $\eta^2_p$ for the associated interaction was entered, as was the correlation between flanker congruent and incongruent values for that dependent variable and the sample size. Estimates of power are discussed below.
Chapter 4

Results

Analyses of Background Variables

Continuous background variables were entered into analyses of variance with either diagnosis (ADHD/Control) or Subtype (Combined/Inattentive) as a between-subjects factor. Categorical variables were analyzed by chi square tests.

Demographic and Psychoeducational Variables

Research participants included 26 control participants and 37 subjects with ADHD. The ADHD sample was composed of 17 subjects with the Predominantly Inattentive Subtype and 20 subjects with the Combined Subtype.

Table 2 presents demographic and psychoeducational information for the sample. Statistical analyses gauging the comparability of the samples employed analyses of variance and chi square tests with two-tailed alpha = .05. Controls and participants with ADHD did not differ on age, $F(1, 61) < 1$, n.s., $\eta^2_p < .01$, sex composition, $\chi^2(1, N = 63) < 1$, n.s., proportion of Hispanic/Not Hispanic, $\chi^2(1, N = 63) < 1$, n.s., proportion of minorities, $\chi^2(1, N = 62) = 1.55$, n.s., proportion of foreign students, $\chi^2(1, N = 63) < 1$, n.s., handedness, $\chi^2(1, N = 63) < 1$, n.s., or years of education, $F(1, 61) = 1.95$, n.s., $\eta^2_p = .03$. There was a slight, but significant, difference between controls and participants with ADHD on Hollingshead four-point socioeconomic status (SES), $F(1, 61) = 4.37, p < .05, \eta^2_p = .07$. SES was higher for controls than ADHD subjects ($Ms \pm SE = 56.69 \pm 2.82$ vs. $49.00 \pm 2.36, M_d = 7.69$).
ADHD subtypes did not differ on age, $F(1, 35) < 1$, n.s., $\eta^2_p < .01$, proportion of Hispanic/Not Hispanic, $\chi^2 (1, N = 37) < 1$, n.s., proportion of minorities, $\chi^2 (1, N = 37) = 1.80$, n.s., proportion of foreign students, $\chi^2 (1, N = 37) = 1.80$, n.s., handedness $\chi^2 (1, N = 37) < 1$, n.s., years of education, $F(1,35) < 1$ n.s., $\eta^2_p = .03$, or SES, $F(1,35) < 1$, n.s., $\eta^2_p < .01$. There was a marginal sex difference between subtypes, $\chi^2 (1, N = 37) = 3.78$, $p = .052$, such that the male/female ratio was higher for the Inattentive subtype (13/4) than for the Combined type (9/11).

There were no significant differences between controls and ADHD subjects on psychoeducational measures. Diagnostic samples were comparable on prorated Wechsler Adult Intelligence Scale III IQ, $F(1,61) = 1.01$, n.s., $\eta^2_p = .02$, and on Woodcock-Johnson III Basic Reading cluster scores, $F(1, 61) < 1$, n.s., $\eta^2_p < .01$. Control subjects’ Woodcock-Johnson III Calculation scores were marginally higher than those of ADHD subjects ($Ms \pm SE = 117.58 \pm 3.23$ vs. $109.57 \pm 2.71$, $M_d = 8.01$), $F(1, 61) = 3.60$, $p = .06$, $\eta^2_p = .06$. There were no subtype differences on prorated IQ, $F(1,35) < 1$, n.s., $\eta^2_p < .01$, Basic Reading scores, $F(1, 35) = 2.68$, n.s., $\eta^2_p = .07$, or Calculation scores, $F(1,35) < 1$, n.s., $\eta^2_p < .01$.

ADHD and control groups did not significantly differ on reading disability diagnosis, $\chi^2 (1, N = 63) < 1$, n.s.. Diagnostic groups also did not significantly differ on math disability diagnosis, $\chi^2 (1, N = 63) = 1.57$, n.s.. Similarly, subtypes did not differ on reading, $\chi^2 (1, N = 37) < 1$, n.s., or math disability diagnosis, $\chi^2 (1, N = 37)$
International students would be expected to score low on reading ability, but eliminating them from the analyses did not affect these results.

When patients’ Full Scale, rather than prorated, IQ scores were used for classifying LD, no participants with ADHD met criteria for reading disability and only one did so for math disability.

**Psychiatric Diagnoses and Treatment History**

Table 3 presents the frequency of various psychiatric diagnoses and treatment history for the current sample. Subjects with ADHD were more likely to be diagnosed with Oppositional Defiant Disorder (ODD) in childhood compared to controls, $\chi^2 (1, N = 63) = 4.49, p < .05$. More ADHD subjects diagnosed with the Combined subtype had a history of childhood ODD than those with the Predominantly Inattentive subtype, $\chi^2 (1, N = 37) = 4.22, p < .05$. Few participants met criteria for Conduct Disorder or Antisocial Personality Disorder diagnoses and, likely as a result, there were no significant differences between groups on the frequency of these disorders.

When compared to controls, participants with ADHD had a significantly higher frequency of lifetime depressive disorders (Major Depressive Disorder, Dysthymic Disorder, Seasonal Affective Disorder, or Bereavement Disorder) than controls, $\chi^2 (1, N = 63) = 6.34, p < .05$. A larger proportion of ADHD subjects diagnosed with the Combined subtype had a history of depression spectrum disorders compared to those with the Predominantly Inattentive subtype, $\chi^2 (1, N = 37) = 7.54, p < .01$. The two diagnostic groups did not differ in the likelihood of receiving an
anxiety disorder diagnosis, $\chi^2 (1, N = 63) < 1$, n.s.. Participants with ADHD reported a marginally higher frequency of an alcohol abuse/dependence history compared to controls, $\chi^2 (1, N = 63) = 3.82, p = .051$. However, there were no significant differences between control and ADHD participants on history of other types of substance abuse/dependence disorders, $\chi^2 (1, N = 63) < 1$, n.s.. There was also a marginal excess of history of psychotropic treatment among subjects with ADHD, $\chi^2 (1, N = 63) = 3.82, p = .051$. Similarly, individuals with ADHD nonsignificantly exceeded control participants with respect to stimulant therapy at the time of the referral, $\chi^2 (1, N = 63) = 3.00, p < .10$, and in childhood, $\chi^2 (1, N = 63) = 2.21$, n.s..

**Analyses of Dependent Variables**

Each of the performance and variability measures described in Chapter 3 was entered into a separate univariate analysis of variance with one between-subjects variable: Diagnosis (ADHD/control) and two repeated measures: Flanker condition (congruent/ incongruent) and Response hand (right/left). The presence of a significant Flanker x Diagnosis status effect would support the hypothesis that subjects with and without ADHD differ with respect to interference control. Two-tailed .05 probability levels were utilized. Effect sizes were estimated as $\eta_p^2$.

The proportions of directional errors and nonresponses are not independent of the proportion of correct responses to targets, but they merit separate analyses because they clarify the factors underlying decrements in accuracy due to the task, hand, or diagnostic sample.

E+1 reaction time was entered into a univariate analysis of variance with
Diagnosis as a between subjects factor, and one repeated measure: Reaction time trial category (E+1 and C+1 matched for E+1). A similar design was employed for the analysis of reaction time for error trials and matched C+1 trials. The presence of a significant interaction of Reaction time trial category x Diagnosis would support the hypothesis that ADHD subjects differ from controls in error compensation. Because several subjects lacked enough E or E+1 trials, the number of subjects available for statistical analyses was reduced to 20 controls and 32 subjects with ADHD for error trials and 19 controls and 28 subjects with ADHD for E+1 trials.

Because of the importance of the interactions of Flanker x Diagnosis and Reaction time trial category x Diagnosis for study hypotheses, a power analysis is reported for nonsignificant instances of these tests.

For exploratory purposes, the preceding analyses were repeated separately for ADHD and control participants to investigate the flanker effect. In addition, analyses were repeated with subtype of ADHD (Predominantly Inattentive vs. Combined) in adulthood as a between-subjects factor.

**Accuracy Measures**

**Proportion of correct responses to targets**

Table 4 displays findings for all dependent variables. Because the proportion of correct responses to S/H displayed heterogeneity of variance, an arcsine transformation was utilized. There were significant effects of hand, $F(1,61) = 6.48, p < .05, \eta^2_p = .10$, and flanker, $F(1,61) = 37.87, p < .001, \eta^2_p = .38$. Specifically, correct responses were more common when the target required a right compared to a
left hand response \((M_s \pm SE = .8654 \pm .0195 \text{ vs. } .8386 \pm .0193, M_d = .0268)\). In addition, as depicted in Table 5, correct responses were more likely for trials involving congruent than incongruent flankers \((M_s \pm SE = .8547 \pm .0188 \text{ vs. } .8402 \pm .0192, M_d = .0145)\).

