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THE CONTRIBUTION OF CENTRAL AND PERIPHERAL PROCESSES TO SLOW REACTION TIMES IN CHILDREN WITH AND WITHOUT ATTENTION-DEFICIT/HYPERACTIVITY DISORDER (ADHD)

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ABSTRACT

Children with attention-deficit/hyperactivity disorder (ADHD) have been found to respond more slowly than typically-developing controls across a number of simple cognitive tasks. However, the locus of these group differences is unclear because reaction times reflect the influence of peripheral processes (e.g., motor output) and central processes (e.g., basic cognitive efficiency), which have been independently implicated as being impaired in children with ADHD. This study sought to examine the degree to which these processes contribute to group differences in reaction times on a four-choice cognitive task by taking advantage of the differential effect of practice on central but not peripheral demands. That is, when external task demands are held constant, peripheral processing demands are believed to be relatively stable across a task and central processing demands are thought to decrease with practice as participants become increasingly efficient at completing a task. Results revealed that children with ADHD responded more slowly than controls throughout the task, and that children with ADHD did not show greater improvement relative to controls as central demands diminished. Implications and future directions of the results are discussed.

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Introduction

Between three and seven percent of school age children meet the diagnostic criteria for attention-deficit/hyperactivity disorder (ADHD), making ADHD one of the most prevalent childhood mental disorders (American Psychiatric Association [DSM-IV-TR], 2000; Ford, Goodman, & Meltzer, 2003; Froehlich et al., 2007). Children are diagnosed with ADHD based on the presence of developmentally inappropriate levels of inattention, hyperactivity, and/or impulsivity which cause impairment in two or more settings (DSM-IV-TR, 2000). Although many children experience at least a partial remission of symptoms with age, at least 30% of children with ADHD continue to exhibit the disorder into adulthood (Wilens, Biederman, & Spencer, 2002). Children with ADHD face proximal risks for academic underachievement and impairments in peer relationships during elementary school (Hoza et al., 2005; Landau & Moore, 1991), and they face serious distal risks for negative outcomes in adolescence and adulthood, including substance abuse, delinquency, and relationship difficulties (for a review, see Barkley, 2003). In addition to the high costs for treatment incurred by individuals with ADHD and their families, the societal cost of childhood and adolescent ADHD alone is estimated to be between $36 and $52 billion dollars annually, given a 5% prevalence rate (Pelham, Foster, & Robb, 2007).

To date, extensive research has focused on identifying the nature and etiology of ADHD. Establishing a clearer etiology may pave the way for more targeted treatments designed to address core symptoms of ADHD, or at least symptoms that are amenable to intervention, rather than treating factors that are less central to the disorder. One principal vein of ADHD research has focused on identifying the cognitive deficits that may underlie ADHD, particularly deficits in executive function (EF) skills such as working memory, inhibitory control, and attention set-shifting (Barkley, 1997; Diamond, 2005). Overall, these studies suggest that although EF deficits characterize a substantial proportion of children with ADHD, the majority of children with ADHD do not exhibit significant EF deficits (Nigg, Willcutt, Doyle, & Sonuga-Barke, 2005).

Given that EF deficits are neither necessary nor sufficient to account for the etiology of ADHD (Nigg et al., 2005; Willcutt, Doyle, Nigg, Faraone, & Pennington, 2005), some researchers have begun to speculate whether impairments in more basic cognitive processes, such as decision making or motor output, may underlie ADHD-related deficits. Indeed, children with ADHD tend to respond more slowly than typically developing children across a number of simple cognitive tasks (e.g., Douglas, 1999; Lijffijt, Kenemans, Verbaten, & van Engeland, 2005; Oosterlaan, Logan, & Sergeant, 1998; Shanahan et al., 2006), supporting the inference that impairments in basic cognitive efficiency (e.g., Pennington & Ozonoff, 1996) may underlie ADHD-related deficits. Yet one of the difficulties in interpreting the cause of slow reaction times observed among children with ADHD is that reaction time is not a clean measure of a single process (see Luce, 1986, for a review). Indeed, even reaction times generated in minimally cognitively demanding tasks reflect the contribution of at least two broad factors: (1) central processing efficiency, which is reflected in the speed with which participants make decisions; and (2) peripheral processing efficiency, or the speed of non-decision processes (i.e., stimulus perception and motor execution; see, e.g., Donkin, Brown, & Heathcote, 2011). In addition, central and peripheral processes are also differentially susceptible to changes in task demands, such as number of response choices (Hick, 1952; Hyman, 1953) or amount of motor force (for a review, see Sanders, 1998), respectively. Group difference in simple reaction times, then, might not be due to differences in the central processing efficiency, but to impairments in peripheral processes, a supposition which is bolstered by evidence of motor output deficits in children with ADHD (see Harvey & Reid, 2003, for a review).

Central and peripheral processing impairments have been found in children with ADHD. However, these impairments have largely been studied separately, thereby making their unique contributions to reaction time deficits in children with ADHD unclear. The present study will extend previous research by comparing the degree to which peripheral and central processes contribute to slow reaction times in children with ADHD, thereby creating the potential for isolating more specific deficits that contribute to slow processing speed in this population. In the present study, the contribution of central and peripheral processes to group differences in processing speed will be evaluated by comparing group differences in mean reaction times across a four-choice cognitive task (i.e., the Serial Reaction Time task [SRT]). That is, the cognitive demands involved in simple tasks are thought to be greatest initially, when participants are forming stimulus-response associations (for a review, see Luce, 1986). However, these demands decrease with practice, which is reflected by a concomitant decrease in mean reaction time (for reviews, see Luce, 1986; Ritter, Baxter, Kim, & Srinivasmurthy, in press). Therefore, if cognitive processing speed deficits contribute to slow reaction times in children with ADHD, the influence of these deficits on mean reaction time should be evident at the start of the SRT task, when cognitive demands are relatively high, but not at the end of the task, when participants have completed a large number of trials and cognitive demands are relatively minimal. In contrast, the length of time needed to execute a motor response is not expected to decrease across the course of the task (for a review, see Anderson, 1995), and therefore, if motor speed deficits contribute to slow reaction times in children with ADHD, group differences in mean reaction time should be apparent throughout the task. This study will contribute to the growing research literature pinpointing the etiology of ADHD, thereby supporting the development of more targeted treatments for children with ADHD.

In the following sections, prior research is reviewed to provide a foundation for the present study and its hypotheses. First, theoretical models and data are presented that implicate executive function deficits as an important cognitive mechanism in ADHD. Next, data will be reviewed which suggest that widespread EF deficits in a significant proportion of children with ADHD may be explained by a more general cognitive inefficiency that has primarily been indexed by slow processing speed. Then, because any given RT is the culmination of a series of cognitive processes (e.g., Luce, 1986), I will discuss the cognitive processes that contribute to reaction times and review the results of recent studies that have attempted to parse these processes using mathematical models. Last, theoretical models and data will be presented that suggest that difficulties in motor output may contribute to slow reaction times in children with ADHD. Following this literature review, I describe the research plan and hypotheses of the present study, which is designed to evaluate the degree to which motor speed and cognitive processing speed contribute to slow processing speed in children with ADHD.

