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PROCESSING SPEED AND WORKING MEMORY IN CHILDREN WITH ADHD: IMPROVING MEASUREMENT USING MULTIPLE METHODS

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Hilary Galloway-Long

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The thesis of Hilary Galloway-Long was reviewed and approved* by the following:

Cynthia Huang-Pollock
Associate Professor of Clinical Psychology
Thesis Adviser

Peter Arnett
Professor of Clinical Psychology

Janet Van Hell
Professor of Psychology and Linguistics

Melvin Mark
Department Head, Penn State Department of Psychology

*Signatures are on file in the Graduate School

ABSTRACT

Slower and more variable processing speed, indexed by reaction time (RT), is among one of the most prominent cognitive signatures in Attention Deficit Hyperactivity Disorder (ADHD). However, the use of RT to index global processing speed is confounded by the presence of poor fine and gross motor skills in this population. Thus, it remains uncertain whether the slower/ variable RTs found in those with ADHD indicate slower central processing speed, or whether they are instead primarily indices of impaired peripheral motor coordination. One promising alternative to motor RT is vocal articulation speed, which has been found to predict better verbal as well as visuospatial WM performance. Additionally, distributions of reaction time trials are non-normal, and typically better described with an ex-Gaussian distribution, including parameters of mean (mu), variance (sigma), and skew (tau).

The current study compares the distributions of reaction times from both traditional motor and speech-based reaction time tasks in children with and without ADHD. Findings indicate that regardless of diagnostic status, larger tau (indicating a greater number of exceedingly slow responses) for preparatory interval and motor reaction time were associated with worse verbal and non-verbal working memory span. When the ex-Gaussian parameters for preparatory interval, speech rate, and motor speed were all combined in a factor analysis, only the factor representing the shared variance of tau from all 3 measures of processing speed predicted performance on the verbal and visuospatial complex span tasks.

Combining measures using multiple assessment techniques reduces the effects of possible methodological confounds, resulting in a more “pure” measure of cognitive processing speed. The association between tau, but not mu or sigma, and WM suggests that observed WM deficits may largely be due to lapses in attention during encoding, rather than truly slower processing.

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Introduction

Attention Deficit Hyperactivity Disorder (ADHD) is a highly complex and heterogeneous disorder, characterized by difficulties with sustaining attention, hyperactivity, and impulsivity (American Psychiatric Association, 2013). Estimated to affect 3-7% of children in the United States, ADHD is the most common of childhood psychiatric diagnoses, and as such, represents one of the largest sources of academic underachievement and mental health service costs. Typically beginning in early childhood and identified by parents and teachers as children begin school, ADHD can impair learning throughout the school-aged years. These impairments include significantly worse performance on academic achievement tests, lower grades, and higher likelihood of repeating a grade in school (Biederman et al., 2004). But the impairments associated with ADHD are also more widespread; affecting all parts of a child's life outside of school as well. It has also been found that children with ADHD have poorer social skills and more stressful parental relationships than children without ADHD (Dupaul, McGoey, Eckert, & Vanbrakle, 2001). Given these negative outcomes, it is imperative that the roots of the disorder be better understood so that assessment and intervention might improve.

Though the variability of symptomology within ADHD indicates the likelihood of a broad range of factors leading to ADHD, impairment in executive functioning (EF) is considered a primary feature of the disorder and has been found to be significantly impaired in nearly one third of all children diagnosed with the disorder (Barkley, 1997; Nigg, Willcutt, Doyle, & Sonuga-Barke, 2005). Executive functions include high level cognitive processes such as attention, inhibitory control, planning, problem solving, and working memory (Castellanos, Sonuga-Barke, Milham, & Tannock, 2006). Working memory (WM) deficits specifically, defined as impairment in the ability to store and manipulate information during short periods of time, explain a significant portion of the attentional and academic impairments observed in children with ADHD (Martinussen, Hayden, Hogg-Johnson, & and Tannock, 2005).

Much research examining both typically developing children and children with ADHD has been conducted attempting to better understand what drives these individual differences in WM performance (Baddeley & Logie, 1999; Bayliss, Jarrold, Baddeley, Gunn, & Leigh, 2005). Though little consensus exists, processing speed, as indexed by reaction time (RT) to simple and forced choice RT tasks stands out as one of the most promising mechanisms (Epstein et al., 2011b; Fry & Hale, 2000; Hervey et al., 2006; Kail & Salthouse, 1994; Kalff et al., 2005; Karalunas & Huang-Pollock, 2013; Leth-Steensen, Elbaz, & Douglas, 2000; Magimairaj & Montgomery, 2012; Salthouse, 1996) .

However, with the exception of a small handful of studies (Bayliss et al., 2005), most research examining developmental and individual differences in the processing speed/WM relationship have used single variables of motor reaction time speed in their analyses. Such an approach is vulnerable to idiosyncrasies of the individual measures chosen, and as a result, is associated with lower reliability and confidence in interpretation. This is particularly worrisome in studies of ADHD when motor speed is used as the sole predictor of processing speed, given that children with ADHD are also more likely to exhibit deficits in both fine and gross motor skills (Dewey, Kaplan, Crawford, & Wilson, 2002; Gillberg, 2003; Kadesjo & Gillberg, 1999; Kadesjö, 1998; Piek et al., 2004; Piek, Dyek, Francis, & Conwell, 2007; Piek, Pitcher, & Hay, 1999; Pitcher, Piek, & Hay, 2003; Ramussen & Gillberg, 2000). Thus, the association between slower and more variable reaction times and poorer WM might be confounded by motor preparation or coordination difficulties rather than the intended concept of cognitive processing speed.

In light of this, it is important to identify alternative indices of cognitive speed that may be less constrained by this limitation, and could be combined with motor reaction time tasks to create a more reliable and comprehensive latent “speed” variable. One promising alternative index is articulation speed, a general construct that represents several key aspects of speech including time to initiate a vocal response and the elapsed time from stimulus onset to the completion of a vocal response. Like motor reaction time, speech rate, commonly measured as the entire duration of a spoken response, has been found to predict verbal as well as visuospatial Working Memory (WM) (Burkholder & Pisoni, 2003; Cowan, 1992, 1999; Cowan et al., 1992; Cowan, Keller, Hulme, Roodenrys, & McDougall, 1994; Cowan, Saults, Nugent, & Elliott, 1999; Cowan et al., 2003; Cowan et al., 1998; Kail, 1992, 1997a, 1997b; Towse, Cowan, Hitch, & Horton, 2008; Towse, Cowan, Horton, & Whytock, 2008; Towse, Hitch, Hamilton, & Pirrie, 2008; Towse, Hitch, Horton, & Harvey, 2010; Van De Voorde, Roeyers, Verte, & Wiersema, 2010) but the extent to which articulation speed and motor speed index are overlapping constructs, and the degree to which they may each contribute unique variance in the prediction of WM, is not yet clear. Figure 1 illustrates Robert Kail’s model in which age-related improvements in processing speed also improve working memory via articulation speed.

Given the clear consequences of EF dysfunction for children with ADHD in both academic and social contexts, it is imperative that researchers elucidate the mechanisms that lead to these deficits. Studies examining the links between fine-motor based reaction time and working memory performance show promising evidence indicating the influence of processing speed on higher level EF functioning. But more needs to be done to explore the ways in which processing speed can be effectively assessed. The current work seeks to expand upon the existing literature using articulation speed as a single indicator for general processing speed as well as exploring the strength of a latent processing speed variable combining more traditional motor reaction time and articulation speed variables together. Before discussing the specific hypotheses and methods of this study, the major models of working memory will be discussed, with particular attention to the role of processing speed and the ways in which it has been examined in previous developmental and clinical research.

I. Major Models of Working Memory

One of the earliest models of working memory, and the foundation of most proceeding models, was proposed by Alan Baddeley and Graham Hitch (1974). As Baddeley explains, before WM became such a predominant concept, Short Term Memory (STM) was the most common term used to describe both the processes of storing and maintaining relatively small pieces of information in mind for only a few short seconds (Baddeley, 2012). However, as research concerning the processes involved in maintaining those pieces of information expanded, the terms divided such that STM now refers exclusively to short-term storage (Baddeley, 2012). The second general type of memory is called Long Term Memory (LTM), and involves the more permanent storage of information, to be recalled at any point in the future (Cowan, 2008). In contrast to both STM and LTM, working memory is a more complex function. The modern definition of WM describes multiple processes requiring both immediate recall similar to STM in addition to active manipulation (or processing) and storage of information while other mechanisms are completed (Alloway, Pickering, & Gathercole, 2006).

While various previous models have differed in the ways they have operationalized the core components of working memory, the current study proceeds with the current definitions for both storage and processing. Storage can be broadly defined as the individual capacity to retain information, and it functions as a reserve from which information can be pulled (Fry & Hale, 2000). In contrast, processing speed generally refers to the speed with which an individual is able to efficiently complete relatively simple cognitive tasks (Fry & Hale, 2000).

Baddeley argues that WM consists of the storage and processing of information, which can be divided into four specific components: first, the central executive, which functions as a supervisory system over the phonological loop, the visuospatial sketch pad, and the episodic buffer (1974). Baddeley's conceptualization of the subcomponents within WM is invaluable for its emphasis on the division of visuospatial and phonological constructs. The phonological loop is used to maintain speech-based (or verbal) information, while the visuospatial sketchpad maintains visual imagery (or non-verbal information) for recall (Baddeley, 1992). This early conceptual separation of verbal and visual processes is valuable, as these two domains involve unique stimuli and likely unique processes. As such, much of the research to be discussed later focused primarily on either verbal or non-verbal working memory tasks and processes, but rarely both. These distinctions will be noted throughout, as various models and previous research are discussed.

Though a valuable framework with which to think of WM, Baddeley's model didn't sufficiently delineate the roles of storage vs. processing, and according to Nelson Cowan, failed to account for additional factors used during both storage and processing, such as covert use of mnemonic processes (Cowan et al., 1994). Instead, Cowan proposed a theory with John Towse known as the "Task Switching Theory" (Cowan et al., 1994). This model suggests that during WM span tasks, individuals switch between processing and rehearsing items in storage throughout the task (Towse, Hitch, & Hutton, 1998). Towse and colleagues argue that the active processing phases of WM tasks prevent the rehearsal of to-be-recalled information, and it is during that period of time in which to-be-recalled information decays. Put simply, rather than representing interrelated functions, which rely on one another or utilize the same mechanism, they are instead competing functions: each time an individual switches from storage to processing, the additional time and effort required for processing directly reduces the remaining time and effort available to maintain storage, which then leads to degradation (Towse et al., 1998). Given this, The Task Switching Model posits that time-based decay can be reduced, and recall can be maintained, by implementing more rapid switching between processing and storage such that less degradation occurs during shorter periods of processing between periods of refreshing.

Barrouillet and colleague's "Time-Based Resource Sharing Model", builds on previous models such as Towse's "Task Switching Theory" but argues that because both storage and processing require active attention, memory therefore decays whenever attention is switched away to the other function (Barrouillet, Bernardin, & Camos, 2004). Therefore, the TBRS suggests that the key to better WM performance during complex tasks is not frequent switching between processing and storage as in the Task Switching Model, but rather more efficient processing, such that more time is then available for storage (Barrouillet, Gavens, Vergauwe, Gaillard, & Camos, 2009). The TBRS suggests that within a given trial, faster processing of current stimuli allows for greater time to be spent refreshing the previous items in storage (Barrouillet et al., 2004). While their original work focused on adults, TBRS is particularly interesting to the current study due to its ability to explain performance differences in younger vs. older children. Barrouillet argues that children developmentally increase the efficiency of their reactivation, and are then better able to use the time between stimuli to reinforce, or maintain, the previously learned stimuli (Barrouillet et al., 2009).

Donna Bayliss and colleagues assert a model which shares many similarities with

Barrouillet’s TBRS, but attempts to address what they felt were key flaws. They argue that though the TBRS is a generally strong model explaining the link between processing and storage factors, it fails to account for the independent influence of storage capacity apart from variance that is also explained by overall working memory or processing speed (Bayliss, Jarrold, Gunn, & Baddeley, 2003). That is, Bayliss’ model asserts that even given that improvements in processing speed likely allow for greater time to maintain information within storage, it is important to recognize that processing speed and storage capacity should be viewed as independent factors which can also predict WM performance regardless of the other. In support of her model, and examining several speed, processing, and span tasks, (including auditory and visual speed, verbal and visuospatial processing, Corsi and digit span tasks), Bayliss et al. found that while speed and storage were highly correlated, each factor independently explained a significant portion of variance in complex span performance (Bayliss et al., 2005). It is with this model, recognizing speed and storage as separate though interrelated factors influencing WM, that the current study proceeds.

II. Processing Speed Predicts Developmental Changes in WM

Theories of working memory such as those described above hypothesize that more efficient processing allows for faster and more accurate mental manipulation of stimuli, which in turn allows for more rehearsal time and greater recall (Kail, 1992). However, the methods used to measure processing speed have evolved as our technologies and methods have evolved, with implications for understanding the nature of the relationship between processing speed and working memory. The three most common methods of indexing speed within this context have included: (a) the time required to complete relatively simple pencil and paper tasks (e.g. Coding and Symbol Search subtests within the Wechsler intelligence testing batteries (WAIS and WISC)

(2003), (b) the calculation of the Mean Reaction Time (MRT) to simple forced-choice motor responses during computerized tasks (Kail, 1992), and (c) the average speed of verbal articulation, commonly referred to as articulation speed (Sternberg, Monsell, Knoll, & Wright, 1978). Paper-and-pencil as well as motor RT measures of processing speed have been explored extensively in working memory research with adults, typically developing children, and children with ADHD. While less frequently used, articulation speed proponents argue that articulation speed is a particularly valuable measure of processing speed as it reflects the rate at which information can be refreshed and rehearsed within the articulatory loop (Baddeley, 1981). Findings using all three methods and the value of a possible latent "speed" variable combining these methods will be discussed within this review.