Importantly, control subjects exhibited a greater proportion of correct responses than ADHD subjects \((M_s \pm SE = .9045 \pm .0164 \text{ vs. } .8074 \pm .0284, M_d = .0971), F(1,61) = 6.78, p < .05, \eta^2_p = .100\). However, the hypothesized Flanker by Diagnosis interaction, was only marginally significant, \(F(1,61) = 3.25, p < .10, \eta^2_p = .05\), despite an adequate power estimate of 1.00. Exploratory analyses indicated that the flanker effect was significant for both controls, \(F(1,25) = 41.21, p < .001, \eta^2_p = .62\), and ADHD subjects, \(F(1,36) = 9.24, p < .01, \eta^2_p = .20\). However, both effect sizes and inspection of means suggest that the effect of flanker incongruence was more pronounced for controls \((M_s \pm SE = .9141 \pm .0160 \text{ vs. } .8950 \pm .0170, M_d = .0191)\), than for participants with ADHD \((M_s \pm SE = .8131 \pm .0281 \text{ vs. } .8018 \pm .0290, M_d = .0113)\).

**Proportion of directional errors**

A square root transformation was applied to the proportion of directional errors to reduce heterogeneity of variance. As hypothesized, there was a significant flanker effect, \(F(1,61) = 43.76, p < .001, \eta^2_p = .42\), with participants making more errors during flanker incongruent versus congruent trials \((M_s \pm SE = .0400 \pm .0068 \text{ vs. } .0317 \pm .0069, M_d = .0083)\).
The overall effect of diagnosis was not significant, $F(1,61) < 1$, n.s., $\eta^2_p < .01$. However, more importantly, the hypothesized Flanker by Diagnosis interaction was significant, $F(1,61) = 4.88$, $p < .05$, $\eta^2_p = .07$. Simple effects analyses disclosed that the flanker effect was significant for both controls, $F(1,25) = 35.06$, $p < .001$, $\eta^2_p = .60$, and ADHD subjects, $F(1,36) = 10.80$, $p < .01$, $\eta^2_p = .23$. Although both groups exhibited more directional errors on incongruent trials, this effect was more pronounced for controls ($Ms \pm SE = .0341 \pm .0051$ vs. $.0212 \pm .0045$, $M_d = .0129$) than for participants with ADHD ($Ms \pm SE = .0441 \pm .0110$ vs. $.0390 \pm .0112$, $M_d = .0051$).

**Proportion of false alarms**

Proportions of false alarms (responses to “X” arrays) were also subjected to a square root transformation to eliminate heterogeneity of variance. There was a marginal flanker effect, $F(1,61) = 3.98$, $p = .051$, $\eta^2_p = .06$. As expected, subjects made more false alarm errors to incongruent than congruent flankers ($Ms \pm SE = .0406 \pm .0088$ vs. $.0359 \pm .0095$, $M_d = .0047$). There was not a significant diagnosis effect, $F(1,61) < 1$, n.s., $\eta^2_p < .01$. In addition, the hypothesized Flanker by Diagnosis interaction was not significant, $F(1,61) < 1$, n.s., $\eta^2_p = .02$, despite adequate power to detect differences (estimated power = .95). However, exploratory analyses revealed a significant flanker effect for only ADHD subjects, $F(1,36) = 8.96$, $p < .01$, $\eta^2_p = .20$. ADHD subjects made more false alarm errors during flanker incongruent than congruent flankers ($Ms \pm SE = .0443 \pm .0106$ vs. $.0363 \pm .0118$, $M_d$
Proportion of nonresponses to targets

The proportion of nonresponses to targets was subjected to a square root transformation aimed at eliminating heterogeneity of variance. There were significant flanker, $F(1,61) = 8.47, p < .01, \eta^2_p = .12$, and hand effects, $F(1,61) = 6.51, p < .05, \eta^2_p = .10$. Specifically, participants more often failed to respond during flanker incongruent than congruent arrays ($Ms \pm SE = .1117 \pm .0178$ vs. $=.1167 \pm .0185, M_d = .0050$). Nonresponses were also more prevalent when the correct response required a left compared to a right hand response ($Ms \pm SE = .1194 \pm .0179$ vs. $=.1090 \pm .0189, M_d = .0104$).

Subjects with ADHD exhibited more failures to respond, $F(1,61) = 5.58, p < .05, \eta^2_p = .08$, ($Ms \pm SE = .1477 \pm .0277$ vs. $=.0665 \pm .0152, M_d = .0812$). However, the hypothesized Flanker by Diagnosis interaction was only marginally significant, $F(1,61) = 3.01, p < .10, \eta^2_p = .05$, despite moderate power to detect differences (estimated power = .70). Exploratory analyses revealed a significant flanker effect for control participants, $F(1,25) = 4.96, p < .05, \eta^2_p = .17$. Specifically, control subjects failed to respond more often during flanker incongruent compared to congruent arrays ($Ms \pm SE = .0692 \pm .0159$ vs. $=.0638 \pm .0148, M_d = .0054$). There was only a marginal flanker effect for ADHD subjects, $F(1,36) = 4.02, p = .053, \eta^2_p = .10$, suggesting a trend of more nonresponse errors during flanker incongruent than congruent arrays ($Ms \pm SE = .1501 \pm .0284$ vs. $=.1454 \pm .0273, M_d = .0047$).
**Reaction Time for Correct Responses**

As expected, the two samples combined responded faster during flanker congruent than flanker incongruent trials ($Ms \pm SE = 566 \pm 14$ vs. $608 \pm 14$ ms, $M_d = -42$ ms), $F(1,61) = 199.34$, $p < .001$, $\eta^2_p = .77$. In addition, as predicted, participants with ADHD responded slower than controls ($Ms \pm SE = 618 \pm 16$ vs. $556 \pm 20$ ms, $M_d = 62$ ms), $F(1,61) = 5.53$, $p < .05$, $\eta^2_p = .08$). However, the hypothesized Flanker by Diagnosis interaction was not significant, $F(1,61) < 1$, n.s., $\eta^2_p = .01$, despite adequate power to detect differences (estimated power = 1.00).

As mentioned earlier, the above analyses were repeated for reaction times less than or equal to 1 second. Responses exceeding 1 second could not be analyzed because they were too infrequent. For the combined samples, the flanker effect remained significant, $F(1,61) = 69.69$, $p < .001$, $\eta^2_p = .53$. Specifically, subjects responded faster during flanker congruent than incongruent trials ($Ms \pm SE = 532 \pm 8$ vs. $564 \pm 10$ ms, $M_d = -32$ ms). Once again, diagnostic groups differed significantly, $F(1,61) = 4.59$, $p < .05$, $\eta^2_p = .07$, with ADHD subjects exhibiting longer reaction times when compared to controls, ($Ms \pm SE = 566 \pm 10$ vs. $528 \pm 14$ ms, $M_d = 38$ ms). However, the size of both effects was smaller than when all trials were considered, presumably because subjects with ADHD made more responses that exceeded 1 second. The Flanker by Diagnosis interaction was not significant, $F(1,61) < 1$, n.s., $\eta^2_p < .01$. 
Standard Deviation of Reaction Time for Correct Responses

Averaging over groups, the effects of response hand and flanker condition interacted, $F(1,61) = 6.21, p < .05, \eta^2_p = .092$. Follow-up analyses indicated that the standard deviation of reaction time for right hand responses was greater for incongruent than congruent trials ($Ms \pm SE = 194 \pm 10$ vs. $174 \pm 10$ ms, $M_d = 20$ ms), $F(1,61) = 13.72, p < .001, \eta^2_p = .18$. Left hand responses, in contrast, were not affected by flanker condition, $F(1,61) < 1$, n.s., $\eta^2_p < .01$.

As hypothesized, subjects with ADHD demonstrated greater standard deviation of reaction time compared to controls ($Ms \pm SE = 206 \pm 12$ vs. $160 \pm 14$ ms, $M_d = 46$ ms), $F(1,61) = 6.17, p < .05, \eta^2_p = .092$. However, despite adequate power of 1.00, the hypothesized Flanker by Diagnosis interaction fell short of significance, $F(1,61) = 2.82, p < .10, \eta^2_p = .04$. Exploratory separate analyses for each group indicated that, for control subjects, standard deviation was greater for flanker incongruent than congruent trials, $F(1,25) = 7.05, p < .05, \eta^2_p = .22$, ($Ms \pm SE = 172 \pm 10$ vs. $148 \pm 10$ ms, $M_d = 24$ ms). In turn, the effects of flanker incongruence for subjects with ADHD varied with response hand, Flanker x Hand $F(1,36) = 6.15, p < .05, \eta^2_p = .15$, such that flanker incongruence increased reaction time standard deviation for only right hand responses ($Ms \pm SE = 218 \pm 16$ vs. $198 \pm 14$ ms, $M_d = 20$ ms), $F(1,36) = 6.11, p < .05, \eta^2_p = .15$.

When the above analyses were conducted on reaction times less than or equal to 1 second, only the effect of diagnosis remained, $F(1,61) = 4.59, p < .05, \eta^2_p = .07$,
with ADHD subjects exhibiting greater standard deviation compared to controls, ($M_s \pm SE = 130 \pm 3$ vs. $118 \pm 4$ ms, $M_d = 12$ ms). However, once again, this effect was smaller than when all trials were considered. The hypothesized Flanker by Diagnosis interaction was not significant, $F(1,61) < 1$, n.s., $\eta^2_p < .01$.