Executive Functioning in ADHD

Much of the evidence of slow responding in children with ADHD emerged as a byproduct of research into executive functioning (EF) deficits in this population. Executive functioning is the higher-order capacity to flexibly engage specific cognitive processes in order to perform goal-directed problem-solving activities and adapt to new, complex situations (see Banich, 2009) that includes but is not limited to 1) Set-shifting, the ability to flexibly shift attention to different features of a task and avoid perseveration, 2) working memory, the ability to hold and update information in mind in order to use it for reasoning and problem-solving, and 3) inhibition, the ability to withhold a predominant response in order to initiate an alternative response (Huizinga, Dolan, & van der Molen, 2006; Miyake et al., 2000). Dominant theoretical perspectives on the etiology of ADHD (e.g., Barkley, 1997; Diamond, 2005) have argued that deficits in one or more EFs are the source of observed behavioral, academic, and social difficulties in children with ADHD. Response inhibition and working memory have been the main focus of EF research in children with ADHD due to their proposed centrality to the disorder (e.g., Barkley, 1997; Diamond, 2005). In addition to deficits in response inhibition (Nigg, 2001; Oosterlaan et al., 1998) and working memory (Martinussen, Hayden, Hogg-Johnson, & Tannock, 2005), set-shifting (J. A. Sergeant, Geurts, & Oosterlaan, 2002), and planning (Pennington & Ozonoff, 1996) have also been implicated as impaired in children with ADHD (see Willcutt, Doyle et al., 2005, for a review).

Although etiological theories that identify EF deficits as the primary cause of ADHD appear, on the surface, to provide a parsimonious explanation of ADHD symptomatology, overall empirical studies have not supported the centrality of EF deficits to the etiology of ADHD. Indeed, two recent papers concluded that EF deficits are neither a necessary nor a sufficient etiology to account for ADHD symptomatology based in part on findings that: (1) only 31% of children with ADHD exhibit impairment across multiple EFs (compared to 9% of control children), which indicates that EF deficits are not necessary to the etiology of ADHD (Nigg et al., 2005); and (2) effect sizes of differences in EF in children with and without ADHD are moderate and highly variable (from $d = 0.4$ to 0.7) , suggesting that EF deficits alone are not a sufficient explanation to account for ADHD symptomatology (Nigg et al., 2005; Willcutt, Doyle et al., 2005). Acknowledging that EF deficits are not likely the sole cause of ADHD, more recent etiological theories suggest that the current model of ADHD is likely representative of multiple partially-overlapping disorders with multiple causal pathways, rather than one disorder with a single causal pathway (Castellanos, Sonuga-Barke, Milham, & Tannock, 2006; Nigg et al., 2005; Sonuga-Barke, 2005). As the thrust of research in the field shifts away from homogeneous causal models that focus on EF deficits as the sole source of impairment in ADHD, researchers have begun to consider whether other, more general processes may account for a significant portion of the remaining variance in the etiology of ADHD (Castellanos et al., 2006; Pennington & Ozonoff, 1996).

Evidence of Slow Processing Speed in Children with ADHD

Paper-and-pencil and computerized neuropsychological tasks are frequently used to quantify and compare cognitive abilities in children with and without ADHD. In this section, the literature on processing speed in children with ADHD, as measured by the speed with which individuals execute cognitive operations in the course of completing simple tasks (e.g., Deary, Johnson, & Starr, 2010), will be reviewed. On paper-and-pencil tasks, processing speed is typically quantified by either the amount of time needed to complete all task items or by the total items completed in a set amount of time. In simple computerized neuropsychological tasks, speed of responding is summarized via mean reaction time data, which reflects the average speed with which participants respond to each stimulus presented across a given task. Overall, studies have found that children with ADHD generally tend to respond more slowly than controls across simple paper-and-pencil and computerized neuropsychological tasks (e.g., Pennington & Ozonoff, 1996; Shanahan et al., 2006).

In ADHD research, processing speed is often measured via one or both subtests of the Processing Speed Index of the Wechsler Intelligence Scale for Children (WISC; i.e., Coding and Symbol Search; Wechsler, 1974, 1991, 2003). The WISC is an intellectual testing battery comprised of multiple tasks of varying degrees of complexity designed to evaluate different cognitive abilities in children (Wechsler, 2003). The Coding and Symbol Search tasks measure processing speed based on the number of items participants complete within a set amount of time (Wechsler, 2003). Generally, studies that have included one or both of these measures have found that children with ADHD are significantly slower than controls on the Coding and/or Symbol Search subtests (Chhabildas, Pennington, & Willcutt, 2001; Pennington & Ozonoff, 1996; Shanahan et al., 2006; Tillman, Bohlin, Sørensen, & Lundervold, 2009; Willcutt, Pennington, Olson, Chhabildas, & Hulslander, 2005).

Evidence of group differences has also been found on other simple neuropsychological tasks in which performance is largely based on processing speed, such as the Trailmaking (Reitan & Wolfson, 1985) and Stroop (Stroop, 1935) tasks. There is mixed evidence as to whether children with ADHD are slower than controls on the Trailmaking task (Chhabildas et al., 2001; Dykman & Ackerman, 1991; Sartory, Heine, Müller, & Elvermann-Hallner, 2002; Shanahan et al., 2006; Shue & Douglas, 1992; Willcutt, Pennington et al., 2005). However, children with ADHD are significantly slower than controls on the Stroop task (Homack & Riccio, 2004; van Mourik, Oosterlaan, & Sergeant, 2005), including assessments of baseline speed of word reading and color naming speeds (Homack & Riccio, 2004; Houghton et al., 1999; Nigg, Blaskey, Huang-Pollock, & Rappley, 2002; Savitz & Jansen, 2003; van Mourik et al., 2005). The latter finding is bolstered by rapid automatized naming (Denckla & Rudel, 1974) studies, which have likewise found that children with ADHD tend to be significantly slower than controls in quickly reading words and naming colors (e.g., Carte, Nigg, & Hinshaw, 1996; Shanahan et al., 2006). Thus, evidence from traditional neuropsychological tasks suggests that children with ADHD generally respond more slowly than typically developing controls.

Although data on the total time or total items completed on a task yield valuable, albeit general, information about participants' speed of responding on a given task, reaction time data generated through computerized tasks, such as choice reaction time tasks and dual task paradigms (e.g., SSRT and Go/No-Go), provide more exact estimates of processing speed. Although some studies have failed to find group differences in mean reaction times on cognitive tasks (e.g., Wodka et al., 2007; see Klein, Wendling, Huettner, Ruder, & Peper, 2006), overall, there is strong evidence that children with ADHD exhibit slower responding in speeded reaction time tasks compared to typically developing controls (e.g., Alderson, Rapport, & Kofler, 2007; Andreou et al., 2007; Cardy, Tannock, Johnson, & Johnson, 2010; Lijffijt et al., 2005; Oosterlaan et al., 1998).

On the whole, results of pen-and-paper and computerized neuropsychological indices of processing speed generally support the conclusion that children with ADHD exhibit processing speed deficits (e.g., Alderson et al., 2007; Lipszyc & Schachar, 2010). However, because reaction times reflect the contribution of multiple interacting cognitive processes, the interpretation of group differences in mean reaction times is not necessarily straightforward.

Cognitive Components of Reaction Times

Researchers have used reaction times to reflect processing speed for over a century (e.g., Donders, 1868/1969; for a review, see Luce, 1986). However, reaction times did not become a ubiquitous dependent variable in psychology until after the cognitive revolution in the 1950's, which shifted the focus of research in experimental psychology away from stimulus-response relationships and toward the examination of mental processes and their influence on behavior (for reviews, see Luce, 1986; Proctor & Vu, 2006; Sanders, 1998). The shift also inspired a resurgence of information processing models which characterize the flow of information between the presentation of a stimulus and measurement of a response (e.g., Shannon & Weaver, 1949; Sternberg, 1969; for a review, see Sternberg, 2011). Most classical models of information processing share the assumption that human information processing consists of at least three stages: first, information about a stimulus is perceived (stimulus perception); second, centralized processes integrate that information in order to make a decision (response selection); and third, a response is engaged (motor execution; for a review, see Proctor & Vu, 2003; cf. Spivey & Dale, 2006). These basic processes are thought to be differentially susceptible to changes in task demands (for a review, see Sanders, 1998). Indeed, one of the few laws in psychology, the Hick-Hyman law (Hick, 1952; Hyman, 1953), states that increasing the number of response alternatives produces a logarithmic increase in the length of reaction times resulting, in theory, from the increased decision time needed to choose between a larger number of alternatives (McMillen & Holmes, 2006; Proctor & Vu, 2008). Accordingly, even reaction times generated from the simplest tasks are composite measures of the duration of multiple basic cognitive processes that are susceptible to changes in task demands (see Luce, 1986).