III. Fine-Motor Reaction Time (Motor RT) as a Measure of Processing Speed

Early developmental cognition research has found consistent age-related improvements in working memory performance throughout middle childhood and adolescence such that recall in verbal and non-verbal WM tasks steeply increases throughout childhood, tapering off slightly through adolescence, at which point working memory remains stable throughout early to middle adulthood (Hale, Bronik, & Fry, 1997; Hulme, Thomson, Muir, & Lawrence, 1984; Hulme & Tordoff, 1989; Roodenrys & Hulme, 1993). Whereas the developmental literature presents fairly limited explanations for the cognitive mechanisms that might explain these age-related improvements in working memory, the aging literature has suggested that efficient processing speed is key (Kail & Salthouse, 1994; Salthouse, 1976, 1981, 1991, 1992, 1996). Using primarily paper-and-pencil tasks included in the WAIS, Salthouse and colleagues found that faster processing speed significantly predicted faster and more accurate recall in complex verbal and non-verbal working memory span tasks (Kail, 1992; Kail & Park, 1994; Kail & Salthouse, 1994; Salthouse, 1991, 1996). By comparing men and women in their 60s-80s to men and women in their 20s-30s, Salthouse found that when examined as the sole predictor, age accounted for nearly 31% of variance in working memory. However, after adding speed to the model, the effect of age dropped down to less than 5% (Salthouse, 1991). Though valuable for their original contributions to the research on processing speed and working memory, the coding and symbol search tasks used to index processing speed in those early studies require, for good performance, strong fine motor skills, visual scanning, short term memory, and effective use of strategies.

Subsequent research operationalizing processing speed using computerized reaction time times rather than the paper-and-pencil tasks confirmed previous findings that faster processing speed predicted more accurate recall across several working memory tasks (Kail, 1992; Kail & Park, 1994). It was hypothesized that improvements in processing efficiency allowed for the use of more techniques, such as rapid rehearsal, to maintain and refresh remembered items (Fry & Hale, 2000; Kail, 1992; Kail & Park, 1994). Additional research examining typically developing children also found that faster RTs predicted better performance on tasks of verbal (Barrouillet et al., 2009; Bayliss et al., 2005; Ferguson & Bowey, 2005; Gaillard, Barrouillet, Jarrold, & Camos, 2011) and visuo-spatial (Bayliss et al., 2005; Vicari, Caravale, Carlesimo, Casadei, & Allemand, 2004) working memory.

Not only does MRT predict WM capacity in typically developing populations, but MRT is also associated with WM and other EF impairments in children with ADHD. Children with ADHD consistently exhibit slower MRT (Alderson, Rapport, & Kofler, 2007; Castellanos et al., 2005; Lijffijt, Kenemans, Verbaten, & van Engeland, 2005; Oosterlaan, Logan, & Sergeant, 1998) even when the effects of age are controlled (Nigg, 1999). However, group effect sizes for standard deviation of reaction times (SDRT) are even larger than for MRT (Alderson et al., 2007; Lijffijt et al., 2005), suggesting that behavioral inhibition (and possibly other EFs) may not be as core to ADHD as individual variability in speed. That being said, traditional analyses of SDRT rely exclusively on the assumption that RT is normally distributed, ignoring the fact that RT distributions are positively skewed, having important implications for interpretations of findings.

IV. Evaluating MRT using the ex-Gaussian Distribution.

Many of the most common constructs used within psychological research (e.g., standardized scaled scores including IQ and clinical ratings) are represented by a normal (Gaussian) distribution, in which the mean is the best index of central tendency, with limited skew towards smaller or larger values (Dawson, 1988). In contrast, valid reaction time data is bound by a fastest possible response of zero milliseconds, but potentially infinitely slow responses (Dawson, 1988). As such, RT is best represented by the non-normal (ex-Gaussian) distribution, which integrates an exponential distribution with a normal distribution in a way that accounts for the positive skew caused by substantially more exceptionally slow RTs than fast (see figure 2 for illustration).

Individual difference in the size of a distribution’s skew is important because it may capture an important source of variance in the processing speed to working memory relationship. In particular, the “Worst Performance Rule”, originally introduced by Larson and Alderton (1990), suggests that in tasks when RT is measured across many trials, the trials with the worst performance (i.e., slowest times) represent meaningful attentional lapses, and are therefore predictive of cognitive functions such as general intelligence, working memory, and processing speed (Coyle, 2003). Thus, techniques that analyze ex-Gaussian distributions are likely able to more fully describe the nature and distribution of RTs by including measures of the mean (mu; μ) and standard deviation (sigma; σ) to describe the normal portion of the distribution as well as a measure of skew (tau; τ) to describe the exponential portion (Lacouture & Cousineau, 2008). This increased specificity can in turn be used to better understand the source of group differences in processing speed, as well as the relationship between RT and working memory capacity.

Studies have consistently found that lower levels of intraindividual variability predict better working memory span in a broad range of populations including typically developing children and adults as well as clinical populations including those with ADHD, early Alzheimer’s disease, and intellectual disability (Kofler et al., 2013; Mella, Fagot, Lecerf, & de Ribaupierre, 2015; Shahar, Teodorescu, Usher, Pereg, & Meiran, 2014), suggesting that differences in RT may be linked to greater number of slow trials (as indexed by tau). Specifically, studies of middle childhood through college-age found that smaller tau (i.e., limited skew) predicted better performance on several working memory span tasks above and beyond differences in mu and sigma (mean and standard deviation) (Mella et al., 2015; Schmiedek, Oberauer, Wilhelm, Suss, & Wittmann, 2007). They concluded that although the mean and standard deviation of the normal portion of the distribution are related to working memory, most of the relation between speed and working memory performance is due to the influence of skewed slow responses.

In recent years, a number of studies have found greater skew in the ADHD population (Buzy, Medoff, & Schweitzer, 2009; Castellanos et al., 2005; Epstein et al., 2011b; Gu, Gau, Tzang, & Hsu, 2013; Hervey et al., 2006; Karalunas & Huang-Pollock, 2013; Leth-Steensen et al., 2000; Lijffijt et al., 2005; Shahar et al., 2014), showing that slow processing speed in children with ADHD may be best explained not by generally slower speed, but by variable speed and attention throughout trials. Specifically, ex-Gaussian analyses have shown that much of the group difference in RT is due to longer tau rather than mu (Epstein et al., 2011a). These findings argue that the RT distributions of children with ADHD are marked by a relatively small portion of slow responses that ultimately bias the MRT.

V. Fine-Motor Skill Demands in Processing Speed Measures

Despite the strengths of MRT discussed above, research relying solely on MRT as a measure of processing speed faces a key limitation: these traditional fine-motor based reaction time tasks are highly dependent on the typical development of motor skills (Martin, Piek, & Hay, 2006; Piek et al., 2004; Piek et al., 2007; Piek et al., 1999; Pitcher et al., 2003; Sergeant, Piek, & Oosterlaan, 2006). While less likely to be of concern in working memory research concerning adults, research examining children must take into account the possibility of highly varied stages of development in a broad range of domains, including both gross and fine motor skills. In addition to typical variation in motor skill development throughout childhood, it is estimated that 6-10% of school-aged children display significant impairments in fine motor skills, classified as Developmental Coordination Disorder (DCD) (American Psychiatric Association, 2013). Research has also consistently found higher rates of impaired motor skills and DCD in children with ADHD compared to typically developing peers (Dewey et al., 2002; Fliers et al., 2008; Gillberg, 2003; Kadesjo & Gillberg, 1999; Kadesjö, 1998; Kopp, Beckung, & Gillberg, 2010; Martin et al., 2006; Piek et al., 2004; Piek et al., 2007; Piek et al., 1999; Pitcher et al., 2003; Sergeant et al., 2006). Specifically, several studies of children and adolescents with and without ADHD have found that roughly 30-50% of those with ADHD also experienced significant motor coordination problems (Fliers et al., 2008; Kadesjö, 1998). Given such high comorbidity, these studies address two valuable implications: first, that a common etiology is likely to explain both attentional and fine-motor deficits, and second, that studies using traditional MRT tasks to measure cognitive constructs might be confounding deficits in mental processing speed with deficits in fine-motor speed. As such, studies which measure processing speed without relying on “key-press” motor response tasks are a valuable tool to best understand the relationships among processing speed, working memory, and ADHD.

Despite being less common than fine-motor based tasks of processing, verbal articulation speed has been used in cognitive research for decades, and represents a method by which processing speed can be measured with less confound due to gross/fine motor skill development (Sternberg et al., 1978). Articulation speed is commonly broken down into several subcomponents, including preparatory interval, which measures the time from stimulus offset to the onset of speech, speech rate, which measures the time from onset of speech to the completion of the vocal response divided by the number of items in the stimuli, and Interword Pauses (IP), which measure the silent intervals between items within the response (Cowan et al., 1994; Sternberg et al., 1978).

In comparison to MRT, articulation speed might be considered a cleaner measure of central processing speed because it is less reliant on the influence of fine motor development and capacity. Indeed, articulation speed is often used as an index of processing speed in adults with Parkinson’s disease (PD). Because damage to the basal ganglia and dopamine system are known to impair motor functioning in individuals with PD (Forno, 1996) some studies have used verbal versions of traditional fine-motor based Signal Response Tasks to limit the impact physical symptoms might have on the assessment of cognitive functioning (Smith & McDowall, 2004, 2011; Smith, Siegert, McDowall, & Abernethy, 2001; Sommer, Grafman, Clark, & Hallett, 1999; Stefanova, Kostic, Ziropadja, Markovic, & Ocic, 2000). Using these studies of PD as an example of how alternative methods can be most appropriate for a clinical sample, the following section will summarize key findings from developmental and cognitive studies that utilized articulation speed to assess processing and working memory in children and adults.

VI. Articulation Speed as a Measure of Processing Speed

Robert Kail was also one of the earliest researchers to establish a cognitive model of working memory which incorporated speech as a measure of processing speed (Kail, 1992). Comparing both children and adults, Kail established that motor processing speed was significantly correlated with verbal speed; suggesting that speech might also be used as an index of processing, and might be able to predict working memory span. Although Kail's original studies established the validity of articulation speed as an index of global processing, the methods for measuring articulation speed were relatively rudimentary. Specifically, Kail and many other researchers (Cohen & Heath, 1990; Ferguson & Bowey, 2005; Ferguson, Bowey, & Tilley, 2002; Hulme et al., 1984; Hulme & Tordoff, 1989; Kail, 1992, 1997a; Kail & Park, 1994; Kail & Salthouse, 1994; Roodenrys & Hulme, 1993; Smyth & Scholey, 1996; Swanson & Ashbaker, 2000; Swanson & Kim, 2007) assessed articulation speed simply by recording the time on a stopwatch while participants repeated a wordlist a given number of times. Later studies made use of digital audio recordings and visual waveform displays to carefully code not just response start and stop times, but also the preparatory interval before response start, and the interword pauses within responses (Archibald & Gathercole, 2007; Baker, Hipp, & Alessio, 2008; Burkholder & Pisoni, 2003; Cowan, 1992, 1999; Cowan et al., 1992; Cowan et al., 1994; Cowan et al., 1999; Cowan et al., 2003; Cowan et al., 1998; Finneran, Leonard, & Miller, 2009; Hulme, Newton, Cowan, Stuart, & Brown, 1999; Hulme & Tordoff, 1989; G. Neuhaus, Foorman, Francis, & Carlson, 2001; G. F. Neuhaus & Swank, 2002; Towse, Cowan, Hitch, et al., 2008; Towse, Cowan, Horton, et al., 2008; Towse, Hitch, et al., 2008; Towse et al., 2010; Van De Voorde et al., 2010). Interword pauses will not be reviewed in the current study because they have typically been assessed when articulation speed and WM have been tested during the same task (Cowan et al., 2003; Cowan et al., 1998; Towse et al., 1998). When articulation speed is assessed without simultaneous WM demands, such as in the current study, speech is noticeably more rapid and few responses contain IPs; as such their predictive value is limited. Therefore, the current review focuses on overall speech rate as it has been the most heavily researched and represents the most comprehensive assessment of a verbal response, and the preparatory interval as it measures the time required to initiate a verbal response; conceptually mirroring fine-motor based MRT.

Hulme & Tordoff (1989) found that age predicted significant improvement in both speech rate and wordlist recall among 4, 7, and 10 year old children, and that within each age group, faster speech was associated with better recall (Hulme & Tordoff, 1989). Because speech rate and recall were faster with shorter words than longer words, the authors argued that faster processing and speech allow for greater rehearsal within the articulatory loop, which in turn increased recall (Hulme & Tordoff, 1989). Several additional studies also found consistent age-based improvements in speech rate and memory span, as well as the association between increased speech rate and improvements in span for both word lists and non-word lists (Cowan, 1992; Cowan et al., 1992; Cowan et al., 1994; Hulme et al., 1999; Kail, 1992; Roodenrys & Hulme, 1993).

Cowan and colleagues have also found that preparatory interval was significantly shorter in younger groups and with shorter word lists, and that shorter preparatory interval predicted improved verbal WM span (Cowan et al., 1994; Cowan et al., 2003). Specifically, they found that third-graders with better performance on a digit-span WM task had significantly shorter preparatory intervals than age-matched peers with poor span recall, though this difference was not found in fifth-graders or adults (Cowan et al., 2003). This age effect is consistent with other results discussed previously, and Cowan suggests that preparatory intervals may be more reflective of processing speed during childhood than adolescence or adulthood, perhaps due to greater need for rehearsal compared to older peers. Relatively fewer studies have examined the predictive power of preparatory interval compared to speech rate, likely due to the limitation of earlier methods including lack of audio recording and visual waveform techniques. However, Cowan's finding concerning the value of preparatory interval as a predictor of WM is particularly valuable given the conceptual similarity between preparatory interval and fine-motor RT as measures of the initiation of a response. Given this, the analyses in the current study will pay special attention to the ways in which relationships among processing, WM, and ADHD differ between preparatory interval and motor RT.