**Ex-Gaussian Parameters**

For the mu estimate of reaction time, there were significant effects of hand, $F(1,61) = 11.20, p = .001, \eta^2_p = .16$, and flanker condition, $F(1,61) = 162.82, p < .001, \eta^2_p = .73$. Specifically, mu was greater for left compared to right hand responses ($M_s \pm SE = 428 \pm 6$ vs. $418 \pm 8$ ms, $M_d = 10$ ms) and for flanker incongruent compared to congruent trials, ($M_s \pm SE = 440 \pm 7$ vs. $404 \pm 6$ ms, $M_d = 36$ ms).

In contrast to results for mean reaction time, participants with ADHD exceeded controls nonsignificantly on mu, $F(1,61) = 2.12$, n.s., $\eta^2_p = .03$. In addition, the hypothesized Flanker by Diagnosis interaction only approached significance, $F(1,61) = 2.88, p < .10, \eta^2_p = .05$, despite adequate power of 1.00. Exploratory separate analyses by groups indicated that incongruent flankers elicited larger mu than did congruent flankers for both controls ($M_s \pm SE = 428 \pm 10$ vs. $396 \pm 10$ ms, $M_d = 32$ ms), $F(1, 25) = 81.79, p < .001, \eta^2_p = .77$, and for participants with ADHD ($M_s \pm SE = 453 \pm 10$ vs. $412 \pm 8$ ms, $M_d = 41$ ms), $F(1, 25) = 101.24, p < .001, \eta^2_p = .74$. Although the numeric value of these flanker effects was slightly larger for the ADHD sample, the effect size, as measured by $\eta^2_p$, was trivially greater for controls.
As predicted, sigma was larger for flanker incongruent compared to flanker congruent trials, \( F(1,61) = 18.22, p < .001, \eta_p^2 = .23 \), and for subjects with ADHD compared to controls, \( F(1,61) = 8.82, p < .01, \eta_p^2 = .13 \). In addition, there was a significant Flanker by Diagnosis interaction for sigma, \( F(1,61) = 5.24, p < .05, \eta_p^2 = .08 \). Separate analyses by groups indicated that for controls incongruent flankers evoked only marginally greater sigma (\( M_s \pm SE = 50 \pm 4 \) vs. \( 46 \pm 3 \) ms, \( M_d = 4 \)), \( F(1,36) = 3.87, p < .07, \eta_p^2 = .13 \), whereas this difference reached significance for ADHD subjects, \( F(1,36) = 18.67, p < .001, \eta_p^2 = .34 \) (\( M_s \pm SE = 68 \pm 4 \) vs. \( 54 \pm 2 \) ms, \( M_d = 14 \)).

Analyses for tau disclosed a significant Hand by Flanker interaction, \( F(1,61) = 5.68, p < .05, \eta_p^2 = .08 \). Follow-up analyses revealed that, averaging over groups, for right hand responses tau was larger for flanker incongruent than congruent trials (\( M_s \pm SE = 174 \pm 10 \) vs. \( 158 \pm 10 \) ms, \( M_d = 16 \) ms), \( F(1,61) = 7.83, p < .01, \eta_p^2 = .11 \). The flanker effect was not significant for left hand responses.

As hypothesized, the ADHD sample exceeded controls on tau, \( F(1, 61) = 5.40, p < .05, \eta_p^2 = .08 \). Moreover, there was an interaction of Flanker by Diagnosis for this measure, \( F(1,61) = 4.13, p < .05, \eta_p^2 = .06 \). Among controls, incongruent flanksers elicited significantly larger values of tau (\( M_s \pm SE = 148 \pm 10 \) vs. \( 136 \pm 10 \) ms, \( M_d = 12 \) ms), \( F(1,25) = 7.88, p < .05, \eta_p^2 = .24 \). In contrast, for the ADHD sample incongruent flankers evoked slightly and nonsignificantly smaller tau (\( M_s \pm SE = 184 \pm 10 \) vs. \( 186 \pm 12 \) ms, \( M_d = -2 \) ms), \( F(1,36) < 1, \) n.s., \( \eta_p^2 < .01 \). Thus, unlike
sigma, tau values of subjects with ADHD were less affected by incongruent flankers.

**Prediction of group membership from ex-Gaussian measures**

Logistic regression is a technique that permits predicting group membership from a set of variables (Tabachnick & Fidell, 2007). Like other regression approaches, it provides information on the relative independent contribution of each predictor variable. It seemed desirable to apply this technique to the present measures of mean and variability of reaction time.

Table 6 displays the correlations among mean reaction time and each variability measure; these measures were averaged across the four Hand x Flanker conditions. These correlations were inspected so as to identify highly intercorrelated variables that would result in multicollinearity in predicting diagnosis. As indicated in Table 6, mean reaction time was very highly correlated with all measures. In addition, standard deviation, deviation from the mode, and mu were highly correlated with one or more variability measure. Therefore, only sigma and tau were retained because they were only moderately intercorrelated and because they represented different aspects of the ex-Gaussian model.

Before entering the regression prediction, scores for the two predictors were standardized in order to facilitate interpretation of regression coefficients. As shown in Table 7, sigma and tau in combination significantly predicted diagnosis, $\chi^2 (2) = 11.95$, $p < .01$. The Nagelkerke estimate of $R^2$ of .23 indicated that the size of the effect of prediction by the model including both sigma and tau is large. The model including sigma and tau had a sensitivity of 70.3% and a specificity of 53.8%.
Otherwise put, the model did better at identifying cases with ADHD than healthy subjects.

Inspection of Table 7 indicates that sigma made a greater contribution than did tau to discriminating controls and participants with ADHD. First, only sigma had a significant regression coefficient. Second, sigma yielded an odds ratio nearly twice the size of that for tau. One way of gauging the relative importance of each predictor is to delete it from the model and test the drop in prediction relative to the model that included both predictors. Basing the prediction on sigma alone (i.e., eliminating tau from the model) resulted in a nonsignificant drop in significance for the model in comparison to basing prediction on both sigma and tau, $\chi^2(1) = 1.50$, n.s.. This result suggests a small contribution to prediction from tau. In contrast, basing prediction on tau alone (i.e., deleting sigma from the model) resulted in a significant decrement in comparison to using both predictors, $\chi^2(1) = 6.09$, $p < .05$. In combination, these results indicate that sigma played a far greater role in predicting group membership than did tau.

A similar logistic regression was performed based on the standardized difference between the congruent and incongruent conditions for sigma and tau, respectively. These two estimates of the effect of congruence were significantly negatively correlated, $r(61) = -.54$, $p < .01$.

The model based on these variables was not very successful. Neither the regression coefficient for the incompatibility effect for sigma ($\beta = .595$) nor that for tau ($\beta = -.350$) was significant. The Nagelkerke estimate of $R^2$ was only .14. Finally,
the model had a sensitivity of 81.1% and a specificity of 34.6%, that is, the majority of controls were misclassified. Thus, the ex-Gaussian measures of interference control were far weaker predictors of ADHD diagnosis than the overall mean measures of variability.

**Deviation from the Mode**

As expected, subjects with ADHD displayed larger deviations from the mode than controls, but this difference only approached significance, $F(1,61) = 3.18, p < .10, \eta_p^2 = .05$. There was not a significant effect of flanker on deviation from the mode, $F(1,61) = 2.20, \text{n.s., } \eta_p^2 = .04$. However, importantly, flanker conditions and diagnosis interacted significantly, $F(1,61) = 5.74, p < .05, \eta_p^2 = .09$. Specifically, the effect of flanker congruence was significant for only ADHD subjects, $F(1,36) = 7.71, p < .01, \eta_p^2 = .18$, who demonstrated smaller deviation from the mode during flanker incongruent than congruent trials ($M_s \pm SE = 86 \pm 12 \text{ vs. } 106 \pm 14 \text{ ms, } M_d = -20 \text{ ms}$). In contrast, controls manifested slightly and nonsignificantly larger deviation from the mode during incongruent than congruent trials, ($M_s \pm SE = 70 \pm 12 \text{ vs. } 66 \pm 14 \text{ ms, } M_d = 4 \text{ ms}$), $F(1, 25) < 1, \text{n.s., } \eta_p^2 = .02$. Thus, a lesser impact of incongruent flankers for the ADHD sample was obtained for deviation from the mode, as was the case for tau, but not for sigma.

**Reaction Time on Error and E+1 Trials**

Consistent with the previous analyses of mean reaction time over all trials, subjects with ADHD were slower for the average of error and matched C+1 trials compared to controls ($M_s \pm SE = 662 \pm 22 \text{ vs. } 564 \pm 28 \text{ ms, } M_d = 98 \text{ ms}$), $F(1,50) =$
7.07, \( p < .05, \eta^2_p = .12 \). As also expected, averaging over samples, reaction time on error trials was slower than on matched C+1 trials, \( F(1,50) = 16.60, p < .001, \eta^2_p = .25, (M_s \pm SE = 654 \pm 26 \text{ vs. } 574 \pm 12 \text{ ms}, M_d = 80 \text{ ms}) \). This slowing on error trials was only marginally greater for subjects with ADHD, \( F(1,50) = 3.51, p < .10, \eta^2_p = .07 \), despite sufficient power to detect differences (estimated power = 1.00).