Sequential Sampling Models of Decision Making

A different, although not necessarily contradictory, approach to conceptualizing information processing is that of mathematical models of decision making known as sequential sampling models (for reviews, see Ratcliff & Smith, 2004; Smith, 2010). Like traditional information processing models, sequential sampling models assume that perceptual, cognitive, and motor processes contribute to reaction times. However, unlike information processing models, sequential sampling models do not explicitly divide decision making into stages, focusing instead on characterizing the central decision making process and the factors that influence it (for a review, see Sanders, 1998). Specifically, sequential sampling models assume that decision making occurs via a stochastic process in which noisy information about a stimulus accumulates over time until it reaches a response boundary, resulting in the initiation of a motor response (e.g., Ratcliff, 1978; Usher & McClelland, 2001; for reviews, see Donkin et al., 2011; Luce, 1986). Sequential sampling models are able to accurately characterize reaction time and accuracy data from a number of simple cognitive tasks, including perceptual judgment, signal detection, memory, lexical decisions, and visual search tasks (Ratcliff, Gomez, & McKoon, 2004; Ratcliff, Thapar, Smith, & McKoon, 2005; Smith & Ratcliff, 2009; Usher & McClelland, 2001; Wagenmakers, Ratcliff, Gomez, & McKoon, 2008; for reviews, see Ratcliff & Smith, 2004; Wagenmakers, 2009). Additionally, although the majority of studies have applied sequential sampling models to reaction time data from two-choice tasks, some models have also been successfully applied to data from tasks involving multiple (i.e., more than two) alternatives (e.g., Ditterich, 2010; Leite & Ratcliff, 2010; Usher & McClelland, 2001).

A number of sequential sampling models have been developed to account for reaction time data, including the drift diffusion model (Ratcliff, 1978; Ratcliff & Rouder, 1998) and the leaky competing accumulator model (Usher & McClelland, 2001), among others (e.g., Brown & Heathcote, 2005; Brown, Marley, Donkin, & Heathcote, 2008; Busemeyer & Townsend, 1993; Ratcliff & Smith, 2004; Smith & Vickers, 1988; Vickers, 1970; for a review, see Smith, 2010). Although there are differences between these models, common among them are three primary parameters: drift rate (v), non-decision time (t_{er}), and boundary separation (a; for reviews of these and other parameters, see McMillen & Holmes, 2006; Ratcliff & Smith, 2004; Usher & McClelland, 2001; Vandekerckhove & Tuerlinckx, 2007). Drift rate represents the speed in which information about a stimulus accumulates toward a response boundary (i.e., decision speed; Ratcliff, 1978). Boundary separation indexes the distance between response boundaries, which affects drift rate and reflects participants' speed-accuracy trade-off (e.g., small boundary separation leads to faster decisions but poorer accuracy; Vandekerckhove & Tuerlinckx, 2007).The aptly named non-decision time parameter indexes the amount of time devoted to processes which are not involved in making a decision (e.g., encoding, motor execution; Ratcliff & Smith, 2004). By separating reaction times into decision and non-decision components, sequential sampling models are able to distinguish central and peripheral processing factors which may have otherwise be obscured by traditional descriptive statistics (e.g., Bogacz, Wagenmakers, Forstmann, & Nieuwenhuis, 2010; Ratcliff & McKoon, 2008; Voss, Rothermund, & Voss, 2004).

Despite these benefits, sequential sampling models have yet to achieve widespread use in psychology due in large part to their statistical intractability (e.g., van Ravenzwaaij & Oberauer, 2009; Vandekerckhove & Tuerlinckx, 2007). To date, there have been two studies that have used a sequential sampling model (i.e., the diffusion model; Ratcliff, 1978) to characterize the reaction time distributions of children with ADHD (i.e., Huang-Pollock, Karalunas, Tam, & Moore, 2012; Mulder et al., 2010). The first study involved a perceptual decision making task, and the second was a meta-analysis of the continuous performance task in ADHD research. Both studies found evidence that children with ADHD exhibit deficits in central rather than peripheral processes (Huang-Pollock et al., 2012; Mulder et al., 2010). Thus, sequential sampling models may be promising options for decomposing the reaction time distributions of children with ADHD.

Evidence of Motor Deficits in Children with ADHD

Although impairments in central processing speed may underscore slow processing speed in children with ADHD, there is additional research that suggests that the motor processing demands involved in a task may be more important determinants. ADHD has long been associated with motor functioning difficulties. Indeed, motor impairments were first identified as a central feature of ADHD in the early conceptualizations of the disorder, when ADHD was thought to arise from general cognitive deficits described as “minimal brain dysfunction” (see Barkley, 1999, for a review). At that time, children with minimal brain dysfunction were thought to have central nervous system impairments which were expressed primarily as symptoms of inattention, hyperactivity, and motor control problems (Kalverboer, 1993). The current dominant diagnostic classification systems (i.e., the DSM-IV-TR and ICD-10) maintain separate diagnoses for people with motor problems (i.e., developmental coordination disorder and specific developmental disorder of motor functioning, respectively) and those exhibiting problems with inattention, impulsivity and hyperactivity (i.e., ADHD and hyperkinetic disorder, respectively). However, a Swedish research group has developed and continues to conduct research into the utility of an alternative classification of ADHD known as “Deficits in Attention, Motor control, and Perception”, which combines symptoms of ADHD with those of developmental coordination disorder (for reviews, see Gillberg, 1992, 2003). Hence, there is some ongoing debate about the degree to which motor control deficits are associated with ADHD, and the nature of the interface between motor control deficits and the core attention deficits and hyperactivity that define ADHD.

Mainstream theories of ADHD have also identified the relationship between ADHD and motor deficits. For example, Barkley (1997) proposed that motor problems are secondary to core symptoms of the ADHD, but are nonetheless part of the disorder. According to Barkley (1997), behavioral inhibition, the core deficit in ADHD, underlies deficits in executive functioning which, in turn, result in motor problems. Indeed, several studies have found evidence to support the claim that the ADHD symptom severity is predictive of motor difficulties (Piek et al., 1999; Tseng, Henderson, Chow, & Yao, 2004). Frontal-striatal deficit theories of ADHD have proposed that frontal-striatal dysfunction underlies ADHD symptoms as well as motor problems (e.g., Sagvolden, Johansen, Aase, & Russell, 2005). Indeed, research suggests that children with ADHD exhibit a pattern of deficits in rhythmic motor responding reminiscent of that observed in patients with Parkinson’s disease (Ben-Pazi, Gross-Tsur, Bergman, & Shalev, 2003) and which has, in the latter group, been linked with dopaminergic dysregulation in frontal-striatal neural circuitry (Bergman & Deuschl, 2002; Logigian, Hefter, Reiners, & Freund, 1991). Other theorists have speculated that deficits in ADHD related to timing and variability of motor responses may be the result of malformation or malfunctioning of the cerebellar region of the brain (Castellanos & Tannock, 2002). Although structural and functional evidence indicates that children with ADHD exhibit deficits in multiple brain regions which may contribute to poor motor performance, few studies have explicitly tested the structural and/or functional correlates of motor problems in children with ADHD (Brossard-Racine, Majnemer, & Shevell, 2011).