To date, no studies have examined the relationship between articulation speed and working memory performance in children with ADHD. However, findings from studies examining learning disabilities (LD) (Swanson & Ashbaker, 2000) and Specific Language Impairment (SLI) (Duranovic & Sehic, 2013; Finneran et al., 2009; Miller, Kail, Leonard, & Tomblin, 2001; Miller et al., 2006; Miller & Wagstaff, 2011) have found that children with LD or SLI are more likely to have slower articulation speed and to perform worse on working memory tasks compared to typically developing peers. Due to the high comorbidity of ADHD with LD and SLI, (Sexton, Gelhorn, Bell, & Classi, 2012; Tirosh & Cohen, 1998; Willcutt et al., 2010; Willcutt et al., 2001; Willcutt, Pennington, Olson, Chhabildas, & Hulslander, 2005) similar patterns of slower articulation speed and impaired WM would also be expected in children with ADHD. Similarly, research separating short-term memory store and phonological rehearsal in boys with and without ADHD found significant rehearsal difficulties in those with ADHD (Bolden, Rapport, Raiker, Sarver, & Kofler, 2012). When viewed through the lens of Bayliss' model, this could suggest that slower processing speeds were impeding the ability to rehearse, thereby impairing WM recall. Together, the research examining articulation speed deficits in children with learning disabilities and specific language impairments, and poor phonological recall in children with ADHD suggest that Articulation Speed is likely impaired in children with ADHD, and as such, may explain differences in processing speed and impairments in working memory.

VII. Constructing a Multi-Method Latent "Speed" Construct

In addition to further examining the ability to use articulation speed as an index of global processing speed and exploring fitting RT data to ex-Gaussian distributions, the current study will also explore creating a latent "reaction speed" variable by combining preparatory interval, overall speech rate, and motor reaction times. While Bayliss and colleagues included latent "speed" and "storage" constructs in their model discussed previously, their model used only overall speech rate, without taking preparatory intervals into account (Bayliss et al., 2005). Both speech rate and preparatory interval are likely to account for a unique portion of the variability within processing speed (Cowan et al., 1994), and as such a latent construct including multiple aspects of articulation speed should be conceptually stronger and provide a better model fit. In creating this latent "speed" construct, it is hoped that it can account for differences in motor coordination and any speech difficulties to better explore the ability of increased processing speed to predict better working memory performance. Additionally, comparisons among the motor, speech, and latent processing variables will allow for a robust evaluation of Bayliss' theory suggesting that processing speed is domain general.

VII. Current Study

The purpose of the current study is to compare Articulation Speed to a traditional computerized fine-motor based reaction time task to assess processing speed and working memory impairment in children with ADHD. Specifically, we aim to determine if articulation speed can predict processing and WM as successfully as the more commonly used fine-motor based measures, and to improve the methods by which processing speed can be assessed. To date, no studies have examined ex-Gaussian distributions of Articulation Speed, however, the strong findings of intraindividual variability (IIV) in fine-motor based MRT in typically developing children and children with ADHD discussed previously suggest that a similar pattern of excessively slow responses would likely be found among children with ADHD in Articulation Speed as well. The current study will therefore examine IIV in both preparatory interval and speech rate to determine if, similar to fine-motor RT, articulation speed data is best fit by an ex-Gaussian distribution to account for a relatively high number of exceedingly slow response times. The second goal of the current study is then to evaluate the appropriateness of a latent "speed" construct by integrating both fine-motor and speech variables in a way that more accurately assesses processing speed while minimizing the possible fine-motor or speech confounds associated with either method. By more accurately modelling intraindividual variability of response times and developing a strong latent "speed" construct, the current study can better elucidate the role of processing speed in working memory and the ways in which both speed and WM may be impaired in children with ADHD.

Hypotheses

Hypothesis 1: Compared to same-aged non-ADHD controls, children with ADHD will have:

a. Shorter spans on all memory tasks

b. Slower MRT on both motor and Articulation Speed RT tasks.

Hypothesis 2: Motor and articulation speed RT data will exhibit significant positive skew, and therefore be better represented by the ex-Gaussian distribution than the normal distribution.

Hypothesis 3: If the ex-Gaussian distribution is a better fit, analyses will demonstrate that:

a. Children with ADHD will not have significantly slower motor or speech RT (indexed by mu) compared to same-aged non-ADHD matched controls

b. Children with ADHD will have significantly more variable (indexed by sigma) and more positively skewed (indexed by tau) motor and speech RT compared to same-aged non-ADHD matched controls

c. Greater variation in response time (indexed by sigma) and more exceedingly slow responses (indexed by tau) should predict worse performance on both verbal and visuospatial working memory tasks, regardless of ADHD status.

Hypothesis 4: If motor RT and articulation speed both reflect a global, central processing speed, then exploratory Factor Analyses will indicate a latent "variability/skew" construct combining variables from both measures.

Hypothesis 5: If EFA confirms a "variability/skew" construct, it will be a strong indicator of global processing speed.

Methods

Participants

Boys and girls between the ages of 8 and 12 years old, with and without ADHD, were recruited from Centre, York, and Harrisburg counties of Pennsylvania to participate in a larger study on attention and learning conducted at The Pennsylvania State University between 2008 and 2014. 192 children are included in the current study.

ADHD status and study eligibility were determined using a multi-gated process. Children were excluded for parent report of neurological or sensorimotor disorders, pervasive developmental disorder, an estimated Full Scale IQ (FSIQ) <80, or use of any non-stimulant psychoactive medications (e.g., antidepressants). Typically developing children (without ADHD) with an IQ above 115 were also excluded.

Participants were assessed for ADHD using the DSM-IV criteria (American Psychiatric Association, 2013). A parent reported on symptomatology using the National Institute of Mental Health's Diagnostic Interview Schedule for Children–Version 4 (DISC-4), and both a parent and teacher completed the ADHD Rating Scale- IV (ADHD-RS; DuPaul, Power, Anastopoulos, & Reid, 1998), Conners Rating Scales–Revised (CRS-R; Conners, 2001), and Behavioral Assessment Scale for Children (2nd ed.; Barticulation speedC-2; Reynolds & Kamphaus, 2004).

Participants were placed in the ADHD group if parent or teacher reports indicated 6 or more Inattentive symptoms or 6 or more Hyperactive/Impulsive symptoms during the DISC-4 or ADHD-RS (1998), and if parent or teacher ratings exceeded the 85th percentile on either the Cognitive Problems/Inattention, Hyperactivity, or ADHD Index subscales of the Conners or the Attention Problem or Hyperactivity subscales of the BASC-2. ADHD Subtype was determined using the "or" algorithm (Lahey et al., 1994) to combine the DISC-4 and teacher ADHD-RS scores. Children with 5 symptoms of either hyperactivity/impulsivity or inattention were excluded, as subtype could not be confidently determined.

Participants were placed in the non-ADHD Control group if parents and teachers endorsed 3 or fewer Inattentive symptoms and 3 or fewer Hyperactive/Impulsive symptoms during the DISC-4 and ADHD-RS, if parent and teacher reports on all previously mentioned scales were below the 80th percentile, and if the child had no previous diagnosis of or treatment for ADHD.

All children who were prescribed psychostimulant medications were required to complete a medication-free “wash-out” period of 24 or 48 hours before testing. ADHD and non-ADHD participants were not specifically matched, but age was balanced across both groups. Comorbid diagnoses were allowed to vary naturally. Because there are established gender differences in the timing of language development throughout childhood and preadolescence (Whiteside, Dobbin, & Henry, 2003; Yu, De Nil, & Pang, 2015), and in ADHD prevalence (American Psychiatric Association, 2013), participant gender is included as a possible moderator in all analyses.

Of the 192 children included within this study, 173 completed the SSRT task. 10 children (9 with ADHD, 1 without) were excluded from analyses due to insufficient accuracy (<70%), resulting in a total 163 children included in analyses of motor Reaction Time. Excluded children were significantly younger than those included (p=.009), but did not differ in gender, estimated IQ, or number of inattentive or hyperactive symptoms (All $p<.160$, all $n^2<01$).

Measures

All participants completed the following measures as part of a larger test battery completed during two 3-hour sessions.

Working memory tasks

Reading span. The reading span task is one of several Eprime-based working memory tests provided by Randall Engle and colleagues (Conway et al., 2005). For the first section of the reading span task, children are presented short sentences on the computer screen, and are prompted to read them aloud before determining if they are true or false. For the second section, children view a 4x4 grid of boxes, and watch, as individual boxes turn red. A blank grid then appears, and the child is prompted to select the box (or boxes) that previously turned red. 3 trials are presented for each span of red boxes, and the task is discontinued when the child cannot correctly recall all 3 trials within a set. In the final section, the two prompts are combined: true/false sentences are interspersed between each box, and box recall is measured in the same way as previously.

Symmetry span. The symmetry span task is also one of several Eprime-based working memory tests provided by Randall Engle and colleagues (Conway et al., 2005), and followed the same procedure as the reading span task above, but rather than reading sentences, children are presented with a design made by the red and white boxes on the 4x4 grid, and asked to determine if the design is symmetrical or non-symmetrical.

Digits backwards. This portion of the Digit Span task from the WISC-IV (Wechsler, 2003) assesses verbal working memory. Children listen to a trained research assistant list a series of digits at a rate of one digit per second. They then are told to recall the list of digits in the opposite order in which they were originally recited. Two sets of digits are recited per digit span length, and the task is discontinued when the child cannot correctly recall either set of digits within the same span length.

Motor Reaction Time.

The Stop Signal Reaction Time (SSRT) Task was administered to assess fine-motor based reaction time to a simple forced-choice (Logan, 1985). The task includes 200 total trials administered as 5 blocks of 40 trials each. For 75% of trials ("go" trials), an "X" or "O" was displayed on the center of a computer screen for 1,000 ms, and children were required to make the forced-choice decision and respond by pressing a key on a stimulus box to correctly identify which letter was displayed. For the other 25% of trials ("no-go" trials"), the program also presented an auditory tone, which signaled the children to not give any response.

Following criteria previously used for similar analyses (Karalunas & Huang-Pollock, 2013), "go" trials immediately following "no-go" trials were excluded so as to reduce the possible effect of inhibitory control on the RT distribution (Schachar et al., 2004). RTs <150ms were also excluded, as they are believed to reflect anticipation rather than genuine reaction time. This resulted in a minimum of 76 trials per participant, with a mean of 100 (sd=9).

Articulation speed.

Task description. During the task, participants are instructed to listen to digital audio recordings of a female voice reciting stimuli at the rate of one item per second, followed by a computer-generated tone signaling the end of stimuli presentation. Participants then respond by repeating the same stimuli into a microphone as quickly as possible. The stimuli include 23 trials split into practice, experimental, and fatigue sections. The practice section includes 3 trials of the ordered digits 1-10, 3 trials of the ordered letters A-G, and 2 trials of the ordered digits 1-3. The Experimental section includes 3 trials of 2 random digits, 3 trials of 3 random digits, and

3 trials for 4 random digits, all randomly ordered. The fatigue section includes 3 trials of the ordered digits 1-10 and 3 trials of the ordered letters A-G.

Parts of speech. Each response is divided into several components detailed below; figure 3 provides an example. The preparatory interval measures the time between the computerized tone prompting the child's response and beginning of speech. Speech Duration represents the entire length of time the participant was articulating a response, and was calculated by subtracting the end of the last item spoken from the start of the first item spoken. Analyses are conducted using preparatory interval and speech rate, which was calculated by dividing Speech Duration by the total number of items in the stimuli.

Coding procedure. Previously published studies using waveforms for visual and audio coding in both cognitive psychology and linguistics journals have used widely varied software programs and audio criteria (Cowan, 1992; Cowan et al., 1992; Finneran et al., 2009; Hulme et al., 1999; G. Neuhaus et al., 2001; G. F. Neuhaus, Carlson, Jeng, Post, & Swank, 2001; Towse, Cowan, Horton, et al., 2008; Van De Voorde et al., 2010), as such, the authors of this project chose the audio program with the best functionality, and underwent multiple coding trials to determine the best criteria for the available data. Audacity®, an open-source software for recording and editing audio, (web.audacityteam.org) was selected for its comprehensive interface, which allowed for detailed viewing of waveforms.

One data collection site was found to have substantially greater background noise/static in the samples, which obfuscated the computer's stimulus tone or part of the child's response. Therefore, all samples collected at this site underwent standardized noise removal. Because audio recording continued for roughly 2 seconds after participants completed their response, the end of each file includes solely ambient "background noise". The final .25 seconds of this "background noise" was identified using Audacity's "noise removal" function, and the program removed all comparable noise from the entire sample. Because the second data collection site had minimal background noise/static, "noise removal" was found to be unnecessary and coding was most accurate when not conducted at this site.

Though Audacity includes a "sound finder" function designed to automatically identify and label all sections exceeding specified changes in amplitude, extensive pilot testing could not establish standardized amplitude criteria that was able to accurately identify the start and stop of the signal tone or the start and stop of speech. It is likely that this difficulty is due to both high levels of variation in audio quality and individual differences in participant speech volume and patterns. As such, all coding used for analysis was completed by an individual research assistant, who completed an extensive initial training with the author and met reliability criteria throughout the coding process (described in detail below).

All audio files were standardized to equalize variations in amplitude, and the display was magnified to a minimum range of -.5 to .5 linearly transformed decibels. Time was also magnified such that gridlines marked time to .01 seconds. Correct start and stop points were determined primarily visually using the waveform display to identify the point at which amplitude decreased and returned to baseline levels. Audio playback was also used to confirm decisions made visually.

Reliability procedure. 20% of all audio samples were coded a second time, by the author, to test for coding reliability and consistency over time. Trials from 26 participants were used during initial training and to establish preliminary reliability; these participants are not included in any of the following reliability statistics. The following three specific time points were needed from each audio file to calculate preparatory interval and speech rate: the end of the computerized tone, the beginning of speech, and the end of speech. Interrater reliability was calculated for each of these three variables by examining correlations between the primary and secondary coder. Based on common conventions (LeBreton & Senter, 2007; Shrout & Fleiss, 1979), reliability was assessed by measuring the Pearson Correlation of the time points for both raters. Final correlations for end of tone, start of speech, and end of speech were r=.846, .987, and .989 respectively. Because all correlations were equal to or above the common r= .80 criterion (Shrout & Fleiss, 1979), all coding was considered reliable.