Exploratory analyses revealed the slowing of reaction time on error trials was significant for subjects with ADHD \( (M_s \pm SE = 722 \pm 32 \text{ vs. } 604 \pm 16 \text{ ms}, M_d = 118 \text{ ms}), F(1,31) = 22.10, p < .001, \eta^2_p = .42, \) and nonsignificant for control subjects \( (M_s \pm SE = 586 \pm 42 \text{ vs. } 544 \pm 20 \text{ ms}, M_d = 42 \text{ ms}), F(1,19) = 2.11, \text{n.s.}, \eta^2_p = .10 \).

Unlike overall reaction time and the mean of error reaction time and matched C+1 trials, diagnostic groups did not differ on the mean of E+1 and matched C+1 trials, \( F(1,45) = 1.37, \text{n.s.}, \eta^2_p = .03 \). The analyses of E+1 trials disclosed the expected slowing on reaction times following an error compared to matched C+1 trials, \( F(1,45) = 11.96, p < .001, \eta^2_p = .21 (M_s \pm SE = 624 \pm 22 \text{ vs. } 574 \pm 12 \text{ ms}, M_d = 50 \text{ ms}) \). Contrary to the hypothesis, there was not a significant interaction of Reaction time categories by Diagnosis, \( F(1,45) = 1.08, \text{n.s.}, \eta^2_p = .02 \), despite sufficient power to detect a difference (estimated power = .86). Exploratory analyses revealed that among controls mean reaction times on E+1 trials were significantly slower than those for matching C+1 trials \( (M_s \pm SE = 612 \pm 34 \text{ vs. } 548 \pm 20 \text{ ms}, M_d = 64 \text{ ms}), F(1,18) = 22.65, p < .001, \eta^2_p = .53. \) In contrast, for ADHD subjects the slowing on E+1 trials was less pronounced \( (M_s \pm SE = 636 \pm 28 \text{ vs. } 602 \pm 16 \text{ ms}, M_d = 64 \text{ ms}) \).
Subtype Differences

As shown in Table 8, no significant differences were found for the Flanker by Subtype interaction on any dependent variable ($p_s = .15 - .93$). Separate analyses of subtypes similarly did not yield significant differences. The only trends that approached significance involved larger sigma ($p < .10$) and greater frequency of nonresponses ($p < .10$) by subjects with the Combined subtype.

The lack of significant differences may be due to the fact that certain analyses (mu, sigma, false alarms, E, E+1) were underpowered (power $< .42$). SD was moderately powered (estimated power $=.73$). However, power was 1.00 for mean reaction time, proportion of correct responses, directional errors, and nonresponses, and tau and .85 for deviation from the mode.

Confounding Variables

For each dependent variable, the following potential confounders were examined: age, sex, ethnicity, race, and SES. As noted earlier, only SES differed between groups, but SES was not significantly correlated with any dependent variable ($p > .10$). Therefore, no correction for SES appeared indicated. The remaining confounders also were not correlated with any dependent variable ($p > .10$).
Chapter 5

Discussion

The purpose of this study was to examine whether adults with ADHD, consistent with several studies of children with this disorder, exhibit deficient interference control, greater intrasubject variability, and reduced error compensation. To address these issues, this investigation focused on accuracy, reaction time, and contemporary distributional measures of intrasubject variability during a flanker task.

Participant Characteristics

Efforts to match groups on background characteristics (e.g., sex, age, race, ethnicity, foreign birth, handedness, and years of education) during recruitment of control subjects were largely successful in achieving comparability of the diagnostic groups on these factors. However, similar to studies considering risk factors for ADHD, the present participants with ADHD came from families with somewhat lower SES compared to controls (Barkley, 2006; Biederman et al., 1995b).

In contrast to previous findings of a meta-analysis (Frazier et al., 2004) concluding that both children and adults with ADHD have lower IQs than controls, the present sample of ADHD subjects were comparable to controls on WAIS-III IQ and on Woodcock-Johnson Basic Reading cluster scores. This result is consistent with reports that clinic-referred adults with ADHD do not differ from controls on IQ (Barkley et al., 1996; Murphy & Barkley, 1996; Murphy, Barkley, & Bush, 2002). In addition, the fact that the present ADHD sample was composed primarily of college students or college graduates probably militated against detecting differences in IQ or
reading abilities. On the other hand, the current ADHD cohort demonstrated marginally lower Woodcock-Johnson Calculation scores, consistent with prior research of depressed performance on mathematics in samples of children with ADHD (Barkley, 1997).

Comparisons of subtypes revealed no differences on any psychoeducational measure, pointing to the homogeneous background of the ADHD samples.

Consistent with past research, the current sample of adults with ADHD experienced higher rates of lifetime depressive disorders (Biederman, 2004; Biederman et al., 1992, 1993; 1995c). Also in accord with previous research on children with ADHD (Milich et al., 2001), adults with ADHD were more likely to meet criteria for Oppositional Defiant Disorder in childhood. Similarly, more adults with the Combined subtype met criteria for a childhood diagnosis of Oppositional Defiant Disorder and criteria for a lifetime depressive spectrum diagnosis.

The present sample exhibited trends for greater prevalence of a lifetime alcohol use disorder and greater use of nonstimulant psychotropic medications. Both tendencies may be accounted for by the greater proportion of participants with ADHD with a history of depressive disorders.

It may seem surprising that subjects with ADHD were not more likely to have a history of stimulant therapy than control subjects. This finding can be attributed to the fact that the majority of the sample was not previously diagnosed and, as a result, most were not treated previously.
Another initially puzzling result was that the current samples did not differ on a history of externalizing or substance problems (childhood Conduct Disorder, Antisocial Personality Disorder, substance abuse); in fact, very few subjects met criteria for these disorders. This finding is consistent with reports that individuals diagnosed with ADHD as adults demonstrate lower rates of disruptive disorders when compared to those diagnosed as children (Barkley, Fischer, Edelbrock, & Smallish, 1990; Fischer, Barkley, Smalley, & Fletcher, 2002; Weiss & Hechtman, 1993).

Yet another seemingly unusual finding was the excess of females in the present ADHD cohort relative to epidemiological samples of adults (Kessler et al., 2006) and children with ADHD (Barkley, 2006). Furthermore, the higher female to male ratio in the Combined than in the Inattentive group may seem paradoxical, but it is characteristic of most research samples of adults with ADHD (Barkley et al., 2008; Biederman et al., 1993). Clearly, these discrepancies from population findings reflect self-referral practices that characterize several other studies of adults with ADHD and the greater proneness of women to seek professional help for personal problems. In conclusion, the current sample is comparable to other cohorts of clinically referred adults with ADHD except for their higher level of education.

**Interference Effects on Performance Measures**

I hypothesized that performance for both samples would reflect interference, that is, lower accuracy and speed in response to incongruent than congruent flankers. Consistent with prediction, participants had a smaller proportion of correct responses to targets during flanker incongruent versus congruent trials. Participants’ errors also
reflected interference, that is, they demonstrated more directional errors, failures to respond, and nonsignificantly more false alarms during flanker incongruent trials.

Also as hypothesized, incongruent flankers elicited slower responses than congruent flankers. This effect remained when the analyses were limited to reaction times less than or equal to 1 second and, therefore, cannot be ascribed to an excess of aberrantly long responses during flanker incongruent trials. As already noted, the low frequency of slower reaction times precluded assessing the extent to which they were affected by flanker incongruence.

Similar to reaction time, subjects demonstrated a greater mu during flanker incongruent versus congruent trials. This finding indicates that both overall speed and the faster reactions subsumed by the normal portion of the distribution of reaction time were slowed by flanker incongruence. In summary, measures of performance indicated that the present task replicated previously established characteristics of Eriksen and Eriksen’s (1974) flanker task.

**Effects of response hand**

Another expected effect on performance pertained to the advantage of right hand responses. As previously reported (Wheaton, 2008), subjects made more detections and fewer failures to respond to targets when responses required a right hand response. This finding may be due to the very high proportion of right handed participants, such that during left hand responses they were required to inhibit the prepotent dominant hand response. The low number of left handed subjects
precluded determining whether they also exhibited greater accuracy for their dominant hand.

Similar results of superior performance for right hand responses were found for mu. As would be expected, the predominately right handed sample demonstrated a smaller mu, reflecting faster reactions, when correct responses required a right hand response. These findings indicate that during right hand trials, subjects exhibited faster overall mean reaction times associated within the normally distributed portion of the distribution.

**Interference Effects on Variability Measures**

I hypothesized that participants’ reaction time would be more variable during flanker incongruent trials. Specifically, greater mean standard deviation, deviation from the mode, sigma, and tau were expected. In fact, flanker incongruence increased the standard deviation of reaction time, but this effect of interference was found for only right hand responses, that is, only for responses with the dominant hand. Once again, the small number of left handed subjects precluded evaluating whether a symmetric effect was present for them. It is possible that when initiating left hand responses, right handed subjects need to overcome their initial bias to respond with their dominant hand and, therefore, respond more deliberately, with less variable responses, thus attenuating this interference effect.