Consistent with the hypothesis that motor control is often impaired in ADHD, descriptive research indicates that motor performance problems are common among children with ADHD. Indeed, approximately 50 percent of children with ADHD may experience motor problems (Barkley, 1990; Hartsough & Lambert, 1985; Piek et al., 1999), including problems in fine motor functioning (Brossard-Racine, Majnemer, Shevell, Snider, & Bélanger, 2011; Douglas, 1972; Pitcher, Piek, & Hay, 2003; Tseng et al., 2004; Whitmont & Clark, 1996), handwriting (Brossard-Racine, Majnemer, Shevell et al., 2011) gross motor functioning (Carte et al., 1996; Harvey et al., 2007; Tseng et al., 2004), and motor coordination (Harvey & Reid, 1997). In addition, it is estimated that between 30-50% of children with ADHD meet diagnostic criteria for developmental coordination disorder (Kadesjo & Gillberg, 1998; Kaplan, Wilson, Dewey, & Crawford, 1998; Pitcher et al., 2003).

Children with ADHD may exhibit deficits in one or more output-related variables that contribute to their speed of motor responding. In an initial study, Sergeant and Scholten (1985a) found that children with ADHD did not exhibit deficits in input-related processes, but they did show evidence of a speed-accuracy trade-off. In a follow-up study, Sergeant and Scholten (1985b) manipulated the degree to which task instructions emphasized the importance of speed or accuracy and found that children with ADHD exhibit a deficit in response output, in that they were not able to effectively adjust their strategy for completing the task to emphasize speed or accuracy in accordance with task instructions. However, because the speed-accuracy trade-off is linked to both response selection and response output (e.g., Rinkenauer, Osman, Ulrich, Müller-Gethmann, & Mattes, 2004), poor speed-accuracy trade-off in children with ADHD may not be specific to the response output stage, per se. Nonetheless, other studies have demonstrated that children with ADHD are differentially susceptible to task demands that affect output-related processes, including manipulations of stimulus-response compatibility (van der Meere, van Baal, & Sergeant, 1989; although see Oosterlaan & Sergeant, 1995; van der Meere, Vreeling, & Sergeant, 1992), event rate (e.g., Carte et al., 1996; Klimkeit, Mattingley, Sheppard, Lee, & Bradshaw, 2005; van der Meere et al., 1992), and timing production (e.g., Van Meel, Oosterlaan, Heslenfeld, & Sergeant, 2005). Thus, research suggests that children with ADHD may exhibit deficits in one or more output-related processes, but cognitive studies have yet to consistently demonstrate a locus of delayed motor responding in children with ADHD. Overall, these findings indicate that group differences in reaction times may not be due to a deficit in central processing efficiency (as noted in the preceding section), but rather may be the result of slowed motor speed.

Summary

Children with ADHD respond more slowly than typically developing controls across a variety of simple tasks (e.g., Douglas, 1999; Lijffijt et al., 2005; Oosterlaan et al., 1998; Shanahan et al., 2006), implicating a deficit in central processing in children with ADHD. Additional research suggests that children with ADHD may exhibit deficits in motor output (e.g., Barkley, 1990; Hartsough & Lambert, 1985; Piek et al., 1999). However, because these factors have largely been studied separately, the relative contribution of central processing speed and motor speed to slow reaction times in children with ADHD is unknown.

The overall goal of the present study is to better assess and document the degree to which central processing speed and motor speed deficits underlie the pattern of slow reaction times that are characteristic of children with ADHD across simple cognitive tasks. In the present study, cognitive processing speed and motor speed were assessed using a reaction time data from the serial reaction time (SRT) task, a four-choice implicit sequence learning task. Consistent with previous research, I expect that children with ADHD will exhibit deficits in both central processes (Huang-Pollock et al., 2012; Mulder et al., 2010) and peripheral processes (Barkley, 1990; Hartsough & Lambert, 1985; Piek et al., 1999). Specifically, if children with ADHD exhibit deficits in motor speed, it is expected that children with ADHD will respond more slowly than controls throughout the task. Further, children in both groups are expected to respond more quickly as the task progresses. However, if children with ADHD exhibit deficits in central processing speed, it is expected that the magnitude of the predicted decrease in mean reaction time across the task will be greater for children with ADHD than for controls.

Methods

Sample and Participant Selection

Children between the ages of 8 and 12 (*M* = 10.40, *SD* = 1.36) with ADHD (*n* = 66, 42 males) and without ADHD (*n* = 43, 21 males) were recruited from the Central Pennsylvania, York, and Central Dauphin area. Recruitment was conducted through advertisements in local newspapers, postings on online community message boards, flyers posted in doctor's offices and community centers, flyers sent home with all children at schools, and radio advertisements.

Children were excluded from participation in the study if they met any of the following criteria, based on parent report: estimated Full Scale IQ (FSIQ) < 80, Pervasive Developmental Disorder, psychosis, frank neurological disorder, or sensorimotor impairment that would prevent them from fully participating in the study. Control children, although not children with ADHD, were required to have IQs < 110 in order to control for the potential confound of high IQ in children with few ADHD symptoms. Children taking non-stimulant psychotropic medication were excluded from the study. Children taking stimulant medications were only included in the study if their parents were willing to refrain from giving their children stimulant medication for at least 24 hours before the day of testing and on the day of testing itself.

Screening Procedure

Participants were screened into the study based upon whether they met three levels of increasingly stringent screening criteria. At the first and broadest level, parents who expressed interest in the study were contacted via phone and administered a brief phone screening in order to determine whether their child met criteria for the study. Parents whose children met criteria and who consented to participate in the study were mailed one set of questionnaires to fill out and another set of questionnaires for their child's teacher to complete. Only one parent was permitted to complete the questionnaires. If a child was taking ADHD medication, their parent was asked to rate their child's behavior off medication. All parents and teachers completed the ADHD Rating Scale-IV (ADHD-RS; DuPaul, Power, Anastopoulos, & Reid, 1998), the

Behavioral Assessment Scale for Children (2nd ed.; BASC-2; Reynolds & Kamphaus, 2004), and the Conners' Rating Scales-Revised (CRS-R; Conners, 1997). The ADHD-related scales used to determine eligibility for the sample include the BASC Hyperactivity and Attention Problem subscales; the CRS-R Hyperactivity, Cognitive Problems/Inattention, and ADHD Index subscales; and the total ADHD-RS scale. In keeping with the methods used in the DSM-IV field trial (Lahey et al., 1994), a symptom was considered "present" if either a parent *or* teacher indicated that it occurred "often" or "very often" on these scales.

Validation Process for Participant Selection and Sub-grouping

Children who were determined to be eligible for possible inclusion in the study in the ADHD or non-ADHD control groups were scheduled for a three-hour visit in our laboratory. During this visit, the same parent who filled out the initial questionnaires completed a structured clinical interview (i.e., the National Institute of Mental Health's Computerized Diagnostic Interview Schedule for Children-Version 4 [CDISC-IV]). The preliminary sample was narrowed into the final sample based on data obtained through questionnaires and the CDISC-IV.

To be included in the final ADHD sample, children were required to: (1) have scored above the 85th percentile on at least one ADHD-related subscale of the BASC or CRS-R based on parent report; (2) have scored above the 85th percentile on at least one of the ADHD-related subscales of the BASC or CRS-R based on parent *and* teacher report; and (3) meet DSM-IV-TR criteria (DSM-IV-TR, 2000) for the inattentive (ADHD-IA) or combined (ADHD-C) ADHD subtypes, as determined by parent report on the CDISC-IV and teacher report on the ADHD-RS. Specifically, children whose parent or teacher endorsed six or more inattentive symptoms and less than five hyperactive-impulsive symptoms on the CDISC-IV (parent report) or ADHD-RS (teacher report), respectively, were diagnosed with ADHD-IA, and children who presented with six or more inattentive symptoms and six or more hyperactive-impulsive symptoms were diagnosed with ADHD-C. In an attempt to prevent misclassification of children with ADHD (see Lahey et al., 1994) and to establish homogeneous subtypes, children with subthreshold ADHD-C (i.e., children with 6 or more symptoms of inattention, and 5 symptoms of hyperactivity, or children with 6 or more symptoms of hyperactivity and 5 symptoms of inattention) were excluded from the study. To be diagnosed with ADHD children were required to: (1) meet symptom criteria in the six months prior to diagnosis, (2) meet age of onset criteria (i.e., some symptoms present before age 7), and (3) exhibit impairment in multiple settings, including clinically significant impairment in at least one setting.