<u>Data Analysis Plan</u>

Demographics. Initial analyses will be conducted to compare the ADHD and control groups on key community demographic variables. Child age and IQ will be assessed as dependent variables in one-way ANOVAs and child gender will be assessed using a chi-square test, with ADHD group status as the independent variable. Null results will suggest that the samples of children with and without ADHD participating in the study are sufficiently similar.

Hypothesis Testing. Diagnostic group differences in WM span performance, fine-motor RT, preparatory interval, and speech rate will be assessed using multiple regression to confirm that children with ADHD have poorer working memory and slower processing when indexed with Mean Reaction Time. The normality of motor RT, preparatory interval, and speech rate will be assessed using traditional data exploration techniques, then ex-Gaussian distribution parameters (mu, sigma, and tau) will be fitted using criterion set by LaCouture and Cousineau's "egfit" statistics in MATLAB (2008). It is expected that all three RT variables will demonstrate positive skew (tau), indicating a better ex-Gaussian than normal distribution fit. Multiple regressions will then compare diagnostic group differences in the ex-Gaussian parameters mu, sigma, and tau. It is expected that no differences will be found in mu, though the ADHD group is expected to have higher sigma and tau indicating greater variability and positive skew towards slow responses. Additional multiple regressions will be used to determine if higher sigma and tau predict poorer performance on verbal and visuospatial working memory tasks as expected.

Factor Analyses will be conducted using SPSS to develop latent "speed" factors by combining and consolidating the ex-Gaussian parameters from fine-motor RT from the SSRT task and preparatory interval and speech rate from the Articulation Speed task. Working Memory performance will then be regressed on these factors, and it is expected that worse performance on these "speed" factors will predict worse Working Memory performance. As with analyses using individual processing speed variables, the moderating effect of participant gender will also be assessed.

Results

Preliminary Group Analyses.

Table 1 provides descriptive statistics. Validating the diagnostic groups, children with ADHD had more inattentive, *F*(1,191)= 411.389, *p*<.001, and hyperactive symptoms, *F*(1,191)= 66.663, *p*<.001, than typically developing controls. There were no group differences in age *F*(1,191)= .460, *p*=.498 or FSIQ *F*(1,191)= .921, *p*=.339. Consistent with expectations, there were more boys (n=91) than girls (n=53) with ADHD, compared to typically developing controls X^2 (1, *N*=191)=6.841 , *p*=.011. Gender will be included as a moderator in the following analyses.

Diagnostic Group Differences on Working Memory Performance.

Table 2 provides means and SDs of performance for all dependent variables. Table 3 provides summary statistics from group analyses. Children with ADHD had significantly worse recall than controls for verbal (Reading) and non-verbal (Symmetry) complex span tasks, (all p<.01, all β<-5), but not for Digit Span Backward (See Table 3). There were no significant main effects of gender (all *p*>.05, all β<-6) on any index of working memory. There were also no interactions between ADHD status and gender (all *p*>.75, all β>2.09, <-0.55).

Diagnostic Group Differences on Traditional RT Parameters.

Compared to non-ADHD controls, children with ADHD had slower Stop Signal Reaction Times (*p*=.001, β=.83.731) but did not differ on mean or standard deviation of motor RT, preparatory interval, or speech rate (all *p* >.06, all β>-5.6, <.26.75; see Tables 2 and 3). There was an unexpected main effect of gender where girls had slower/larger mean motor RT, as well as larger standard deviation for motor RT, preparatory interval, and speech rate, (all p <0.02, all β>61.2). There were no significant interactions between ADHD status and gender on any of these traditional RT parameters.

The Coefficient of Variance (CV), which is the ratio of the standard deviation of RT to Mean RT (i.e. SD/Mean) has often been used as an index of variability which controls for the fact that standard deviation and mean reaction times are positively correlated. The CV therefore represents variability in performance controlling for mean RT (Whiteside et al., 2003). It was thought to be particularly appropriate here as a method to address generally slower speeds found in the motor vs. articulation task. Compared to non-ADHD controls, children with ADHD had larger CV for motor RT, (*p*=.005, β=0.03), and marginally larger CV for speech rate (*p*=.06, β=-0.041). There were also main effects of gender, such that boys had greater CV for preparatory interval (p <.001, β=-.281), but girls had greater CV for speech rate (*p*=.03, β=.041). There were no significant interactions between ADHD status and gender on CV for motor RT, preparatory interval, or speech rate, see Table 3 for details.

Diagnostic Group Differences on Ex-Gaussian RT Parameters.

Tests of normality (see Table 4) confirmed that the RT variables are not well described by a normal distribution. Histograms for motor RT, preparatory interval, and speech rate (Figures 4a, 5a, and 6a) all demonstrate positive skew, with a greater number of very slow than very fast responses. This is also supported by the QQ plots (Figures 4b, 5b, and 6b), which do not follow a linear fit-line and curve up on the positive (right) tail. Instead, ex-Gaussian parameters mu and sigma (representing the mean and standard deviation of the normal portion of the distribution) and tau (representing the mean of the exponential tail of the distribution) were better fits to the data.

There were no diagnostic group differences in mu, sigma, tau, or ex-Gaussian CV (sigma/mu) for motor RT, preparatory interval, or speech rate (all $p>.06$, all $\beta<19.4$; see Table 3). There was, however, a main effect of gender in which girls had longer preparatory interval, slower speech rate mu, and slower motor RT tau (all $p<.04$, all $\beta >19.3$) than boys. There were no interactions between ADHD status and participant gender (all $p>0.17$, all $\beta <18.37$).

Ex-Gaussian RT Parameters Predicting Working Memory.

Mu, sigma, tau, and ex-Gaussian CV (sigma/mu) for all speed measures did not predict Reading Span, Symmetry Span, or Digit Span Backwards performance (all $p >0.06$, $\beta < -15.68$; See Table 5), with the following exceptions. Greater speech rate mu and sigma were associated with worse performance on Reading Span ($p=.041$, $\beta=-0.027$; $p=.048$, $\beta=-0.04$), and larger preparatory interval CV was associated with worse performance on Digit Span Backward ($p=032$, $\beta=-1.23$). Greater MRT tau and preparatory interval were also associated with worse performance on both Reading and Symmetry Span (all $p<.05$, $\beta>-0.07$). There was a single significant gender x speech rate interaction, such that slower speech rate mu was associated with worse performance on Digit Span Backward for girls but not boys (*p*=.049, β=.-0.011; See Figure 7).

Of the ex-Gaussian RT parameters that were associated with working memory performance, ADHD status was not a moderator (See Table 6). The lack of an interaction suggests that the mechanisms behind working memory differences function similarly for children with and without ADHD. That is, more variable and more heavily skewed reaction time reflects impaired attentional control universally, and in turn, leads to worse working memory.

Multi-Measure Reaction Time Factors Predicting Working Memory.

An initial factor analysis including all mu, sigma, and tau parameters for motor RT, preparatory interval, and speech rate resulted in a 4 factor model. Factors 1-3 each represented the combined mu and sigma for each measure of RT, while Factor 4 represented the combined taus across all measures. These factors are conceptually valuable because they separate the parameters representing the normal portion of the distribution (mu and sigma) from the parameter representing the exponential portion of the distribution (tau). The scree plot can be seen as Figure 8, and the Component Matrix is Table 7.

The overall Tau factor (Factor 4) was significantly associated with poorer performance on Reading and Symmetry complex span tasks, (all p<.01, all β>-2.0; see Table 8), but there was not a significant interaction between Factor 4 and ADHD on working memory (*p*>.6, β<.21) (see Table 6). There were no significant associations between Factors 1-3 (representing combined mu and sigma for each RT measure) on any of the Working Memory measures (all *p*s>.09; see Table 8). There was a significant interaction between participant gender and Factor 2 (motor RT mu and sigma), such that for girls but not boys, greater combined speech rate mu and sigma was associated with poorer performance on Digit Span Backward (*p*=.031, β=.-0.894). There were no other interactions between participant gender and RT. See Table 8 and Figure 9 for details.

Post-hoc alternative factor analyses

Because mu and sigma clustered together by measure in the initial factor analysis, a second factor analysis was conducted using the CV (sigma/mu) to allow those two parameters to combine into a single, and potentially more comprehensive/conceptually meaningful, variable. The CV for each speed measure was entered into the factor analysis along with tau for each speed measure (see Table 9a for the component matrix). This did not provide a more meaningful set of factors than the initial factor analysis; instead, it resulted in a 3 factor model in which the CV and tau of each measure grouped together respectively. This resulted in a model which essentially undermined the value of describing the distributions with multiple parameters rather than relying solely on mean RT. As such, this second FA was discarded.

Two other alternative factor analyses were examined. In the first (Table 9b), mu was excluded on the grounds that it is conceptually distinct from sigma and tau because it does not measure variability. In the second (Table 9c), speech rate was excluded on the grounds that it is conceptually distinct from motor RT and preparatory interval because it does not index response initiation. Neither factor analyses were more appropriate than the initial factor analyses using all 9 processing speed parameters (Table 7).

Discussion

Slower mean reaction time (Barrouillet et al., 2004; Bayliss et al., 2005; Kail, 1992; Kail & Park, 1994; Kail & Salthouse, 1994) and greater intraindividual variability (i.e. SDRT and the ex-Gaussian parameter tau) (Kofler et al., 2013; Mella et al., 2015; Schmiedek et al., 2007), have long been found to be negatively associated with working memory capacity. In fact, major theories of working memory capacity including the Task Switching Theory and the Time-Based Resource Sharing (TBRS) Model, have argued that developmental changes in processing speed are responsible for developmental changes in working memory recall (Barrouillet et al., 2009; Bayliss et al., 2005; Cowan et al., 1994; Towse et al., 1998). The TBRS (Towse et al., 1998) has argued that this relationship exists because faster speed gives more time to refresh to-be-recalled items, leading to better WM. Others have argued that greater variability in speeded performance (commonly found in ADHD) reflects inconsistent attention and encoding (Buzy et al., 2009; Lijffijt et al., 2005) and that poor WM can be at least partially explained by these attentional lapses (Mella et al., 2015; Schmiedek et al., 2007; Shahar et al., 2014). Some have recently integrated this literature and argued that individual differences in processing speed may be able to explain individual differences in working memory, particularly in those with ADHD (Buzy et al., 2009; Karalunas & Huang-Pollock, 2013). The majority of this previous body of work has come from studies examining the relationship between motor processing speed and WM capacity. However, articulation speed is an aspect of speeded performance that has not previously been examined in children with ADHD, and may be particularly relevant to verbal working memory processes as a reflection of time required to subvocally rehearse in the phonological loop.

Consistent with the above literature, the current study found that regardless of diagnostic status, larger tau for preparatory interval and larger tau on a motor reaction time task were associated with worse verbal and non-verbal working memory span. There were no interactions between tau and ADHD status. When the ex-Gaussian parameters for preparatory interval, speech rate, and motor speed were all combined in a factor analysis, only Factor 4, which represented the shared variance of tau from all 3 measures of processing speed, predicted performance on the verbal and visuospatial complex span tasks. There was no interaction between Factor 4 and ADHD status on working memory, and Factors 1-3, which represented shared variance for mu and sigma for each of the 3 measures separately, were not predictive. Thus, the more highly skewed the distributions for both motor RTs and preparatory interval were, the worse performance became on the complex span tasks, regardless of ADHD status. This latter analysis is particularly convincing because combining measures using multiple assessment techniques reduces the effects of possible methodological confounds. As a result, the tau factor combining motor RT, preparatory interval, and speech rate is a more robust measure of response variability than any single assessment method. These results also further highlight the value of methods such as ex-Gaussian analyses which enable isolating individual components of the RT distribution. Specifically, previous (Karalunas & Huang-Pollock, 2013) and current analyses indicate that rather than examining overall processing speed, research should aim to better understand the ways in which lower level mechanisms (such as attentional lapses) may be more strongly linked to WM deficits.

Because it represents the time between the onset of a “go” signal and the beginning of a verbal response, preparatory interval conceptually mirrors motor RT in that it measures the time required for an individual to initiate a response. Two-alternative forced-choice and simple reaction time tasks remain the standard indices for processing speed (Barrouillet et al., 2004; Bayliss et al., 2005; Kail, 1992); however, there are several important advantages of utilizing an articulation speed task rather than, or in addition to, a motor RT task when indexing processing efficiency. First, as designed, the current articulation speed task did not require children to make a forced choice decision before initiating the appropriate response, and thus represents a presumably more pure measure of simple speed that exclusively captures the time required to generate a single (and in this case, overlearned) response. Recent studies using advanced statistical techniques such as Drift Diffusion Modeling (DDM) have been able to tease apart processing time, decision time, and motor initiation time (Karalunas & Huang-Pollock, 2013; Weigard & Huang-Pollock, 2014; White, Ratcliff, Vasey, & McKoon, 2010), but are still not universally applied. The value of tasks such as articulation speed, as designed and applied in the current study, is that it does not require a decision, which then must be parsed out, to be made in the first place. Second, though motor RT tasks often use verbal stimuli (e.g., “is this a word or non-word?” or “is this an X or an O?”), they are not typically designed to focus on verbal processes and are just as likely to use non-verbal stimuli (e.g., “are there few or many?” or “square or circle?”). In contrast, articulation speed is a specifically verbal task. As such, it is expected to be particularly relevant to examining strengths or deficits in verbal working memory processes. This is because, as originally suggested by Baddeley and Hitch (1975), verbal working memory relies on the use of subvocal rehearsal (e.g., mentally repeating the stimuli) to maintain and refresh information within the phonological loop. As Baddeley suggests, the more quickly an individual is able to articulate a response, the more often they can practice it, and finally, the more likely they are to correctly recall it once prompted. Given the consistent links between verbal fluency and verbal working memory (Baddeley, 1981; Baddeley & Hitch, 1974; Bayliss et al., 2005) the value of measuring articulation speed to estimate performance on verbal memory tasks is clear.

Compared to boys, girls demonstrated slower mean motor RT, preparatory interval, and speech rate. They were also more variable (CV) in speech rate, but not preparatory interval. It is most likely that these differences in speed variability reflect idiosyncrasies within the sample rather than notable, true, gender differences. However, the greater variability in preparatory interval for boys is consistent with language development studies which have frequently found that boys' speech coordination to be more immature than that of age-matched girls (Walsh, Mettel, & Smith, 2015; Whiteside et al., 2003; Yu et al., 2015). That being said, girls had greater CV for speech rate, though the effect size was much smaller than for preparatory interval.