Similar to the standard deviation, tau was magnified by flanker incongruence primarily when the task required right hand responses. This result indicates that incongruence slowed the relatively longer right hand reactions found in the positively
skewed portion of the ex-Gaussian distribution. Once again, the lack of interference effects for tau on left hand responses may indicate that most subjects were primed to initiate a right hand response and, therefore, needed to counteract the initial bias to respond with their dominant hand. The resulting responses may have been made in a more effortful and consistent manner, leading to fewer aberrantly slow responses compared to right hand responses.

The most clearcut evidence for the hypothesized increase in variability during flanker incongruent trials was obtained for sigma. This result indicates greater standard deviation of the normal portion of the reaction time distribution during flanker incongruent compared to congruent trials. In contrast, no effects of flanker incongruence were significant for deviation from the mode, indicating that this measure of reaction time variability, which provides information regarding the direction and degree of skew, was not sensitive to the interference effect produced by incongruent arrays.

It is useful to compare the aspects of variability measured by each of the measures studied. Sigma explains variability in the normal component, whereas tau is a measure of the mean and standard deviation of the exponential component and provides information regarding the positive skew of the distribution (Ratcliff, 1979). Deviation from the mode, which is the difference between an individual’s mean and modal reaction time, is a measure of intrasubject variability related to the direction and degree of skew (Bickel, 2002). Therefore, similar to tau, deviation from the mode takes into account the skewed nature of reaction times. However, unlike tau, it
does not focus solely on the positive skew and does not separately assess variability in this portion of the curve.

Insofar as incongruent flankers most clearly affected sigma relative to other measures of variability, it appears that interference adversely affected the normally distributed component of reaction time, that is, relatively faster reactions rather than atypical slower responses. This inference suggests that when subjects are responding most efficiently, resistance to distraction exacts its clearest toll. In contrast, when subjects respond unusually slowly, perhaps because of lapses in attention, task demands exert relatively less influence on their speed.

**Overall Performance and Intrasubject Variability in Adults with ADHD**

As hypothesized, subjects with ADHD were less accurate overall. Specifically, they made fewer correct responses, more nonresponses to targets, and more false alarms to nontargets. As also predicted, subjects with ADHD responded more slowly than controls. Surprisingly, despite the slower overall reaction times of adults with ADHD, there were no significant diagnostic differences for mu, that is, reaction times in the normal component of the distribution.

Also consistent with hypothesized results, ADHD participants demonstrated greater reaction time variability than controls as measured by standard deviation of correct reaction times, sigma, tau, and, marginally, deviation from the mode. In combination, these results imply that adults with ADHD differ from controls in greater variability in both their normally distributed, relatively faster, reaction times as well as for their relatively slower and less frequent responses.
Previous studies of pediatric samples and one adult sample of ADHD patients have been inconsistent with respect to the measure of variability distinguishing these clinical samples from typical subjects. Some studies reported finding increased variability for tau (Leth-Steensen et al., 2000; Kollins et al., 2009) and others for both sigma and tau (Buzy et al., 2009; Fassbender et al., 2009; Hervey et al., 2006; & Vaurio et al., 2009). None of the studies reviewed found larger sigma for children with ADHD.

**Interference Control Deficits in Adults with ADHD**

In contrast to my hypothesis, a specific deficit in interference control, as determined from performance measures, was not found for adults with ADHD. In fact, controls were more adversely affected by incongruent arrays with respect to the proportion of correct responses, directional errors, and nonresponses to targets. Only for false alarms was there a greater interference effect among adults with ADHD. In summary, unexpectedly, control subjects had relatively greater difficulty differentiating S/H targets flanked by incongruent flankers. In contrast, subjects with ADHD made relatively more inappropriate responses to incongruent (HHXHH and SSXSS) than to congruent (XXXXX) No Go arrays. However, it is reaction time, rather than accuracy, that is primarily used in the cognitive literature to index interference effects in the flanker task, and there were no diagnostic differences in this regard. Therefore, accuracy and reaction time measures did not point to deficits by subjects with ADHD in interference control, as was found in many studies of children with ADHD. It should be noted as well, that some studies of children with
ADHD have also failed to find interference control deficits based on reaction time (Castellanos et al., 2005; Di Martino et al., 2008; van Meel et al., 2005), accuracy (Ridderinkhof et al., 2005), or both reaction time and accuracy measures (McLoughlin et al., 2009). Thus, the lack of greater susceptibility to incongruent flankers among the present adults with ADHD does not represent a clearcut discontinuity from the literature on deficits in interference control in pediatric ADHD.

Despite the largely negative diagnostic differences in interference control based on accuracy and reaction time, it is useful to consider differences between groups in the impact of incongruence on measures of reaction time variability. I hypothesized that for trials requiring greater interference there would be greater variability among adults with ADHD. This hypothesis required greater standard deviation, sigma, tau, and deviation from the mode during flanker incongruent compared to congruent trials.

For standard deviation there was a significant flanker effect for controls, whereas for subjects with ADHD the increase in the standard deviation was limited to right hand responses. The disappearance of this finding for reaction times less than or equal to 1 second suggests that these diagnostic differences in flanker effects on standard deviation were carried by atypical, long reaction times.

Diagnostic differences for sigma accorded more closely with my hypothesis. Specifically, subjects with ADHD, to a greater extent than controls, demonstrated larger sigma during flanker incongruent than congruent trials. On the other hand, incongruent flankers increased tau and, marginally, deviation from the mode during
flanker incongruent compared to congruent arrays only for control participants. In combination, these findings suggest that interference by incongruent flankers affected the normally distributed portion of reaction times for participants with ADHD whereas for controls, interference had a greater impact on the skewed portion of the reaction time distribution containing aberrantly long responses. These results are consistent with studies that used FFT and found greater overall variability in the slow portion of the distribution in children with ADHD along with no effect of flanker incongruence on variability involving these relatively slower reactions (Castellanos et al., 2005; Di Martino et al., 2008).

Also in contrast to the hypothesized interference control deficits in ADHD, the deviation from the mode measure indicated that, compared with controls, subjects with ADHD unexpectedly demonstrated greater reaction time variability during flanker congruent than incongruent trials. Therefore, participants with ADHD paradoxically obtained more responses in the positively skewed portion of the distribution during flanker congruent compared to incongruent arrays.

In summary, to the extent that the ex-Gaussian approach represents a good fit for the present reaction time distributions, the results suggest that flanker incongruence affected the relatively faster responses of adults with ADHD to a greater extent than their atypically slower reactions whereas the opposite pattern characterized their control peers. These results imply that for the current sample, controls processed incongruent flankers more slowly, largely on those trials in which
they were not fully engaged in the task. On the other hand, adults with ADHD were especially affected by incongruent flankers on their relatively faster trials.

**Error Compensation Deficits in Adults with ADHD**

As expected, overall, participants responded slower on E and E+1 trials compared to matched correct trials. Therefore, participants slowed down on error trials, indicating that their directional errors were not due to impulsiveness in responding, but more likely to difficulty with the task. In addition, across groups, participants responded slower on correct trials following an error (E+1), suggesting the expected error compensation, that is, slowing after an error aimed at improving performance on the subsequent trial.

Subjects with ADHD demonstrated marginally greater slowing on error trials compared to controls. This result indicates that errors made by subjects with ADHD cannot be attributed to impulsivity, but rather to inattention or greater difficulty with the cognitive demands of the task. Slower reaction times on error trials may provide support for Sergeant and colleagues’ (1990, 1999) resource allocation hypothesis, which posits that performance deficits, including deficits in error monitoring and compensation, are a result of differences between an individual’s state, or overall alertness, and the state required for optimal task performance. However, it needs to be recalled that the present E trials represent a small fraction of directional errors during the task so that generalization to other errors cannot be made easily.

In the present study, the analysis of E and E+1 trials was reduced in power by the fact that some subjects, as also found by Hall et al. (2007), made too few errors to
be included in the analysis. Nevertheless, the results indicated that subjects with ADHD, in contrast to controls, failed to slow after an error. This exploratory analysis supports the hypothesis that adults with ADHD are deficient in error compensation and this finding is consistent with previous findings for pediatric samples (Schachar et al., 2004; Sergeant & van der Meere, 1988; Wiersema et al., 2005). Although E+1 trials comprise only 1.2% of the responses of ADHD subjects, they may have a profound influence on subjects’ performance by representing a proverbial tapping of the brake by which the subject prompts himself/herself to increase caution and deliberateness in the task. The apparent deficit in error compensation, suggesting an inability to react appropriately to mistakes, may help explain the lower accuracy of subjects with ADHD compared to controls.

The diminished post-error slowing among the present subjects with ADHD is consistent with a hypothesized reduction in error compensation, a failure of executive functioning previously found in children with ADHD. It is less clear, however, why some studies have failed to detect this deficit in both pediatric and adult samples of ADHD (e.g., Groom et al., 2010; Jonkman et al., 2007; van de Voorde et al., 2010; Wiersema, van der Meere, & Roeyers, 2009; Wild-Wall et al., 2009; Yordanova et al., 2011). The resolution of this question awaits further research.