To be eligible for the non-ADHD control group, children were required to: (1) have fewer than three inattentive symptoms, fewer than three hyperactive/impulsive symptoms, or fewer than four total ADHD symptoms as endorsed by their parent *or* their teacher on the ADHD-RS; (2) score below the 80th percentile on all five ADHD-related subscales of the BASC and CRS-R based on parent *and* teacher report; (3) not meet criteria for ADHD as determined by parent report on the CDISC-IV and teacher report on the ADHD-RS; and (4) have not been previously diagnosed with ADHD based on parent report.

Laboratory Assessment Procedures

Children and their parents came into the laboratory for two three-hour visits, spaced at least one week apart. During their first visit, a child and her or his parent were each paired with a trained undergraduate or graduate research assistant and led into separate testing rooms. Upon entering the testing room, the research assistant reviewed the consent form with the parent and the parent provided written consent to participate in the study. The parent then completed a structured clinical interview (i.e., the CDISC-IV). If a child was taking medication for ADHD, her or his parent was asked to answer questions about the child's functioning off medication.

Meanwhile, in the second room, another research assistant briefly reviewed the purpose and procedures of the study with the child and answered any questions that she or he had about the study. The child then provided her or his verbal assent to participate in the study. After assenting to participate, the child completed subtests of the WISC-IV, followed by a series of computerized cognitive tasks, including the Serial Reaction Time task. The research assistant administered all measures and was in the room with the child throughout the entire testing session.

During the second visit, the parent waited in the lobby and completed any remaining questionnaires while her or his child completed additional pencil-and-paper tasks and computerized cognitive tasks. Parents and teachers received monetary compensation for their time. In addition, parents who completed the laboratory visit received informal verbal feedback about their child's performance, and children received a small toy for participating.

Measures

ADHD Rating Scale-IV (ADHD-RS). The ADHD-RS is an ADHD symptom checklist commonly used to obtain information from parents and teachers in order to aid in the assessment of children with ADHD. Each of the 18 items on the questionnaire corresponds with a symptom of ADHD in the DSM-IV-TR. Symptoms are rated on a four-point Likert scale based on the frequency with which they occur: (0) never/rarely, (1) sometimes, (2) often, and (3) very often (DuPaul et al., 1998). In this study, a symptom was considered to be present if the parent or teacher endorsed it as occurring (2) often, or (3) very often. Parent ratings on the ADHD-RS have been shown have good test-retest reliability (*r* = .78-86) and internal consistency reliability (*r* = .86-.92; Collett, Ohan, & Myers, 2003). Teacher ratings on the ADHD-RS have yielded higher test-retest reliability (*r* = .88-.90) and internal consistency reliability (*r* = .88-.96) relative to teacher ratings (Collett et al., 2003).

Behavioral Assessment Scale for Children-2 (BASC-2). The BASC-2 is a behavioral checklist which is used to assess a broad range of adaptive (e.g., social skills, adaptability) and maladaptive (e.g., aggression, anxiety, hyperactivity, inattention) behaviors displayed by children in the school setting and outside of school (Reynolds & Kamphaus, 2004). Data were compiled from ratings obtained by the parents via the Parent Rating Scale (PRS) and from teachers via the Teacher Rating Scale (TRS). The BASC-2 parent and teacher rating scales yield high test-retest reliability coefficients (i.e., *r* = .84 and *r* = .86, respectively; Reynolds & Kamphaus, 2004). Depending on the age of the child, her or his parent and teacher completed either the BASC-2 for children ages 6-11 or for youth ages 12-21.

Conners' Rating Scales-Revised (CRS-R). The CRS-R is a behavioral rating scale frequently used in the assessment of ADHD and similar behavior problems in children (Conners, 1997). Similar to the ADHD-RS, behaviors are rated on a four-point Likert scale—from (1) Not at all to (4) Very often—based on the frequency with which occur. In the present study, parents completed an 80-item long form with test-retest reliabilities from 0.57 to 0.85, and teachers completed a 28-item short form with test-retest reliabilities from 0.75 to 0.92 (Conners, 1997).

Computerized Diagnostic Interview Schedule for Children (fourth edition; CDISC-IV). The CDISC-IV is a computerized structured diagnostic interview used to assess the presence of DSM-IV-TR symptom criteria for disorders in children (Shaffer, Fisher, Lucas, & Comer, 2000). In the present study, trained undergraduate and graduate student research assistants administered the CDISC-IV to each child's parent during a 3-hour laboratory session. Parents whose children were prescribed ADHD medication were asked to rate their child's behavior off medication. The CDISC-IV program contains a number of modules that evaluate whether children have met DSM-IV-TR symptom criteria for a particular disorder in the past month, the past 6 months, the last year, and/or in their lifetime. In the present study, the CDISC-IV modules that were administered included the ADHD module and modules for disorders that are commonly comorbid with ADHD (i.e., anxiety, mood disorders, tic disorder, oppositional defiant disorder, and conduct disorder). The schizophrenia module of the CDISC-IV was also administered, in order to provide an additional screen for symptoms of psychosis.

Wechsler Intelligence Scale for Children-IV (WISC-IV). Estimated full scale intelligence quotient (FSIQ) was calculated using a two-subtest short form of the Wechsler Intelligence Scale for Children-IV (WISC-IV), which was comprised of the Matrix Reasoning and Vocabulary subtests (Wechsler, 2003). This estimated FISQ composite has high reliability (r = .93) and high predictive validity of FSIQ (r = .87; Sattler, 2008).

Serial Reaction Time. The Serial Reaction Time (SRT) task is a self-paced computerized task designed to measure implicit sequence learning (Nissen & Bullemer, 1987) . In this task, participants view a series of stimuli which are briefly presented in one of four horizontally-arranged locations on a computer screen. After each stimulus appears, participants press a key corresponding to the location of the stimulus. In the present study, participants were randomly assigned to one of two conditions, which differed in the order in which stimuli were presented but not in the length of the sequence (i.e., eight items) or the number of times each response option was presented per sequence (i.e., twice per sequence). Participants were not told that they were repeatedly viewing the same sequence of items. Participants completed five blocks of 160 trials each (i.e., 800 total trials).

Performance Measures

Reaction time (RT) and accuracy data were collected during the Serial Reaction Time (SRT) task. A total of eight participants (5 ADHD, 3 control) who obtained less than 80% accuracy across all blocks or within one or more blocks were excluded from analyses. One participant who completed less than half of the task (i.e., 318 out of 800 trials) and another whose data contained a reaction time that was approximately 5 minutes long were also excluded from analyses (both participants were in the ADHD group).

The first trial in each block was excluded from analyses in order to limit the possibility that task instructions carried over into the experiment in block 1 and to establish an equal number of trials in blocks in blocks 2 through 5 relative to block 1. Block mean reaction times and mean reaction time overall were calculated by averaging the remaining reaction times (i.e., 159 RTs per block, 795 total RTs) by block and across the entire task, respectively. All reaction time values were natural log-transformed to normalize the distribution.