Although larger tau values have often been found on speeded reaction time tasks among children with ADHD, we did not find this to be the case in the current study. It is unlikely that these null results were caused by an inappropriate application of the ex-Gaussian analyses. Tests of normality, and visual inspection of the RT distributions indicated that motor RT and speech rate produced an ex-Gaussian distribution characterized by a negative parabolic curve similar to a normal distribution, but with the addition of the exponential tail. The distribution of preparatory interval more closely resembled a purely exponential distribution than an ex-Gaussian one (see Figure 5), and in that case, the tau parameter alone comprehensively describes the entire distribution, as shown in Figure 10 (Lacouture & Cousineau, 2008).

In the end, the lack of diagnostic group differences may simply be sample-specific. However, there are several methodological reasons that could also have affected findings. First, the current study's articulation speed task uses only 23 trials; 8 practice, 9 "experimental", and 7 fatigue stimuli. This is notably lower than the typical number of trails (70 or greater) used in previous research examining RT distributions (Buzy et al., 2009; Hervey et al., 2006; Karalunas & Huang-Pollock, 2013; Leth-Steensen et al., 2000). Given the lower trial number, it may be that that the obtained parameters are less robust than those typically obtained, and therefore, may not sufficiently represent the shape of the distributions for preparatory interval or speech rate.

Second, preparatory intervals were approximately 14 times faster than motor RTs (averaging 50-60 ms rather than 750-900 ms for motor RT; see also Figure 5). Although both represent the amount of time needed to initiate a response, the striking difference in the amount of time needed to do so likely represents categorically different cognitive demands. First, in the articulation speed task, from which the preparatory interval was taken, children were required to repeat either an overlearned sequence of stimuli (e.g. the letters A-G or numbers 1-10 in order) or a short sequence of random digits (max 4) which did not require any decision-making processes. Perhaps most importantly, however, children were given a tone lasting 250ms that allowed them to prepare their response prior to the response being recorded. In contrast, the motor reaction time task (a) is a two alternative forced choice task (X or O), for which the RT necessarily includes the amount of time needed to make a decision, and (b) does not provide preparation-time. Therefore, the removal of the decision-making aspect found in most RT tasks could account for the striking time difference between preparatory interval and reaction time. Consistent with this analysis, a recent study found that when a forced-choice decision was required for a verbal response, the preparatory interval was slower than a traditional motor forced-choice task (Piai, Roelofs, Acheson, & Takashima, 2013). The lack of diagnostic group differences on preparatory interval in turn suggests that the slower mean RTs typically found in children with ADHD may ultimately reflect slower or more variable *decision-making*, rather than slower or more variable basic processing speed.

Third, though used in the current study as a way to eliminate the confounding influence of motor discoordination on traditional motor RT tasks, the generation of speech is a highly complex process which may not be sufficiently addressed within the current task and study. Because the current articulation speed responses are more varied (e.g., the letter “A” or the first sound of any of the numbers 1-10) than those used in mRT task (e.g, either the “X” or “O” button), results may be muddied by the multiple sounds initiating each vocalization.

Specifically, response initiation may be consistently faster or slower for “voiceless” plosives (e.g., “p”, “t”, and “k”) than their “voiced” cognates (e.g. “b”, “d”, “g”) (Whiteside et al., 2003). With only 23 trials and so many possible vocal responses, the current task is not capable of fully exploring the ways in which different vocalizations might influence reaction time. That being said, even after accounting for slower mean speed, preparatory interval had greater variability (mRT CV=.29; preparatory interval CV=.99) and skew (mRT tau/mu=.29; preparatory interval tau/mu=19.33) than motor RT. It is likely that this greater variability in response time for articulation speed than in motor response is at least in part due to the greater variability in possible responses.

Impaired processing speed is among one of the most prominent cognitive signatures in Attention Deficit Hyperactivity Disorder (ADHD). However, the nearly exclusive use of mean motor reaction time to index processing speed limits the ways in which variability in response time can be explored. The current study had two primary goals. First, to use ex-Gaussian parameters to more accurately and comprehensively describe the variability within distributions of reaction times, from both traditional motor and speech-based reaction time tasks in children with and without ADHD. Second, to clarify the association between these parameters of reaction time variability and performance on complex working memory tasks. Preparatory interval tau, motor RT tau, and a factor combining tau from preparatory interval, speech rate, and motor RT were all associated with worse verbal and non-verbal working memory span, regardless of ADHD status. The association between tau, but not mu or sigma, and working memory suggests that observed WM deficits may largely be due to lapses in attention during encoding, rather than truly slower processing speed, and highlights the importance of clarifying the specific mechanisms demanded during cognitive tasks.

Figures and Tables

Figure 1. Robert Kail's model in which age-related improvements in processing speed also improve working memory via articulation speed.

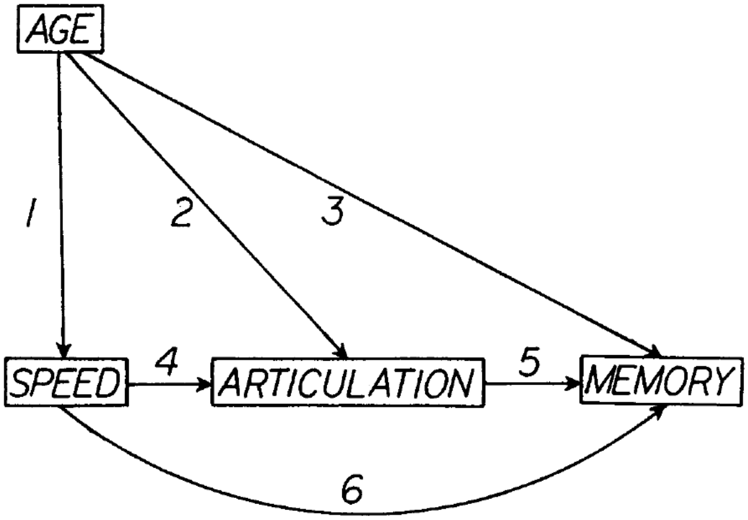

Figure 2. Functions for A) a Gaussian (normal) distribution with mu=500ms, sigma=100ms; B) an exponential distribution with tau = 250ms, and the resulting C) combined ex-Gaussian distribution.

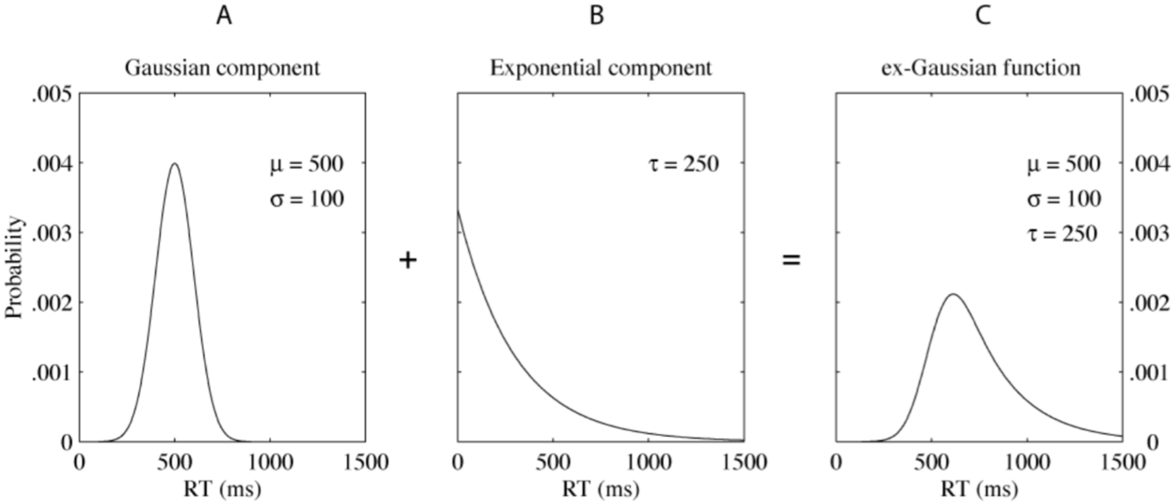

Figure 3. A waveform display of an example articulation speed task response. The end of the computerized tone and participant speech can be seen, and the articulation speed variables are labeled.

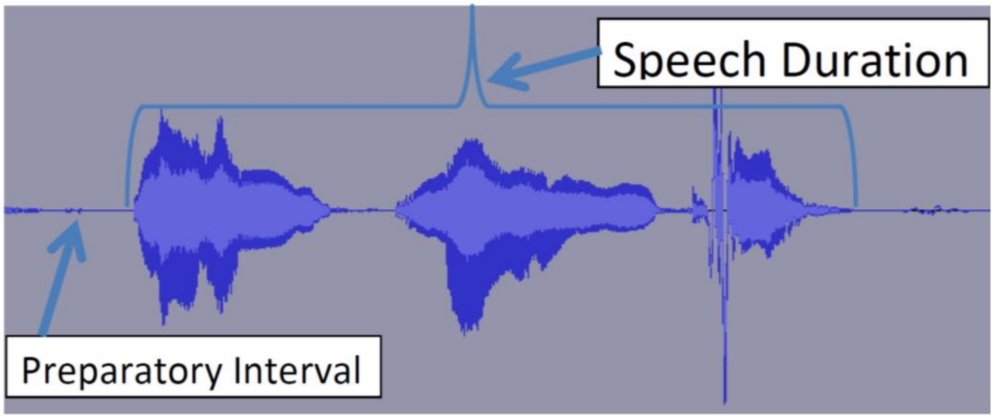

Figure 4a. A histogram of all motor reaction time trials for all participants, separated by ADHD diagnostic status.
Dotted lines represent the normal curve most appropriate for the given trials.

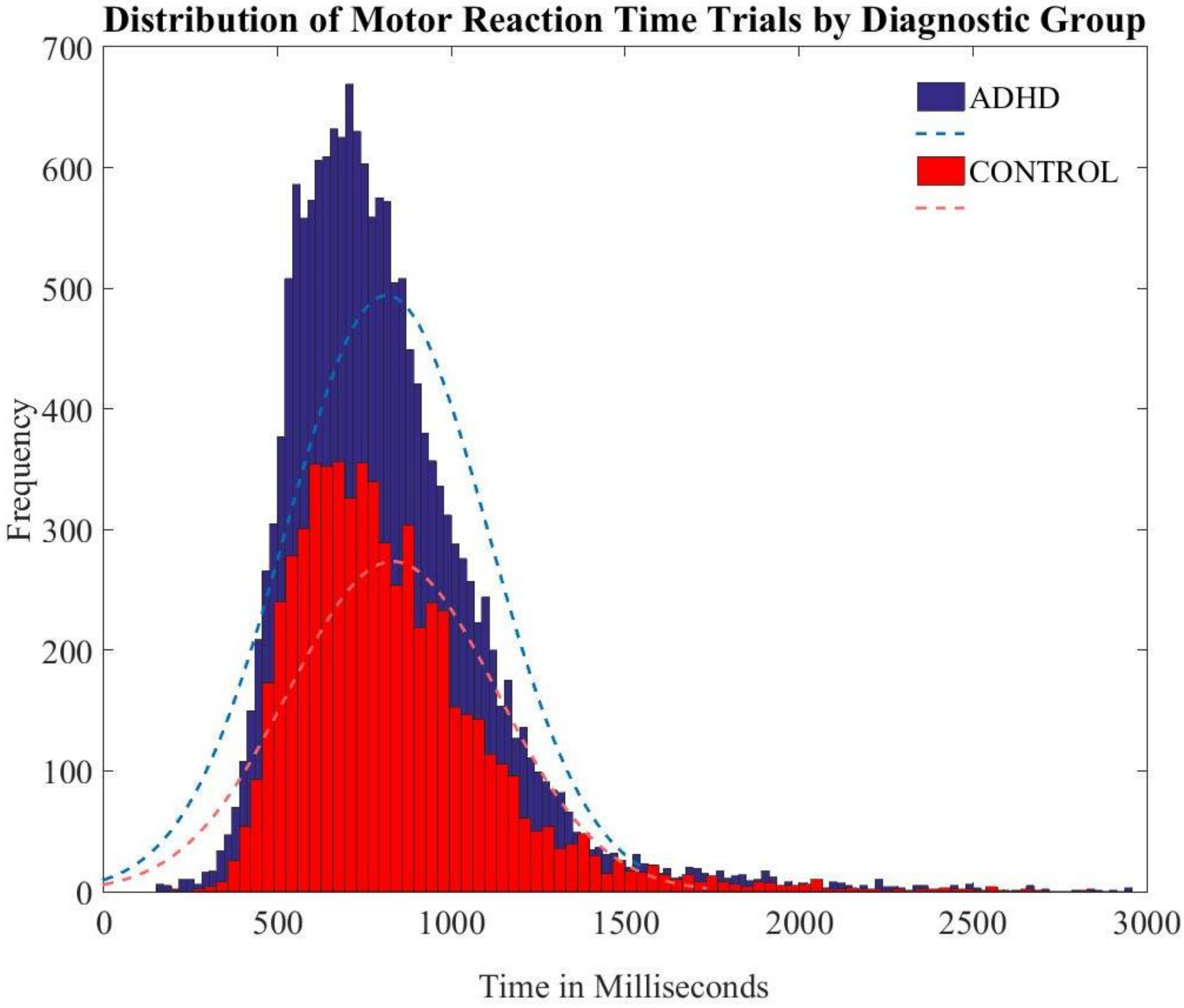

Figure 4b.