**Subtype Effects**

There was no support for the hypothesis that subjects with the Combined subtype would demonstrate greater performance deficits and reaction time variability compared to those with the Predominantly Inattentive subtype. As suggested earlier,
the study was not adequately powered for comparisons between subtypes on several variables. Alternatively, it is possible that subtypes in adult ADHD do not exhibit the differences reported sometimes for childhood subtypes. The lack of such findings in an adult sample may possibly reflect a less sharp differentiation of subtypes due to the well demonstrated pattern of decrements in Hyperactivity/Impulsivity such that children classified as Combined subtype receive a diagnosis of Predominantly Inattentive subtype in adulthood.

**Significance of the Research**

A major finding of the present research was the replication in an adult cohort of greater intrasubject variability previously documented in children with ADHD. The portion of the reaction time distribution affected in patients with ADHD appears to be consistent across the lifespan. Findings indicating that both adults and children with ADHD demonstrate greater variability the positively skew of the reaction time distribution provide support for the default-mode network hypothesis, which posits that longer reaction times are due to lapses in attention (Sonuga-Barke & Castellanos, 2007).

Similar to pediatric samples, adults with ADHD did not manifest clear interference control deficits as defined by greater slowing, inaccuracy, or errors in response to incongruent versus congruent flankers. However, unlike previous studies that have not found a greater effect of flanker incongruence on intrasubject variability of patients with ADHD, the present results indicate that adults with
ADHD have excessive variability in the normal portion of the reaction time distribution.

The findings for post-error slowing also provide evidence of continuity into adulthood of deficits in error compensation often reported in children with ADHD. This result supports the presence of stable deficits in executive functioning, which can be explained by the resource allocation hypothesis (Sergeant & van der Meere, 1990; Sergeant, Oosterlaan, & van der Meere, 1999).

**Limitations**

One limitation of the present study concerns the unrepresentativeness of the sample. The majority of individuals recruited to participate in this study were of middle-class background and high educational attainment. Since approximately 80% of individuals diagnosed with ADHD in childhood do not attend college (Barkley et al., 2006), the study participants were not representative of adults with ADHD, but they were comparable with other research samples (Barkley et al., 1996; Biederman et al., 1993; Murphy and Barkley, 1996; Murphy, Barkley, & Bush, 2002). In addition, whereas participants with ADHD reported symptoms consistent with an ADHD diagnosis in childhood, most were initially diagnosed with ADHD in adulthood. Individuals diagnosed with ADHD in adulthood differ from those diagnosed in childhood and possibly exhibited less severe symptoms in childhood or their difficulties were mitigated by their higher intelligence (Barkley et al., 1996; Murphy and Barkley, 1996; Murphy, Barkley, & Bush, 2002). Furthermore, the greater proportion of females in the current sample, especially in the Combined
subtype group, may have attenuated the effect of subtype on performance since researchers have found that females make fewer errors on the flanker task (Albrecht et al., 2010) and the Continuous Performance Task (Newcorn et al., 2011). Replication of this study with more ADHD subjects in each subtype groups would allow for more power to detect potential differences on variables studied.

Another limitation of this investigation was that the present flanker task precluded the use of the FFT methodology to evaluate response variability. In order to maximize difficulty, the task was designed to include 14% No Go trials. Because FFT requires inclusion of all trials, it would have been necessary to impute an excessive number of trials consisting of the sum of error and No Go trials.

**Directions for Future Research**

There is a need for studies investigating intrasubject variability in flanker tasks among children with ADHD by means of ex-Gaussian and deviation from the mode approaches. This approach would allow for the comparison of children and adults with ADHD on intrasubject variability measures utilized in this study. It would be possible with this methodology to determine whether children with ADHD demonstrate larger sigma during flanker incongruent trials, thus providing evidence that deficits in interference control are best explained by variability in the normal component of the distribution. Alternatively, this strategy might point, not to a larger sigma, but instead to larger tau or no significant differences on ex-Gaussian parameters. Such results would indicate that interference control deficits in children and adults with ADHD cannot be attributed to similarities in intrasubject variability.
In addition, studies utilizing the FFT method should be conducted on adults with ADHD. These analyses would allow for the comparison between children and adults with ADHD on variability in slow frequency oscillations. Specifically, results supporting greater oscillations would provide evidence of greater intrasubject variability in ADHD across the lifespan, consistent with the role of the default-mode network in the performance of both children and adults with ADHD. Differences between children and adults with ADHD would suggest that intrasubject variability is not consistent across the lifespan. FFT analysis would be beneficial also for analyzing task effects, as it would help to delineate diagnostic differences in the impact of cognitive demands. For instance, Vaurio et al. (2009) were able to find significant Diagnosis x Task effects using FFT, but not using the ex-Gaussian approach.

Lastly, studies investigating the effect of stimulant medication on intrasubject variability in adults with ADHD should be conducted. This research would inform the field on the extent of similarity concerning the effect of stimulant medication on intrasubject variability for children and adults with ADHD. Ultimately, this work would increase the understanding of the mechanism by which stimulant medication reduces symptoms of ADHD. Specifically, results would provide information regarding whether stimulant medication improves symptoms of ADHD in the same way in childhood as it does in adulthood.
References


diagnosis and treatment (3rd ed.). New York: Guilford Press.


Bickel, D. R. (2002). Robust estimators of the mode and skewness of continuous data. 

*Computational Statistics and Data Analysis, 39*, 153-163.


Biederman, J., Mick, E., Faraone, S. V., Braaten, E., Doyle, A. E., Spencer, T. J., ...


Biederman, J., Mick, E., Surman, C., Doyle, R., Hammerness, P., Harpold, T., ...


Coolidge, F. L., Thede, L. L., & Young, S. E. (2000). Heritability and the
comorbidity of attention deficit hyperactivity disorder with behavioral disorders and executive function deficits: A preliminary investigation. 

*Developmental Neuropsychology, 17, 273-287.*


Child & Adolescent Psychiatry, 45, 503-511.


Luce, R. D. (1986). *Response times: Their role in inferring elementary mental organization*. New York: Oxford University Press.


Psychopharmacology, 9, 169-184.


Pharmacology, 14, 489-500.


Pharmacoeconomics, 23, 93-102.


Figure 1

Description of selected response categories in E+1 analysis

<table>
<thead>
<tr>
<th>Penultimate Trial</th>
<th>Preceding Trial</th>
<th>Current Trial</th>
<th>Response Category</th>
</tr>
</thead>
<tbody>
<tr>
<td>Any</td>
<td>Correct S/H</td>
<td>Correct S/H</td>
<td>C+1</td>
</tr>
<tr>
<td>Any</td>
<td>Correct X/S/H</td>
<td>Directional Error</td>
<td>E</td>
</tr>
<tr>
<td>Correct X/S/H</td>
<td>Directional Error</td>
<td>Correct S/H</td>
<td>E+1</td>
</tr>
<tr>
<td>Any</td>
<td>Any</td>
<td>Correct X</td>
<td>Correct Rejection</td>
</tr>
<tr>
<td>Any</td>
<td>Directional Error</td>
<td>Directional Error</td>
<td>Error Run</td>
</tr>
</tbody>
</table>
Table 1

Proportion of responses for each response category in E+1 analysis

<table>
<thead>
<tr>
<th></th>
<th>Controls</th>
<th>ADHD</th>
</tr>
</thead>
<tbody>
<tr>
<td>C + 1</td>
<td>.7303 (.1185)</td>
<td>.6203 (.1920)</td>
</tr>
<tr>
<td>XC</td>
<td>.1059 (.0141)</td>
<td>.0938 (.0223)</td>
</tr>
<tr>
<td>S/H Error (E)</td>
<td>.0202 (.0167)</td>
<td>.0207 (.0201)</td>
</tr>
<tr>
<td>E + 1</td>
<td>.0146 (.0122)</td>
<td>.0124 (.0097)</td>
</tr>
<tr>
<td>E Run (R)</td>
<td>.0050 (.0101)</td>
<td>.0158 (.0479)</td>
</tr>
<tr>
<td>R + 1</td>
<td>.0013 (.0022)</td>
<td>.0020 (.0041)</td>
</tr>
<tr>
<td>X Correct</td>
<td>.9641 (.0793)</td>
<td>.9585 (.0683)</td>
</tr>
<tr>
<td>X Error</td>
<td>.0359 (.0793)</td>
<td>.0405 (.0680)</td>
</tr>
<tr>
<td>Other S/H correct</td>
<td>.0522 (.0443)</td>
<td>.0785 (.0561)</td>
</tr>
<tr>
<td>Other S/H error</td>
<td>.0353 (.0400)</td>
<td>.0783 (.0854)</td>
</tr>
<tr>
<td>Other X Error</td>
<td>.0000 (.0000)</td>
<td>.0010 (.0035)</td>
</tr>
</tbody>
</table>

a Correct S/H preceded by correct S/H or correct S/H

b Correct S/H preceded by correct X

c Directional error to S/H preceded by correct S/H

d Correct S/H preceded by directional error to S/H

e Directional error to S/H preceded by directional error to S/H

f Correct S/H preceded by E string

g Correct rejection to X regardless of previous trial

h False alarm to X
Table 1 (Continued)

i Correct S/H preceded by a response other than a directional error to S/H or E string

j Incorrect response to S/H other than a directional error

k Premature, late, or failure to respond to X
Table 2
Demographic and psychoeducational characteristics by group