Group differences motor speed were evaluated by testing for a main effect of group on log mean RT. Group differences in central processing speed were assessed by evaluating the degree to which any initial group differences in mean reaction time diminished across the task (i.e., the interaction between diagnostic group and block on log mean RT).

Statistical Analyses

Mean reaction time data were analyzed with a 2 (group) x 5 (block) mixed-model analysis of variance (ANOVA; with Greenhouse-Geisser correction when the sphericity assumption was violated) with group (ADHD vs. control) as the between subjects factor and block (1 – 5) as the within subjects factor. Significant main effects or interactions were subjected to post-hoc contrasts.

Hypothesis 1: Children with ADHD will exhibit significantly slower motor speed than controls.

If hypothesis 1 is true, I expect to find a main effect of group. Further, I anticipate that post hoc-contrasts will reveal significant group differences in log mean RT in each block, such that children with ADHD responded more slowly than controls throughout the task.

Hypothesis 2: Children with ADHD will exhibit significantly slower central processing speed than controls.

If hypothesis 2 is true, I expect a main effect of block and an interaction between group and block. Specifically, I expect that all children would respond more quickly as the task progressed, but post hoc contrasts will reveal that the magnitude of this decrease in log mean RT was greater for children with ADHD than for controls.

Results

Participant Characteristics

Children in the ADHD group exhibited significantly greater symptoms of inattention, hyperactivity, and impulsivity than did control children based on parent and teacher reports (all *p* values < .001; see Table 1). No significant group differences were observed for gender, $F(1,107)= 2.35$, $p= .13$, $\eta_p^2= .02$, or FSIQ, $F(1,107)= 2.01$, $p= .16$, $\eta_p^2= .02$. Significant group differences were found for age, $F(1, 107)= 6.17$, $p= .02$, $\eta_p^2= .06$, with controls being older than children with ADHD (see Table 1), therefore all subsequent analyses were conducted with age as a covariate. No significant effects of age or gender were found for FSIQ (*p*s > .05).

Reaction Time

SRT Condition. A one-way analysis of covariance confirmed that, controlling for age, the SRT condition to which participants were assigned did not differ between groups, $F(1,106)= 2.34$, $p= .13$, $\eta_p^2 = .02$. Furthermore, SRT condition was not significantly associated with between subject differences in log mean RT, $F(1,106)= 0.16$, $p= .69$, $\eta_p^2 = .002$, or accuracy, $F(1,106)= 0.04$, $p= .85$, $\eta_p^2 < .001$.

Mean Reaction Time. Due to the significant correlation between age and group, linear regression analyses were conducted to evaluate whether: (1) centered age was significantly related to overall log mean RT, and (2) group accounted for a significant amount of variance in log mean RT over and above age. Results of the initial analysis revealed that age was negatively associated with overall log mean RT, $b = -.15$, $p < .001$. When group was added to the model, a significant effect of group over and above age on log mean RT was observed, $\Delta R^2 = .03$, $F(1, 106) = 4.89$, $p = .03$. In order to evaluate the influence of age and group on log mean RT, a 2 (group) x 5 (block) mixed-model analysis of covariance was conducted with age as the covariate. The analysis revealed main effects of group, $F(1, 106) = 4.61$, $p = .03$, $\eta_p^2 = .04$, block, $F(2.98, 315.82) = 25.54$, $p < .001$, $\eta_p^2 = .19$, and age, $F(1, 106) = 53.42$, $p < .001$, $\eta_p^2 = .34$, on log mean RT (see Table 2 and Figure 1). No significant group x block interaction was found, $F(2.98, 315.82) = 0.48$, $p = .69$, $\eta_p^2 = .005$.[1] Post-hoc contrasts revealed that, controlling for age, participants responded more quickly as the task progressed, with all differences between blocks being significant (all *p*s < .01), except block 4 was not significantly different than blocks 3 or 5 (*p*s > .10; see Table 2). Group differences by block are presented in Table 3, but the pattern of group differences is difficult to interpret because the overall interaction between group and block did not emerge as a significant effect.

Accuracy

Due to the significant correlation between age and group, linear regression analyses were conducted to evaluate whether: (1) centered age was significantly related to accuracy, and (2) age accounted for a significant amount of variance accuracy over and above group. Results of the initial analysis revealed a positive, nonsignificant correlation between age and accuracy, $b = .12$, $p = .23$, and indicated that the variance in accuracy accounted for by age over and above group was not significant, $\Delta R^2 = .003$, $F(1, 106) = 0.32$, $p = .57$. Results of a 2 x 5 mixed-model

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[1] Analysis revealed that there was no significant interaction between age and block ($p = .87$, $\eta_p^2 = .002$) or between age and group ($p = .60$, $\eta_p^2 = .003$) in predicting mean RT.

analysis of covariance with group as the between subjects factor and block as the within subjects factor revealed a main effects of block, $F(3.39, 359.17) = 14.12$, $p < .001$, $\eta_p^2 = .12$ and group $F(1, 106) = 7.87$, $p = .006$, $\eta_p^2 = .07$, on accuracy. No main effect of age was found, $F(1, 106) = .50$, $p = .48$, $\eta_p^2 = .005$, and no interaction was found between block and group, $F(3.39, 359.17) = 0.62$, $p = .62$, $\eta_p^2 = .006$.[2] Although accuracy was high in both groups ($M = 95.68$, $SE = 0.29$), children with ADHD were found to be significantly less accurate ($M = 94.81$, $SE = 0.36$) than control children ($M = 96.55$, $SE = 0.44$, see Table 4). Controlling for age, participants responded more accurately in Blocks 1 and 2 than in all other blocks (all *p*s < .05), but participants' accuracy did not significantly differ in Blocks 3 through 5 (all *p*s > .10; although the interaction between block and group was not significant, group differences in accuracy by block are presented in Table 4).

Speed-Accuracy Tradeoff

Additional analyses were conducted in order to evaluate whether participants in either group traded speed for accuracy in blocks 1 and 5. All analyses controlled for centered age. First, partial correlations conducted separately by group revealed that correlations between correct and incorrect log mean RT in blocks 1 and 5 were positive but not significant for controls (*p*s > .30) and were positive and significant for children with ADHD (block 1: $r = .42$, $p = .001$; block 5: $r = .54$, $p < .001$). Second, partial correlations conducted separately by group revealed nonsignificant correlations between mean number of errors and log mean RT for children in both

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[2] Analyses revealed that there was no significant interaction between age and block ($p = .58$, $\eta_p^2 = .006$) or between age and group ($p = .31$, $\eta_p^2 = .01$) in predicting accuracy.

groups (*p*s > .10). Together, these analyses did not support the presence of significant speed-accuracy tradeoffs in either group.

Discussion

Recent studies have found evidence that executive function deficits that were once widely believed to underlie ADHD (e.g., Barkley, 1997; Diamond, 2005) are not able to account for the etiology of ADHD (Nigg et al., 2005; Willcutt, Doyle et al., 2005), raising questions about whether other, more basic cognitive processes may underlie ADHD-related impairments. Indeed, there is accumulating evidence to suggest that children with ADHD experience processing speed impairments across a number of simple cognitive tasks (e.g., Douglas, 1999; Lijffijt et al., 2005; Oosterlaan et al., 1998; Shanahan et al., 2006). Some researchers have speculated that this pattern of slow processing speed in children with ADHD may be the result of impairments in basic cognitive efficiency (e.g., Pennington & Ozonoff, 1996). However, there is also evidence to suggest that children with ADHD exhibit deficits in motor output (e.g., Barkley, 1990; Hartsough & Lambert, 1985; Piek et al., 1999), which is another basic process that could underlie processing speed impairments. The present study sought to inform the debate about the etiology of ADHD by examining whether two basic processes, motor speed and cognitive processing speed, underlie slow reaction times in children in ADHD.