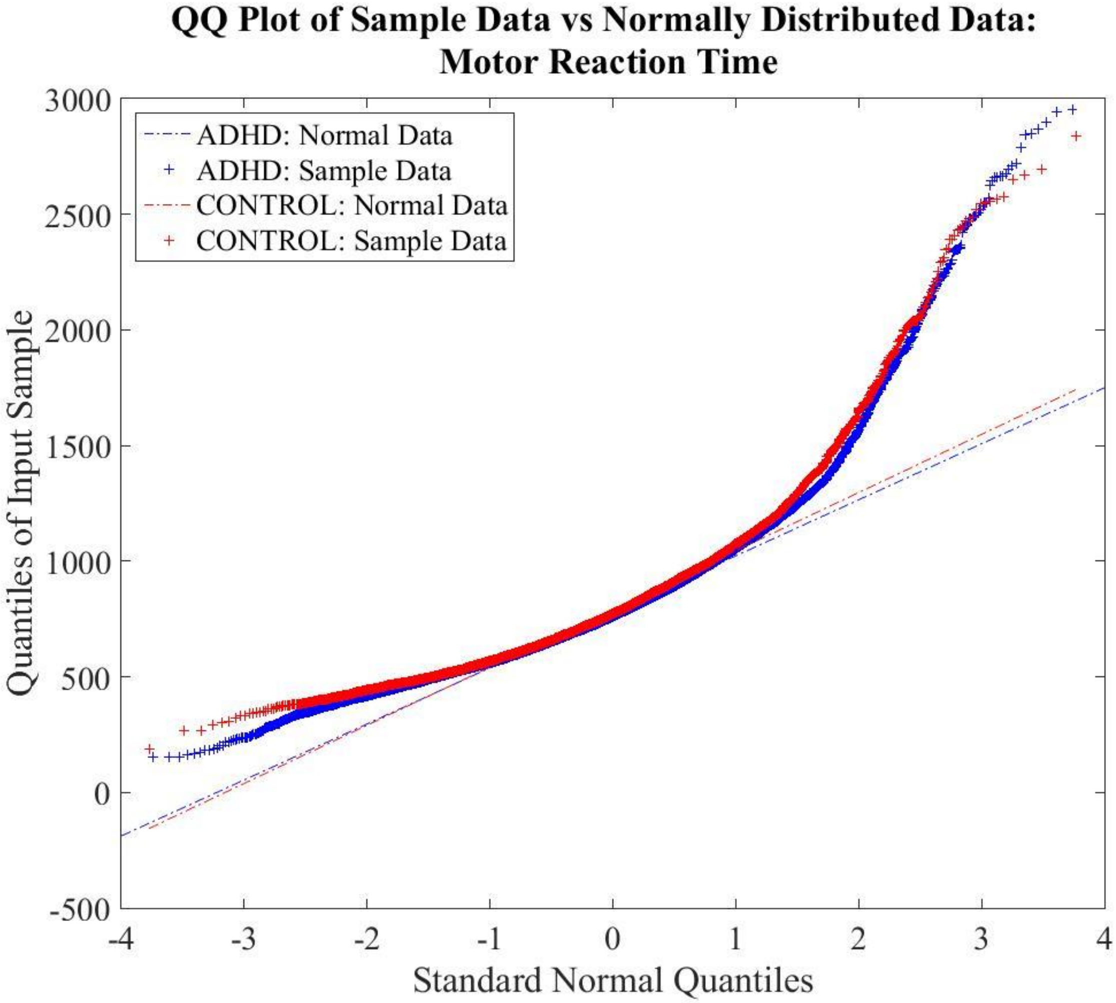
QQ Plot of Sample Data vs Normally Distributed Data:
Motor Reaction Time
ADHD: Normal Data
ADHD: Sample Data
CONTROL: Normal Data
CONTROL: Sample Data
Quantiles of Input Sample
3000
2500
2000
1500
1000
500
0
-500
-4
-3
-2
-1
0
1
2
3
4
Standard Normal Quantiles

Figure 5a. A histogram of all preparatory intervals for all participants, separated by ADHD diagnostic status.
Dotted lines represent the normal curve most appropriate for the given trials.

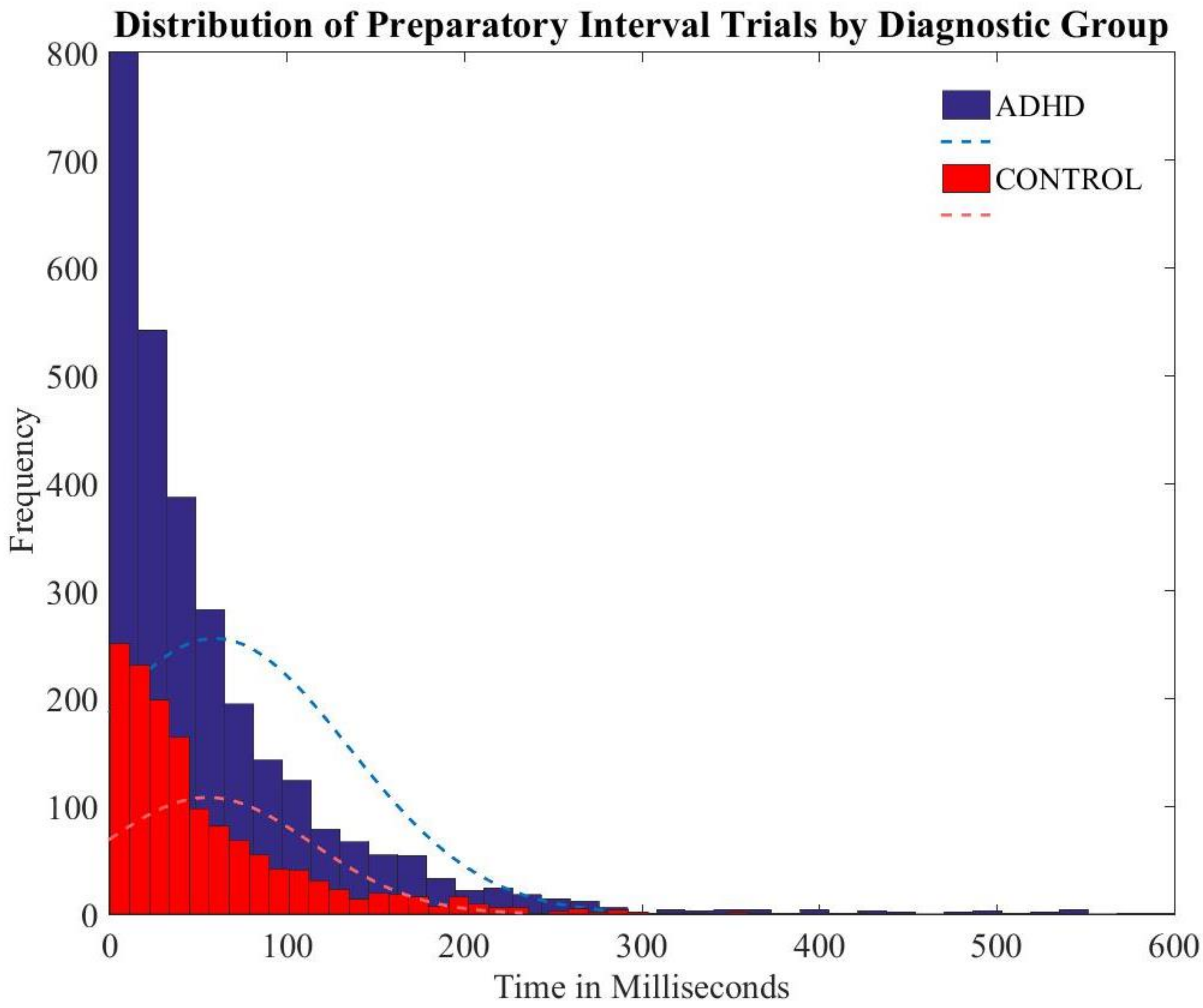

Figure 5b.

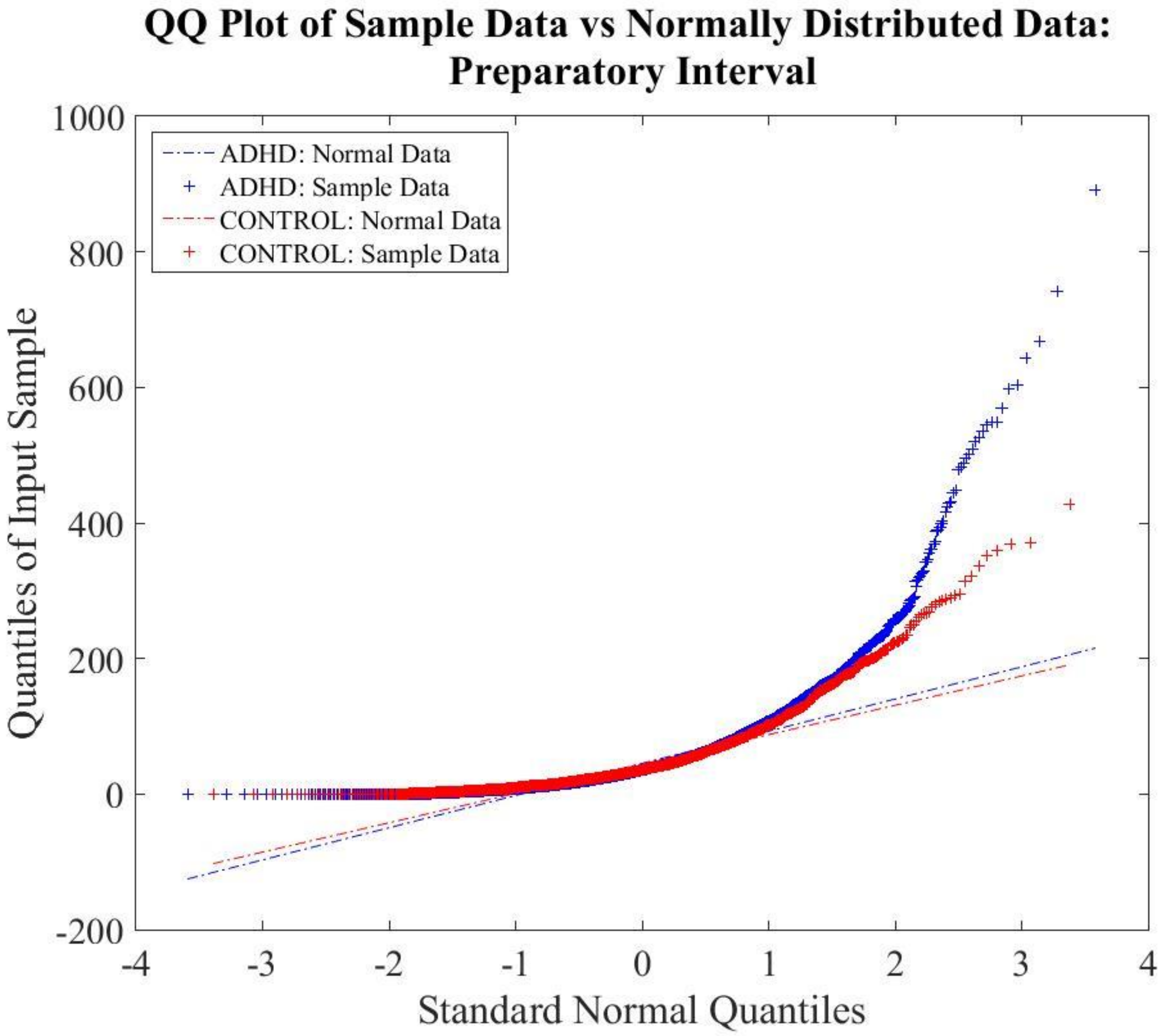
QQ Plot of Sample Data vs Normally Distributed Data:
Preparatory Interval
ADHD: Normal Data
ADHD: Sample Data
CONTROL: Normal Data
CONTROL: Sample Data
Quantiles of Input Sample
1000
800
600
400
200
0
-200
-4
-3
-2
-1
0
1
2
3
4
Standard Normal Quantiles

Figure 6a. A histogram of all speech rate trials for all participants, separated by ADHD diagnostic status.
Dotted lines represent the normal curve most appropriate for the given trials.

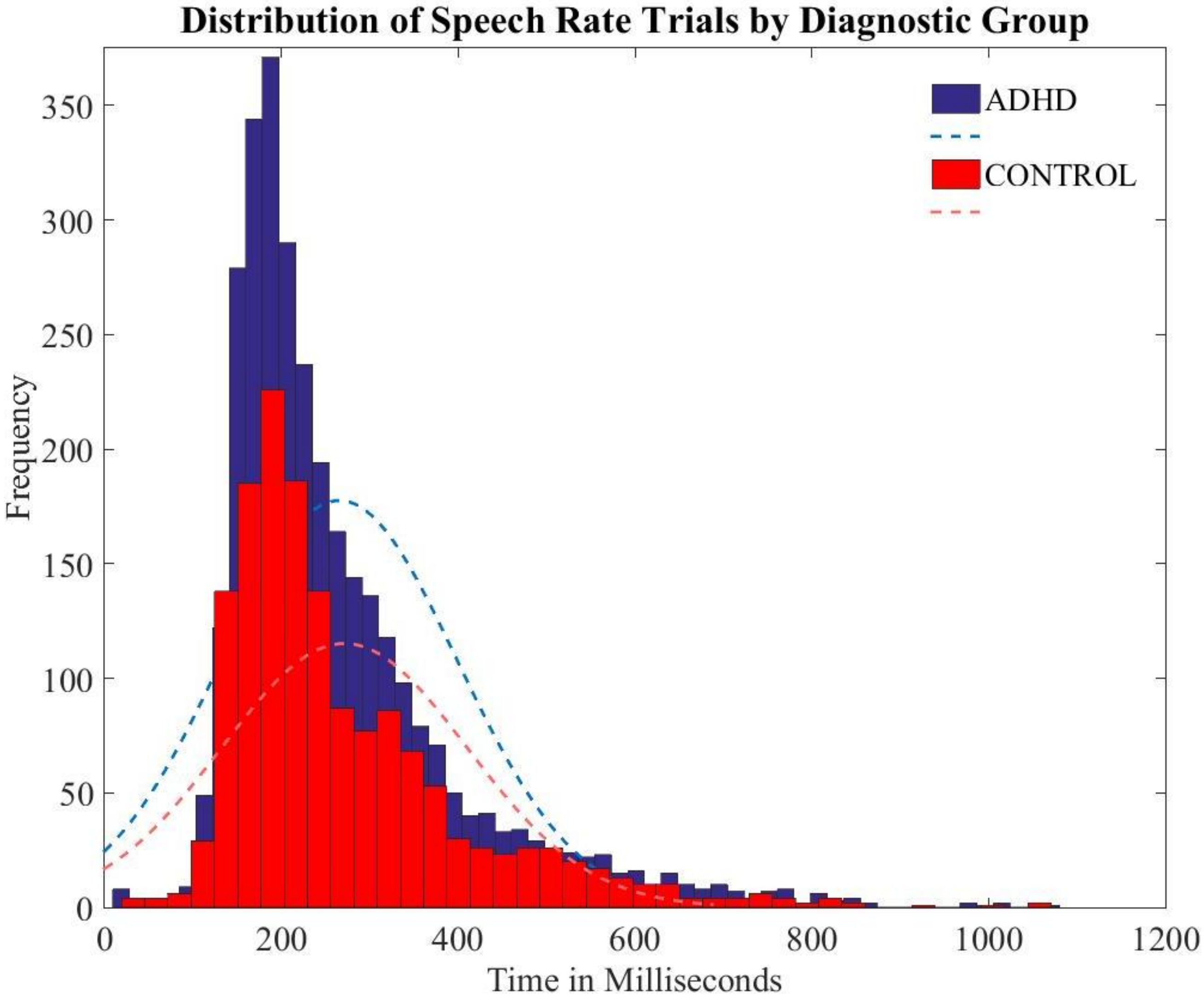

Figure 6b.