<table>
<thead>
<tr>
<th>Variable</th>
<th>Control Group</th>
<th>All ADHD</th>
<th>Inattentive</th>
<th>Combined</th>
</tr>
</thead>
<tbody>
<tr>
<td>Caucasian / Minority</td>
<td>16 / 9</td>
<td>29 / 8</td>
<td>15 / 2</td>
<td>14 / 6</td>
</tr>
<tr>
<td>Hispanic / Not Hispanic</td>
<td>1 / 25</td>
<td>1 / 36</td>
<td>0 / 17</td>
<td>1 / 19</td>
</tr>
<tr>
<td>Males</td>
<td>14 / 12</td>
<td>22 / 15</td>
<td>13 / 4</td>
<td>9 / 11</td>
</tr>
<tr>
<td>Right/ Left handed</td>
<td>25 / 1</td>
<td>34 / 3</td>
<td>16 / 1</td>
<td>18 / 2</td>
</tr>
<tr>
<td>International Students</td>
<td>2 / 24</td>
<td>2 / 35</td>
<td>0 / 17</td>
<td>2 / 18</td>
</tr>
<tr>
<td>Age (years)</td>
<td>23.72 (3.53)</td>
<td>23.65 (6.14)</td>
<td>24.08 (5.84)</td>
<td>23.29 (6.51)</td>
</tr>
<tr>
<td>Education (years)</td>
<td>16.04 (2.16)</td>
<td>15.27 (2.14)</td>
<td>14.91 (2.09)</td>
<td>15.58 (2.18)</td>
</tr>
<tr>
<td>SES</td>
<td>56.69 (11.43)</td>
<td>49.00 (16.11)</td>
<td>48.59 (15.52)</td>
<td>49.35 (16.67)</td>
</tr>
<tr>
<td>Informant</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Parent(s)</td>
<td>21 (80.8%)</td>
<td>30 (81.1%)</td>
<td>14 (82.4%)</td>
<td>16 (80%)</td>
</tr>
<tr>
<td>Other Family</td>
<td>1 (3.8%)</td>
<td>5 (13.5%)</td>
<td>3 (17.6%)</td>
<td>2 (10%)</td>
</tr>
</tbody>
</table>
Table 2 (Continued)

<table>
<thead>
<tr>
<th>Significant other</th>
<th>1 (3.8%)</th>
<th>0 (0%)</th>
<th>0 (0%)</th>
<th>0 (0%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Other</td>
<td>1 (3.8%)</td>
<td>1 (2.7%)</td>
<td>0 (0%)</td>
<td>1 (5%)</td>
</tr>
<tr>
<td>None</td>
<td>2 (7.7%)</td>
<td>1 (2.7%)</td>
<td>0 (0%)</td>
<td>1 (5%)</td>
</tr>
<tr>
<td>Prorated IQ c, e</td>
<td>125.73 (13.17)</td>
<td>122.41 (12.76)</td>
<td>121.76 (14.85)</td>
<td>122.95 (11.20)</td>
</tr>
<tr>
<td>Basic Reading c, f</td>
<td>107.62 (9.48)</td>
<td>107.08 (8.35)</td>
<td>109.47 (7.10)</td>
<td>105.05 (9.01)</td>
</tr>
<tr>
<td>Calculation c, f</td>
<td>117.58 (14.33)</td>
<td>109.57 (17.83)</td>
<td>108.65 (18.82)</td>
<td>110.35 (17.40)</td>
</tr>
<tr>
<td>Reading Disability c</td>
<td>1 (3.8%)</td>
<td>3 (8.1%)</td>
<td>1 (5.9%)</td>
<td>2 (10.0%)</td>
</tr>
<tr>
<td>Math Disability a</td>
<td>2 (7.7%)</td>
<td>7 (18.9%)</td>
<td>5 (29.4%)</td>
<td>2 (10.0%)</td>
</tr>
</tbody>
</table>

\[\text{\textsuperscript{a}} \text{n}\]

\[\text{\textsuperscript{b}} \text{n} = 62 \text{ because one subject did not select a race.}\]

\[\text{\textsuperscript{c}} \text{Mean (SD)}\]

\[\text{\textsuperscript{d}} \text{Hollingshead four-point socioeconomic status}\]

\[\text{\textsuperscript{e}} \text{Wechsler Adult Intelligence Scale III}\]

\[\text{\textsuperscript{f}} \text{Woodcock Johnson III Tests of Achievement}\]
Table 3

Percent of psychiatric diagnoses and treatment history by group

<table>
<thead>
<tr>
<th>Diagnosis</th>
<th>Control</th>
<th>All ADHD</th>
<th>Inattentive</th>
<th>Combined</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oppositional Defiant Disorder</td>
<td>11.5</td>
<td>35.1</td>
<td>17.6</td>
<td>50.0</td>
</tr>
<tr>
<td>Conduct Disorder</td>
<td>0.0</td>
<td>2.7</td>
<td>5.9</td>
<td>0.0</td>
</tr>
<tr>
<td>Antisocial Personality Disorder</td>
<td>0.0</td>
<td>2.7</td>
<td>5.9</td>
<td>0.0</td>
</tr>
<tr>
<td>Depressive Disorders a</td>
<td>7.7</td>
<td>35.1</td>
<td>11.8</td>
<td>55.0</td>
</tr>
<tr>
<td>Anxiety disorders b</td>
<td>23.1</td>
<td>24.3</td>
<td>17.6</td>
<td>30.0</td>
</tr>
<tr>
<td>Lifetime Alcohol Use Disorder c</td>
<td>0.0</td>
<td>13.5</td>
<td>17.6</td>
<td>10.0</td>
</tr>
<tr>
<td>Lifetime Drug Use Disorder c</td>
<td>3.8</td>
<td>8.1</td>
<td>5.9</td>
<td>10.0</td>
</tr>
<tr>
<td>Lifetime Psychotropic Medication</td>
<td>0.0</td>
<td>13.5</td>
<td>11.8</td>
<td>15.0</td>
</tr>
<tr>
<td>Stimulant Therapy, Childhood</td>
<td>0.0</td>
<td>8.1</td>
<td>5.9</td>
<td>10.0</td>
</tr>
<tr>
<td>Stimulant Therapy, Adulthood</td>
<td>0.0</td>
<td>10.8</td>
<td>17.6</td>
<td>5.0</td>
</tr>
</tbody>
</table>

a Lifetime Major Depressive Disorder, Dysthymic Disorder, Seasonal Affective Disorder, or Bereavement

b Any anxiety disorder

c Lifetime abuse or dependence
Table 4
Mean (SD) proportions of response categories, reaction time, and measures of reaction time variability by group

<table>
<thead>
<tr>
<th></th>
<th>Controls</th>
<th>ADHD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Proportion Correct Responses</td>
<td>.9045 (.0836)</td>
<td>.8074 (.1729)</td>
</tr>
<tr>
<td>Arcsine Proportion Correct Responses</td>
<td>2.56 (.26)</td>
<td>2.30 (.45)</td>
</tr>
<tr>
<td>Proportion Directional Errors</td>
<td>.0277 (.0235)</td>
<td>.0416 (.0672)</td>
</tr>
<tr>
<td>Square root Proportion Directional Errors</td>
<td>.16 (.06)</td>
<td>.18 (.11)</td>
</tr>
<tr>
<td>Proportion False Alarms</td>
<td>.0353 (.0775)</td>
<td>.0403 (.0666)</td>
</tr>
<tr>
<td>Square Proportion False Alarms</td>
<td>.18 (.12)</td>
<td>.20 (.12)</td>
</tr>
<tr>
<td>Proportion Nonresponses</td>
<td>.0665 (.0777)</td>
<td>.1477 (.1686)</td>
</tr>
<tr>
<td>Square root Proportion Nonresponses</td>
<td>.22 (.13)</td>
<td>.33 (.22)</td>
</tr>
<tr>
<td>Reaction Time</td>
<td>556 (87.58)</td>
<td>618.87 (115.72)</td>
</tr>
<tr>
<td>Standard Deviation of reaction time</td>
<td>160.34 (48.83)</td>
<td>206.18 (84.56)</td>
</tr>
<tr>
<td>Deviation from the Mode</td>
<td>69.01 (42.57)</td>
<td>97.05 (71.69)</td>
</tr>
<tr>
<td>Mu</td>
<td>412.46 (60.08)</td>
<td>432.83 (50.52)</td>
</tr>
<tr>
<td>Sigma</td>
<td>47.68 (12.18)</td>
<td>61.59 (21.55)</td>
</tr>
<tr>
<td>Tau</td>
<td>143.19 (51.26)</td>
<td>185.89 (83.19)</td>
</tr>
<tr>
<td>Error (E) trials reaction time</td>
<td>586.10 (177.41)</td>
<td>721.96 (190.90)</td>
</tr>
<tr>
<td>Reaction time for Matched E trials</td>
<td>543.63 (83.55)</td>
<td>604.74 (98.86)</td>
</tr>
<tr>
<td>Reaction time for E+1 trials</td>
<td>612.67 (129.04)</td>
<td>636.54 (161.06)</td>
</tr>
<tr>
<td>Reaction time for Matched E+1 trials</td>
<td>547.53 (87.30)</td>
<td>601.46 (86.44)</td>
</tr>
</tbody>
</table>
Table 5