Cognitive processing speed and motor speed were selected for comparison in the present study because both factors contribute to reaction times on simple cognitive tasks (see Luce, 1986, for a review), and because both factors have been independently implicated as being impaired in children with ADHD (e.g., Brossard-Racine et al., 2011; Carte et al., 1996;

Pennington & Ozonoff, 1996; Pitcher, Piek, & Hay, 2003). However, because these factors are typically studied separately, the individual contribution of cognitive processing speed and motor speed to reaction time in children with ADHD is unclear. In the present study, cognitive processing speed and motor speed were simultaneously assessed using a serial reaction time task.

Evidence of Motor Speed Deficits

The present study tested the hypothesis that motor speed deficits underlie slow processing speed in children with ADHD. Evidence of motor speed deficits would be supported by the overall tendency for children with ADHD to respond more slowly than controls; which is, in fact, what was found. This result is consistent with evidence that children with ADHD may exhibit motor functioning problems (e.g., Piek, Pitcher, & Hay, 1999, 2003).

Evidence of Central Processing Speed Deficits

The hypothesis that children with ADHD exhibit central processing speed deficits was not supported by the present study. The presence of central processing speed deficits in children with ADHD would have been supported by a significant group x block interaction showing that the magnitude of decrease in mean RT across the task was greater for children with ADHD than for controls. As expected, children in both groups responded more quickly as the task progressed. However, the group x block interaction was not significant, which suggests that central processing speed deficits were not detected in the present study. Although analyses of group differences in mean reaction times in each block suggest that there may be an effect of central processing speed on mean reaction time (see Table 3 and Figure 1) that was not completely captured in the particular paradigm and statistical analyses used in the present study, this is entirely speculative given that a significant group by block interaction did not emerge. Future studies may be able to further elucidate the role that cognitive processing speed deficits may play in ADHD by conducting more fine-grained analyses using advanced statistical techniques, such as diffusion modeling (e.g., Ratcliff, 1978).

Implications

Overall, the results of the present study suggest that slow processing speed in children with ADHD is driven by differences in motor speed rather than differences in central processing speed. Based on the results of the present study, I would expect that children with ADHD would respond more slowly than controls across simple cognitive tasks; which is, in fact, what has typically been found (e.g., Douglas, 1999; Lijffijt et al., 2005; Oosterlaan et al., 1998; Shanahan et al., 2006). This pattern of slow responding on processing speed tasks has often been interpreted as evidence that children with ADHD exhibit underlying deficits in central processing speed (e.g., Pennington & Ozonoff, 1996). However, this inference is called into question by the present results and by the fact that although processing speed measures are influenced by central processing speed as well as motor speed (e.g., Luce, 1986), most studies that have measured processing speed in children with ADHD have failed to account for group differences in motor speed. Consequently, the results of the present study highlight the importance of assessing and controlling for multiple factors (i.e., motor speed and cognitive processing speed) that may underlie group differences in outcome measures (i.e., processing speed). Accordingly, it is recommended that future studies take into account multiple factors that may account for potential deficits in children with ADHD.

One alternative interpretation of the finding that children with ADHD responded more slowly than controls is that children with ADHD did not learn the task. However, results of this study do not support this conclusion. Across multiple tasks, learning has consistently been found to be associated with a decrease in mean RT (for a review, see Luce, 1986). In the present study, both groups exhibited a significant decrease in mean RT between the first and last block, supporting the inference that both children with ADHD and controls learned the task. In addition, both groups maintained high accuracy throughout the task (ADHD: *M* = 94.81, *SE* = 0.36; Control: *M* = 96.55, *SE* = 0.44), and although accuracy dipped slightly across blocks, it is important to note that percent accuracy values per block never fell below 94% in either group. Thus, because both groups responded more quickly across the task while still maintaining a high level of accuracy, it does not appear that group differences occurred because children with ADHD failed to learn the task.

Another related alternative explanation for the present results is that group differences in mean reaction time occurred because children with ADHD traded accuracy for speed. Indeed, previous studies have found evidence that children with ADHD tend to have difficulty adapting their behavior in accordance with task instructions (e.g., Mulder et al., 2010; Sergeant & Scholten, 1985a, 1985b). Speed-accuracy tradeoff effects are indicated by negative correlations between correct and incorrect mean RT and between mean RT and accuracy. However, at the beginning and end of the present study, correlations between correct and incorrect mean RT were positive for children with ADHD and were nonsignificant for controls, and correlations between mean RT and number of errors were nonsignificant for children in both groups. Thus, results of the present study do not support the conclusion that group differences were the result of differences in the speed-accuracy tradeoff.

The present findings contradict the results of two recent studies that parsed central and peripheral processes using a mathematical model of decision making (i.e., the diffusion model; Huang-Pollock et al., 2012; Mulder et al., 2010).[3] Both of these studies found evidence that children with ADHD display deficits in central, but not peripheral processes (Huang-Pollock et al., 2012; Mulder et al., 2010). Although the source of the discrepancy between the current and previous results is unclear, the most straightforward explanation is that this discrepancy is related to the different statistical methods used to parse central and peripheral processes (i.e., inferential statistics vs. diffusion modeling, respectively). That is, the diffusion model approach is intended to not only separate central from peripheral factors but also to be more sensitive to differences in central processing speed than traditional analyses of mean reaction times, such as those employed in the present study (Ratcliff, 1978; see Voss, Rothermund, & Voss, 2004). For example, the diffusion model approach produces parameters that reflect different facets of central processing, such as response bias, the speed-accuracy tradeoff, and speed of decision making (for reviews, see Ratcliff & McKoon, 2008; Ratcliff & Smith, 2004, Bogacz et al., 2010). Thus, it may be that this more fine-grained approach was able to detect central processing speed differences that were not apparent based on the analyses used in the present study (e.g., Ratcliff & McKoon, 2008; Voss, Rothermund, & Voss, 2004). Consequently, future studies

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[3] Although the ex-Gaussian model is the most frequently used mathematical model of reaction times in ADHD research, because, as reviewed in the introduction, the parameters of the ex-Gaussian model do not map on to specific cognitive processes (e.g., Heathcote et al., 1991; W.E. Hockley, 1984; Luce, 1986; Matzke & Wagenmakers, 2009; Spieler, 2001; Van Zandt, 2002; Yap, Balota, Cortese, & Watson, 2006), ex-Gaussian studies cannot speak to the hypotheses of the present study and are therefore not considered here.

should employ both traditional inferential statistics and mathematical models in order to evaluate whether central processing speed deficits are contingent upon statistical methodology.

Theoretical Implications

The results of the present study have implications for etiological theories of ADHD, especially given the gradual shift in the field away from early theories that conceptualized ADHD as a disorder characterized by central nervous system impairments, including motor control problems (for a review, see Barkley, 1999). The present results suggest that, as suggested by proponents of an alternative conceptualization of ADHD known as “Deficits in Attention, Motor control, and Perception” (for reviews, see Gillberg, 1992, 2003), adding symptoms of motor impairment to current conceptualizations of ADHD may allow for more accurate classification of children with this disorder. The results of the present study are also consistent with other, more mainstream theories of ADHD that implicate motor deficits as being either secondary to symptoms of behavioral inhibition (Barkley, 1997) or the result of structural or functional deficits in brain regions that are thought to be impaired in children with ADHD (e.g., Castellanos & Tannock, 2002; Sagvolden et al., 2005). Similar to processing speed tasks, executive functioning measures also require participants to respond motorically. Given the current evidence that children with ADHD exhibit impairments in motor speed, it is expected that children with ADHD would respond more slowly than controls throughout more complex tasks, such as executive functioning tasks. Therefore, it is important that studies that measure executive functioning in children with ADHD also measure and control for motor speed differences that may contribute to slow responding.