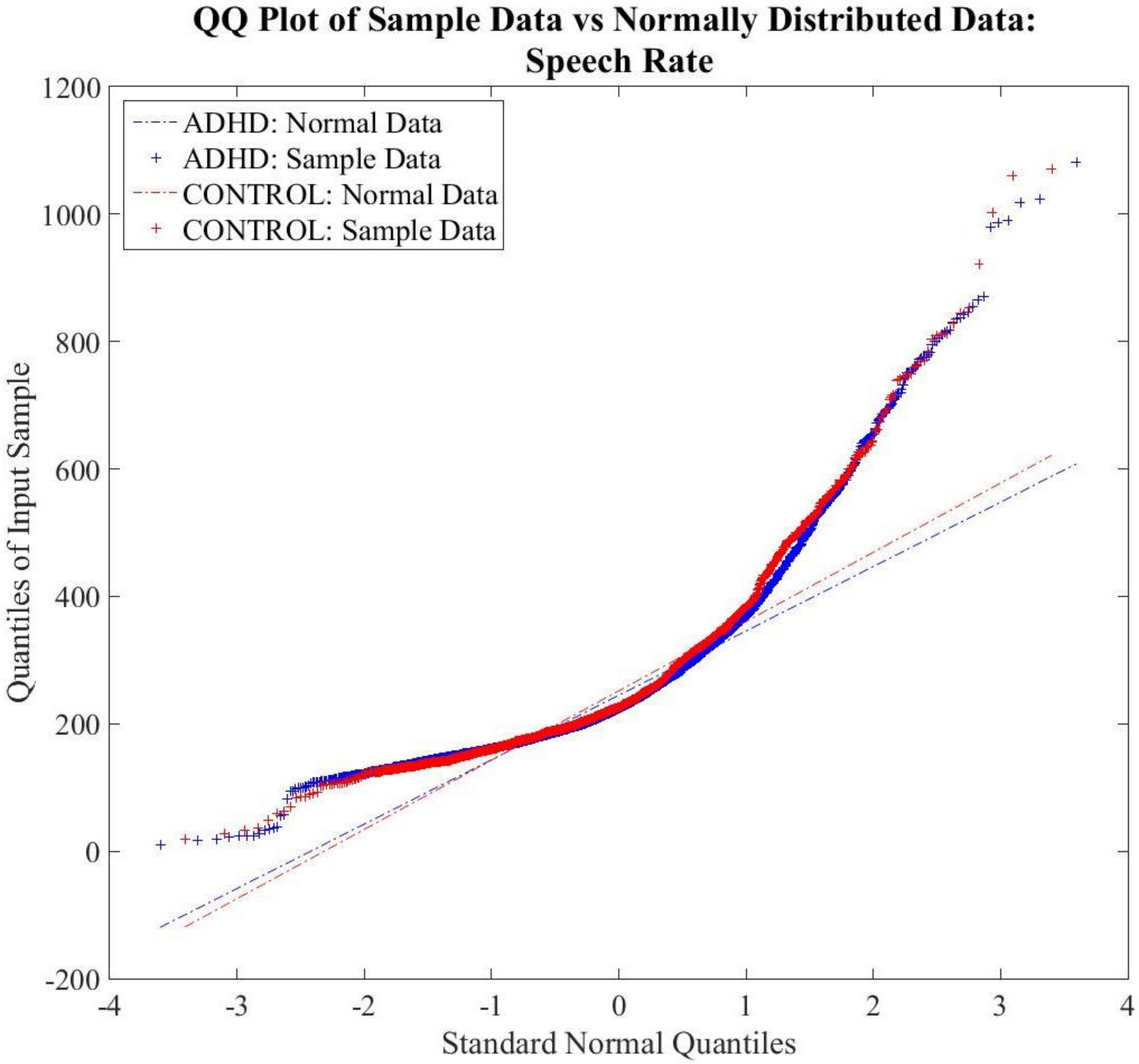
QQ Plot of Sample Data vs Normally Distributed Data:
Speech Rate
ADHD: Normal Data
ADHD: Sample Data
CONTROL: Normal Data
CONTROL: Sample Data
Quantiles of Input Sample
Standard Normal Quantiles
1200
1000
800
600
400
200
0
-200
-4
-3
-2
-1
0
1
2
3
4

Figure 7. Scatterplot of the significant interaction between participant's gender and speech rate mu on performance in Digit Span Backwards.

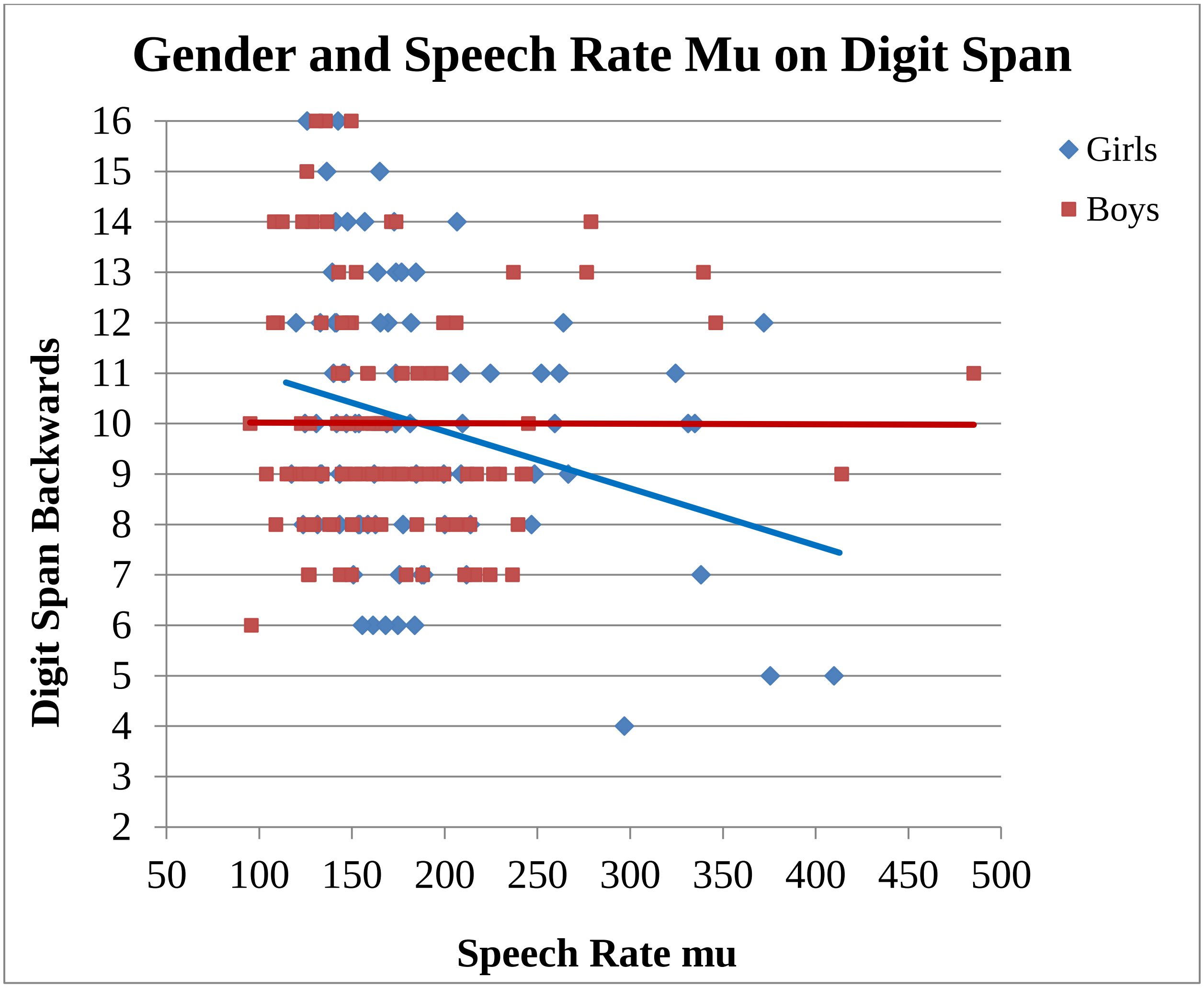

Figure 8. Scree plot for factor analysis of ex-Gaussian processing speed parameters. Components are, in order: motor RT mu, motor RT sigma, motor RT tau, preparatory interval mu, preparatory interval sigma, preparatory interval tau, speech rate mu, speech rate sigma, and speech rate tau.

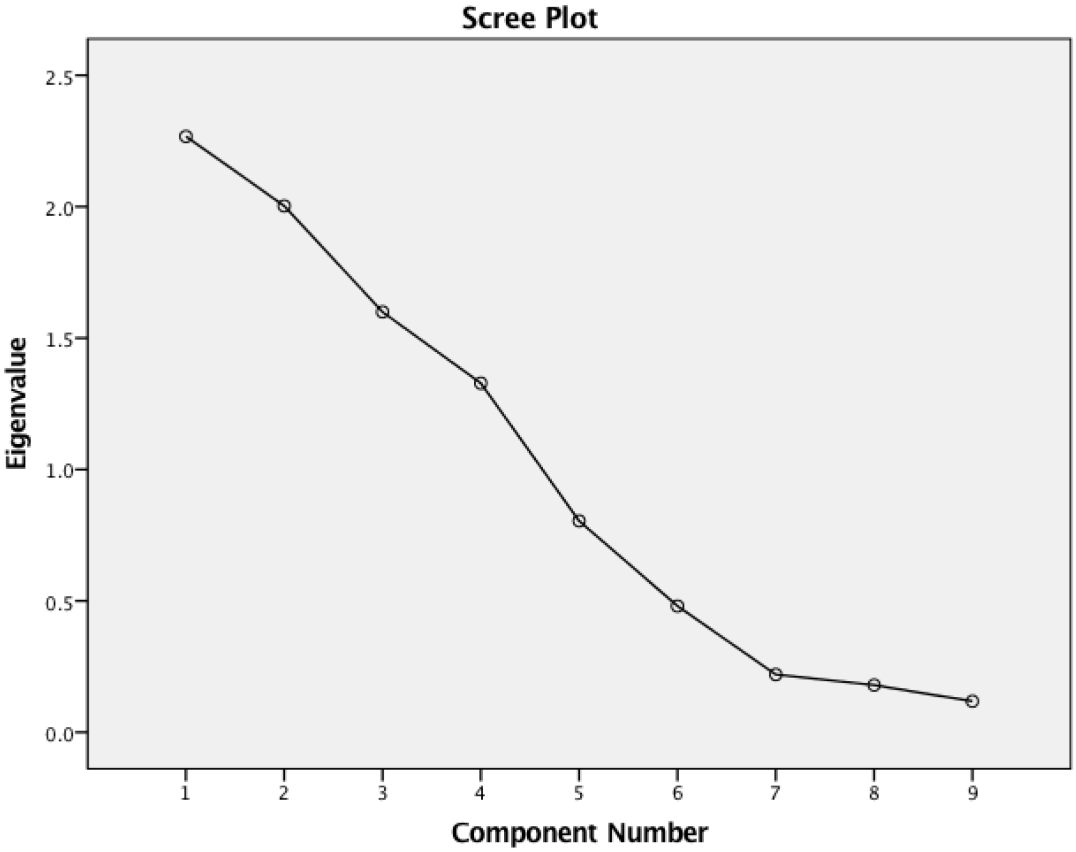

Figure 9. Scatterplot of the significant interaction of participant gender and Factor 2 (speech rate mu and sigma) on digit span backward performance.