Mean (SD) of proportion of response categories, reaction time, and measures of reaction time variability by flanker category and group

<table>
<thead>
<tr>
<th></th>
<th>Controls</th>
<th></th>
<th>ADHD</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Congruent</td>
<td>Incongruent</td>
<td>Congruent</td>
</tr>
<tr>
<td>Correct Responses</td>
<td></td>
<td>.9141 (.0816)</td>
<td>.8950 (.0866)</td>
<td>.8131 (.1712)</td>
</tr>
<tr>
<td>Arcsine Correct Responses a</td>
<td></td>
<td>2.60 (.27)</td>
<td>2.5 (.26)</td>
<td>2.33 (.46)</td>
</tr>
<tr>
<td>Directional Errors a</td>
<td></td>
<td>.0212 (.0231)</td>
<td>.0341 (.0258)</td>
<td>.0390 (.0682)</td>
</tr>
<tr>
<td>Square root Directional Errors a</td>
<td></td>
<td>.14 (.06)</td>
<td>.18 (.07)</td>
<td>.16 (.12)</td>
</tr>
<tr>
<td>False Alarms a</td>
<td></td>
<td>.0352 (.0825)</td>
<td>.0353 (.0780)</td>
<td>.0363 (.0716)</td>
</tr>
<tr>
<td>Square root False Alarms a</td>
<td></td>
<td>.18 (.13)</td>
<td>.18 (.12)</td>
<td>.19 (.12)</td>
</tr>
<tr>
<td>Nonresponses a</td>
<td></td>
<td>.0638 (.0754)</td>
<td>.0692 (.0812)</td>
<td>.1454 (.1661)</td>
</tr>
<tr>
<td>Square root Nonresponses a</td>
<td></td>
<td>.22 (.13)</td>
<td>.23 (.14)</td>
<td>.33 (.20)</td>
</tr>
<tr>
<td>Reaction Time b</td>
<td></td>
<td>534.12 (90.17)</td>
<td>577.18 (85.79)</td>
<td>599.68 (114.77)</td>
</tr>
</tbody>
</table>
Table 5 (Continued)

<p>| | | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Standard Deviation (b)</td>
<td>152.83 (50.77)</td>
<td>167.86 (51.07)</td>
<td>204.43 (88.12)</td>
<td>207.92 (82.82)</td>
</tr>
<tr>
<td>Deviation from the Mode (b)</td>
<td>66.73 (49.58)</td>
<td>71.29 (41.59)</td>
<td>106.75 (80.66)</td>
<td>87.36 (68.36)</td>
</tr>
<tr>
<td>(\text{Mu}b)</td>
<td>396.99 (59.92)</td>
<td>427.92 (61.49)</td>
<td>412.62 (48.37)</td>
<td>453.05 (55.35)</td>
</tr>
<tr>
<td>(\text{Sigma}b)</td>
<td>45.68 (13.99)</td>
<td>49.68 (12.45)</td>
<td>54.96 (19.27)</td>
<td>68.21 (27.07)</td>
</tr>
<tr>
<td>(\text{Tau}b)</td>
<td>137.13 (55.11)</td>
<td>149.25 (49.61)</td>
<td>187.05 (91.47)</td>
<td>184.73 (77.19)</td>
</tr>
</tbody>
</table>

\(a\) Proportion

\(b\) Mean, ms
Table 6
Correlations of mean reaction time and measures of variability of reaction time

<table>
<thead>
<tr>
<th></th>
<th>Mean Reaction Time</th>
<th>Standard Deviation</th>
<th>Deviation from the Mode</th>
<th>Mu</th>
<th>Sigma</th>
<th>Tau</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean Reaction Time</td>
<td>1.000</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Standard Deviation</td>
<td>.859 **</td>
<td>1.000</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Deviation from the Mode</td>
<td>.790**</td>
<td>.887**</td>
<td>1.000</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mu</td>
<td>.778**</td>
<td>.365**</td>
<td>.325**</td>
<td>1.000</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sigma</td>
<td>.701**</td>
<td>.569**</td>
<td>.490**</td>
<td>.589**</td>
<td>1.000</td>
<td></td>
</tr>
<tr>
<td>Tau</td>
<td>.885**</td>
<td>.985**</td>
<td>.913**</td>
<td>.396**</td>
<td>.587**</td>
<td>1.000</td>
</tr>
</tbody>
</table>

Note. $n = 63$

** $p < .01$
Table 7
Results of logistic regression of diagnostic status

<table>
<thead>
<tr>
<th>Predictors</th>
<th>Beta ± SE</th>
<th>Odds ratio</th>
<th>Model $\chi^2$</th>
<th>Model Decrease $\chi^2$</th>
<th>Nagelkerke $R^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sigma and Tau</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sigma</td>
<td>1.024 ± .453 *</td>
<td>2.786</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tau</td>
<td>.463 ± .391</td>
<td>1.589</td>
<td>11.948**</td>
<td></td>
<td>.233</td>
</tr>
<tr>
<td>Sigma</td>
<td>1.167 ± .433 **</td>
<td>3.213</td>
<td>10.446***</td>
<td>1.502</td>
<td>.206</td>
</tr>
<tr>
<td>Tau</td>
<td>.748 ± .354*</td>
<td>2.113</td>
<td>5.857*</td>
<td>6.091*</td>
<td>.120</td>
</tr>
</tbody>
</table>

Note. Predictors are sigma and tau

* $p < .05$

** $p < .01$

***$p < .001$
Table 8

Results of analysis of variance by subtype for each dependent variable

<table>
<thead>
<tr>
<th></th>
<th>Mean RT</th>
<th>Standard Deviation</th>
<th>Deviation from the Mode</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>SV df MS</td>
<td>F</td>
<td>P</td>
</tr>
<tr>
<td>Flanker</td>
<td>1 55237.59 110.11 &lt;.001 .76</td>
<td>481.22 0.73 .40 .02</td>
<td>13147.78 7.23 .01 .17</td>
</tr>
<tr>
<td>Subtype</td>
<td>1 27894.56 0.51 .48 .01</td>
<td>22051.60 0.77 .39 .02</td>
<td>48144.78 2.44 .13 .07</td>
</tr>
<tr>
<td>F x S</td>
<td>1 1106.87 2.21 .15 .06</td>
<td>82.30 0.13 .73 .004</td>
<td>1229.64 0.68 .42 .02</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>Mu</th>
<th>Sigma</th>
<th>Tau</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>SV df MS</td>
<td>F</td>
<td>p</td>
</tr>
<tr>
<td>Flanker</td>
<td>1 59979.45 97.55 &lt;.001 .74</td>
<td>6378.35 17.87 &lt;.001 .74</td>
<td>124.40 0.13 .72 .004</td>
</tr>
<tr>
<td>Subtype</td>
<td>1 18.26 .002 .097 &lt;.01</td>
<td>5730.61 3.28 .08 .09</td>
<td>29063.12 1.05 .31 .03</td>
</tr>
<tr>
<td>F x S</td>
<td>1 5.23 .009 .93 &lt;.01</td>
<td>35.81 .10 .75 .003</td>
<td>1321.98 1.37 .25 .04</td>
</tr>
</tbody>
</table>
Table 8 (Continued)

<table>
<thead>
<tr>
<th></th>
<th>Correct Responses&lt;sup&gt;a&lt;/sup&gt;</th>
<th>Directional Errors&lt;sup&gt;b&lt;/sup&gt;</th>
<th>Non Responses&lt;sup&gt;b&lt;/sup&gt;</th>
<th>False Alarms&lt;sup&gt;b&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>SV</td>
<td>df</td>
<td>MS</td>
<td>F</td>
</tr>
<tr>
<td>Flanker</td>
<td>1</td>
<td>.09</td>
<td>.09</td>
<td>9.48</td>
</tr>
<tr>
<td>Subtype</td>
<td>1</td>
<td>1.98</td>
<td>.12</td>
<td>.07</td>
</tr>
<tr>
<td>F x S</td>
<td>1</td>
<td>.01</td>
<td>.01</td>
<td>.63</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>Error Reaction Time</th>
<th>E+1 Reaction Time</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>SV</td>
<td>df</td>
</tr>
<tr>
<td>Condition</td>
<td>1</td>
<td>238734.07</td>
</tr>
<tr>
<td>Subtype</td>
<td>1</td>
<td>32771.04</td>
</tr>
<tr>
<td>C x S</td>
<td>1</td>
<td>6103.17</td>
</tr>
</tbody>
</table>

<sup>a</sup> Arcsine proportions

<sup>b</sup> Square root proportions