Future Directions

In the present study, we carefully examined the two different groups for confounds, such as differences in gender, IQ, and age, which could influence mean reaction time. We found that although gender and IQ did not differ between groups, age was confounded with group. We therefore proceeded to control for age in all subsequent analyses. The present finding that younger children responded more slowly than older children is not surprising, given results of a recent study which examined developmental changes in SRT task performance and found that 8-10-year-old children responded more slowly than did 11- to 13-year-olds (Karatekin, Marcus, & White, 2007). Consequently, future studies should consider the effect of age as well as other factors, such as IQ, so that the true process(es) underlying impairments in processing speed in children with ADHD can be further illuminated.

Although the present study controlled for a number of confounds, we did not evaluate whether groups systematically differed in the manner in which they responded during the SRT task. That is, in the present study, children were not required to enter responses in a standardized manner (e.g., assigning a particular finger to a particular button) because previous studies had found that coordinating finger movements on one hand was too challenging for younger children (e.g., Thomas & Nelson, 2001). Consequently, in the present study, children may have differed in the number of muscles and joints they engaged in executing responses. For example, some children performed the task by assigning each of the four fingers on one hand to a particular response button and therefore only needed to move one finger per response. However, other children entered their responses using only one index finger, necessitating finger and wrist movements for each response, and potentially evoking forearm or whole arm movements for some or all responses. If, as previous studies have found, younger children have difficulty coordinating responding using only one hand, it may be that they tended to choose to respond in the latter fashion, which may partially explain the main effect of age in the present study. However, it is not anticipated that, after controlling for age, groups systematically differed in this regard. Nonetheless, future studies should rule out this possibility by measuring and evaluating the manner in which children in both groups choose to respond on the SRT task.

In addition, although the results of the present study suggest that children with ADHD may exhibit motor speed deficits, additional research is needed to identify the specific locus of those deficits (e.g., fine motor speed vs. gross motor speed). The present study is not able to speak to the presence of more specific motor impairments for two reasons. First, as reviewed above, the extent of motor processing involved in the SRT task may have differed between participants, depending upon the manner in which each participant entered her or his responses. Second, this study did not include independent measures of fine or gross motor functioning or motor coordination. Because previous studies have found that children with ADHD experience deficits in one or more motor processes (e.g., Brossard-Racine et al., 2011; see Harvey & Reid, 2003, for a review), it is recommended that future studies build on the present study by exploring the degree to which impairments in motor speed in children with ADHD are the result of more specific impairments in motor functioning. Clarifying the true nature and extent of motor speed difficulties in children with ADHD has the potential to lead to more targeted and effective interventions and treatments for children with ADHD.

Summary

In sum, the present study extends previous findings regarding processing speed deficits in children with ADHD by examining the degree to which these deficits are the result of two basic processes that have been found to be impaired in children with ADHD (i.e., motor speed and central processing speed). The results of the present study suggest that impairments in motor speed, not central processing speed, may underlie processing speed deficits in children with ADHD. These results are largely consistent with previous studies which have found group differences in processing speed (e.g., Douglas, 1999; Lijffijt et al., 2005; Oosterlaan et al., 1998; Shanahan et al., 2006) and motor functioning (e.g., Barkley, 1990; Hartsough & Lambert, 1985; Piek et al., 1999), but are inconsistent with two recent mathematical modeling studies that found group differences in central rather than peripheral processes (i.e., Huang-Pollock et al., 2012; Mulder et al., 2010), although the source of the latter inconsistency is unclear. Together, these results inform current conceptualizations of the etiology of ADHD.

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Appendix A

Tables

Table 1. Participant characteristics. Means, standard deviations, and statistics.

	Overall (*N*=109)	Control (*n*=43)	ADHD (*n*=66)	*F*(1,107)
M:F, %	63:46	21:22	42:24	2.35
Age	10.40 (1.36)	10.79 (1.32)	10.14 (1.33)	6.17*
FSIQ	104.90 (12.56)	107.00 (11.33)	103.53 (13.20)	2.01
Total ADHD Symptoms, CDISC	8.50 (6.68)	1.19 (1.24)	13.27 (3.84)	398.38**
Inattention				
Total Symptoms, CDISC	5.22 (3.74)	0.88 (1.03)	8.05 (1.41)	824.62**
BASC T Score: Parent	58.50 (12.49)	43.86 (6.26)	65.35 (13.17)	328.77**
BASC T Score: Teacher	54.88 (10.29)	44.43 (5.58)	61.84 (5.80)	234.04**
Conners T Score: Parent	62.50 (15.53)	46.43 (3.62)	72.73 (10.75)	233.77**
Conners T Score: Teacher	54.93 (11.08)	46.05 (4.65)	60.68 (10.20)	76.04**
Hyperactivity/Impulsivity				
Total Symptoms, CDISC	3.28 (3.48)	0.30 (0.60)	5.23 (3.19)	100.16**
BASC T Score: Parent	56.99 (15.20)	44.95 (5.57)	67.12 (6.56)	97.58**
BASC T Score: Teacher	53.82 (12.74)	44.26 (4.54)	60.19 (12.47)	62.77**
Conners T Score: Parent	59.09 (14.66)	46.48 (3.16)	67.12 (13.38)	96.32**
Conners T Score: Teacher	54.08 (11.67)	46.00 (3.03)	59.31 (12.21)	47.85**

Note: Parent = Parent rated; Teacher = Teacher rated

**p* < .05, †*p* < .01, ***p* < .001

Table 2. Log mean reaction time and accuracy by block, controlling for centered age. Means, standard errors, and *p* values from post-hoc pairwise contrasts.

	Block 1	Block 2	Block 3	Block 4	Block 5
Log Mean RT	6.83 (0.03)^{a}	6.76 (0.03)^{b}	6.72 (0.03)^{c}	6.69 (0.03)^{cd}	6.67 (0.03)^{d}
Accuracy	97.06 (0.24)^{a}	95.92 (0.33)^{b}	95.35 (0.36)^{c}	95.12 (0.39)^{c}	94.91 (0.41)^{c}

Note. RT= Reaction time; Different superscripts represent significant differences between blocks. Means within rows sharing superscripts are not significantly different from each other.

Table 3. Log mean reaction time by block and by group, controlling for centered age. Means, standard errors, statistics, and *p* values from post-hoc pairwise contrasts.

	Block 1	Block 2	Block 3	Block 4	Block 5
ADHD	6.88 (0.03)^{a}	6.82 (0.04)^{b}	6.78 (0.03)^{c}	6.74 (0.04)^{d}	6.72 (0.04)^{d}
Control	6.78 (0.04)^{a}	6.70 (0.04)^{b}	6.65 (0.04)^{c}	6.64 (0.04)^{c}	6.63 (0.05)^{c}
F(1,106)	3.88*	4.84*	5.62*	3.06	2.50

Note. Different superscripts represent within group differences. Means within rows sharing superscripts are not significantly different from each other.

$*p \leq .05$

Table 4. Percent accuracy by block and by group, controlling for centered age. Means, standard errors, statistics, and *p* values from post-hoc pairwise contrasts.

	Block 1	Block 2	Block 3	Block 4	Block 5
ADHD	96.27 (0.31)^a	94.78 (0.41)^b	94.56 (0.46)^b	94.41 (0.49)^b	94.22 (0.52)^b
Control	97.84 (0.38)^a	97.07 (0.52)^a	96.15 (0.58)^b	95.83 (0.61)^b	95.59 (0.65)^b
$F(1,106)$	10.00**	11.63**	4.53*	3.17	2.61

Note. Different superscripts represent within group differences. Means within rows sharing superscripts are not significantly different from each other.

$^*p < .05$, $^{**}p \leq .001$

Appendix B

Figures

Figure 1. Log mean reaction time by block, controlling for centered age.