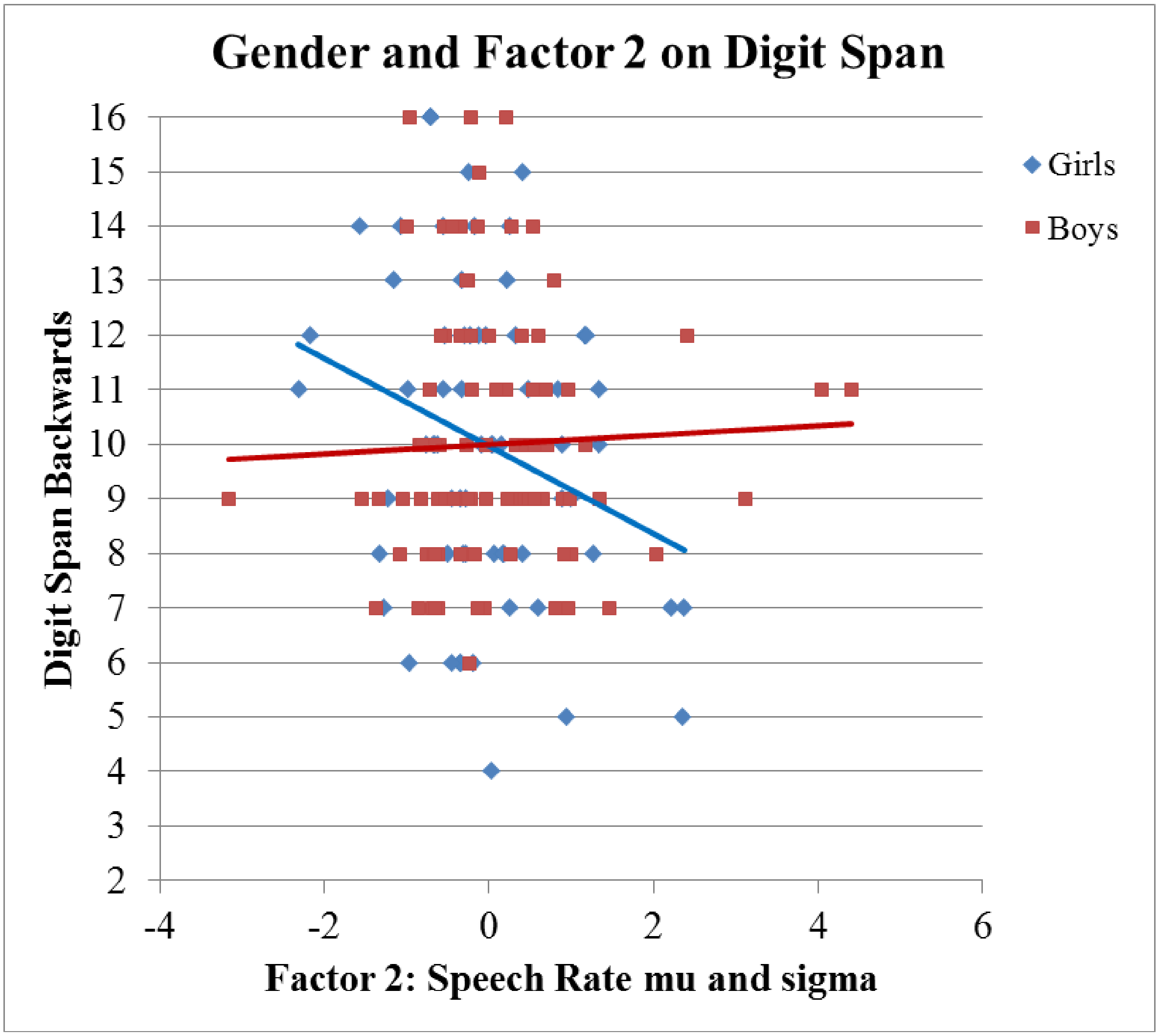

Figure 10. Ex-Gaussian plots for three distributions with varying parameter values.

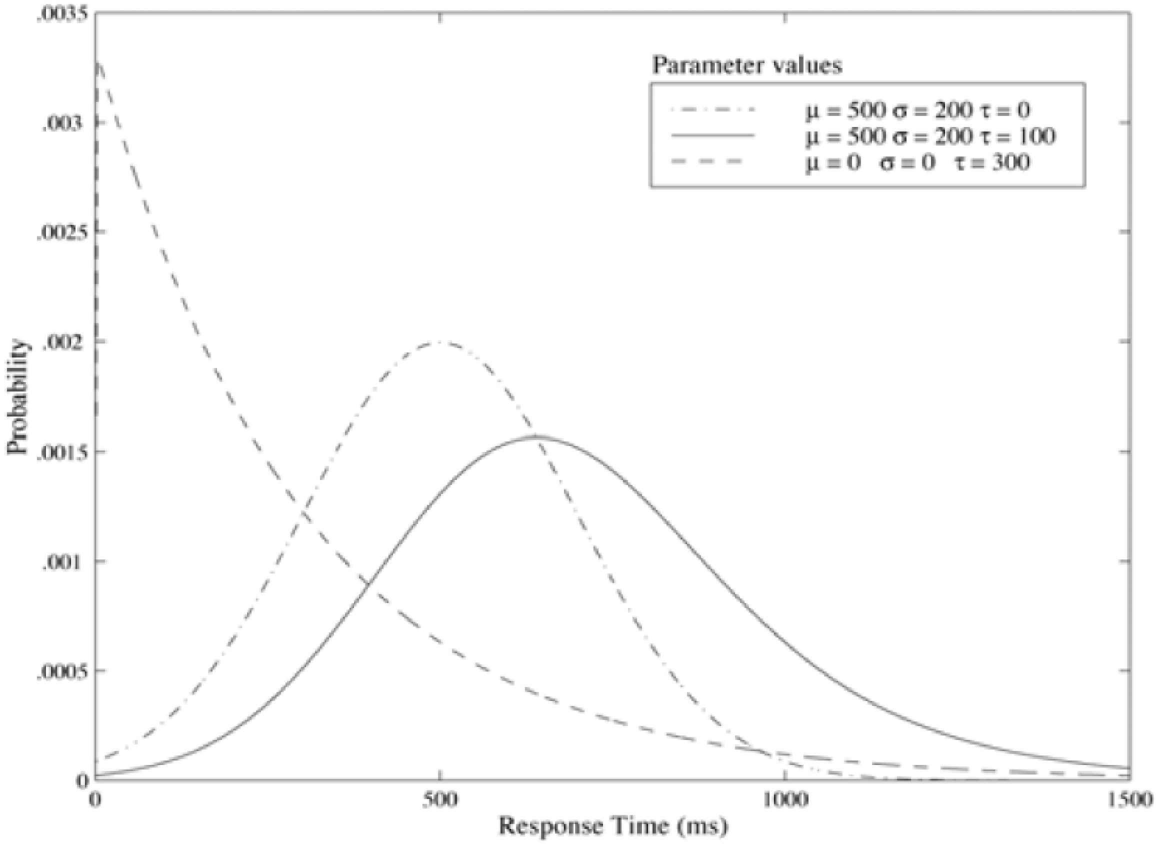

Table 1. Description of groups. Means, with standard deviation in parentheses. All ratings scales reported in T-scores.

	Control	***ADHD***
N (Boys:Girls)	48 (20:28)	144 (91:53)
Age (in years)	9.79 (1.25)	9.65 (1.22)
Estimated FSIQ	105.29 (6.72)	103.47 (12.54)
Inattention		
Total # of Symptoms	.48 (.68)	7.85 (1.50)**
Parent BASC-2	44.19 (6.38)	66.82 (5.46)**
Teacher BASC-2	42.83 (4.86)	61.74 (6.81)**
Hyperactivity/Impulsivity		
Total # of Symptoms	.31 (.55)	5.85 (2.62)**
Parent BASC-2	43.19 (5.26)	65.44 (13.15)**
Teacher BASC-2	43.60 (3.70)	60.41 (12.72)**
Comorbidity (DISC)		
MDD/Dysthymia	0/0	7/8
GAD	1	32
ODD/CD	2/0	54/21

*$p<.05$, **$p<.001$

Note: DISC describes meeting past year symptom count criteria.

Table 2. Mean and standard deviation of reaction time and working memory, by diagnosis and gender. *Note:* N (Motor Reaction Time) =163, N (PI&SR)=191

	ADHD			**Control**		
	total	*boys*	*girls*	*total*	*boys*	*girls*
Working Memory (WM)						
Reading Span (Rspan)	13.71 (10.52)	14.37 (12.02)	12.63 (7.46)	19.00 (11.46)	19.65 (9.04)	18.46 (13.32)
Symmetry Span (Sspan)	22.39 (14.42)	24.19 (14.39)	19.44 (14.18)	32.96 (16.932)	36.38 (15.16)	29.54 (18.50)
Digit Span Backward (DSB)	9.83 (2.49)	9.88 (2.29)	9.74 (2.83)	10.50 (2.15)	10.60 (2.01)	10.43 (2.28)
Motor Reaction Time (RT)						
Motor RT Mean	806.01 (145.08)	788.48 (144.35)	836.78 (142.76)	822.35 (200.20)	769.01 (157.76)	868.07 (224.14)
Motor RT Standard Deviation	242.08 (80.86)	230.16 (73.77)	263.00 (89.04)	220.81 (81.20)	206.49 (64.83)	233.10 (92.79)
Motor RT CV (SD/Mean)	0.30 (0.07)	0.29 (0.07)	0.31 (0.07)	0.27 (0.05)	0.27 (0.05)	0.26 (0.05)
Motor RT mu	625.30 (157.33)	623.99 (174.12)	627.62 (124.26)	659.92 (162.96)	631.31 (159.47)	684.44 (165.74)
Motor RT sigma	154.50 (62.65)	153.73 (62.04)	155.84 (64.39)	151.67 (50.59)	150.53 (45.67)	152.64 (55.56)
ex-Gaussian Motor RT CV (Sigma/Mu)	0.24 (0.05)	0.24 (0.05)	0.24 (0.06)	0.23 (0.03)	0.24 (0.03)	0.22 (0.03)
Motor RT tau	175.10 (98.37)	158.99 (91.89)	203.37 (103.92)	156.65 (100.61)	132.33 (88.21)	177.50 (107.85)
Preparatory Interval (PI)						
PI Mean	59.87 (36.49)	52.56 (26.32)	72.41 (33.53)	55.02 (27.56)	40.99 (24.11)	65.03 (25.76)
PI Standard Deviation	57.88 (42.74)	56.29 (47.35)	60.61 (33.60)	46.88 (23.00)	41.28 (24.42)	50.89 (21.48)
PI CV (SD/Mean)	1.02 (0.41)	1.12 (0.46)	0.85 (0.24)	0.93 (0.40)	1.11 (0.54)	0.80 (0.18)
PI mu	11.14 (12.93)	7.72 (9.65)	17.01 (15.58)	12.06 (13.36)	6.45 (7.38)	16.07 (15.24)
PI sigma	2.93 (7.81)	2.25 (7.31)	4.09 (8.53)	2.86 (7.08)	1.46 (3.65)	3.87 (8.68)
ex-Gaussian PI CV (Sigma/Mu)	0.15 (0.31)	0.13 (0.32)	0.17 (0.30)	0.18 (0.31)	0.12 (0.27)	0.22 (0.34)
PI tau	51.77 (34.13)	47.81 (34.09)	58.56 (33.44)	44.57 (23.55)	38.07 (23.50)	49.22 (22.87)
Speech Rate (SR)						
SR Mean	265.31 (74.41)	252.99 (62.55)	286.47 (87.95)	276.84 (74.90)	261.89 (61.18)	287.51 (82.74)
SR Standard Deviation	98.13 (54.40)	86.66 (46.49)	117.83 (61.41)	114.62 (53.10)	110.83 (45.06)	117.34 (58.83)
SR CV (SD/Mean)	0.35 (0.13)	0.33 (0.13)	0.39 (0.11)	0.40 (0.13)	0.41 (0.10)	0.40 (0.14)
SR mu	183.05 (67.46)	174.21 (62.14)	198.24 (73.88)	167.81 (40.72)	164.51 (45.06)	170.17 (38.00)
SR sigma	27.70 (43.43)	26.98 (42.22)	28.94 (45.81)	15.20 (27.54)	13.84 (24.69)	16.18 (29.82)
ex-Gaussian SR CV (Sigma/Mu)	0.12 (0.15)	0.13 (0.15)	0.11 (0.14)	0.08 (0.12)	0.07 (0.10)	0.08 (0.13)
SR tau	88.36 (66.21)	86.50 (61.53)	91.56 (74.07)	98.62 (59.65)	78.12 (45.65)	113.27 (64.76)

Table 3. Diagnostic group differences in reaction time and working memory, with gender as a moderator

	Block 1				Block 2	
	ADHD		Gender		ADHDxGender	
	unstd β	*p*	unstd β	*p*	unstd β	*p*
			Traditional indices of performance			
Working Memory (WM)						
Reading Span (Rspan)	-5.555	.004**	-1.604	0.333	-0.554	0.884
Symmetry Span (Sspan)	-11.204	.001**	-5.195	0.054	2.095	0.75
Digit Span Backward (DSB)	-0.706	0.087	-0.151	0.676	0.028	0.973
Motor Reaction Time (RT)						
Motor SSRT	83.731	.001**	-17.846	0.428	-32.788	0.527
Mean Motor RT	-5.614	0.848	61.127	.017*	-50.75	0.387
Motor RT Standard Deviation	26.754	0.073	31.272	.016*	6.233	0.834
Motor RT CV (SD/Mean)	0.034	0.005**	0.013	0.224	0.022	0.369
Preparatory Interval (PI)						
Mean PI	9.366	0.096	20.943	<.001**	-4.176	0.711
PI Standard Deviation	12.218	0.065	5.687	0.326	-5.286	0.69
PI CV (SD/Mean)	0.028	0.673	-0.281	<.001**	0.044	0.743
Speech Rate (SR)						
Mean SR	-4.752	0.702	31.449	.004**	7.854	0.753
SR Standard Deviation	-11.151	0.215	24.801	.002**	24.666	0.17
SR CV (SD/Mean)	-0.041	0.058	0.041	.030*	0.071	0.095
			ex-Gaussian parameters			
Motor Reaction Time (RT)						
Motor RT mu	-0.032	0.284	0.016	0.53	-0.05	0.404
Motor RT sigma	0.003	0.775	0.002	0.828	<.001	0.999
Motor RT tau	0.026	0.146	0.045	.005**	-0.001	0.983
Motor RT CV (Sigma/Mu)	0.016	0.065	-0.006	0.406	0.016	0.376
Preparatory Interval (PI)						
PI mu	1.095	0.599	9.379	<.001**	-0.333	0.936
PI sigma	0.489	0.705	1.986	0.08	-0.572	0.825
PI tau	9.53	0.076	10.858	.022*	-0.395	0.971
CV (Sigma/Mu)	-0.021	0.685	0.055	0.231	-0.057	0.59
Speech Rate (SR)						
SR mu	19.392	0.064	19.282	.036*	18.37	0.38
SR sigma	12.939	0.059	2.055	0.731	-0.377	0.978
SR tau	-7.497	0.494	12.832	0.183	-30.1	0.171
CV (Sigma/Mu)	0.042	0.083	-0.014	0.505	-0.032	0.505

Table 4. Descriptive statistcs and test of normality for reaction time variables. All times are in milliseconds.

							Shapiro_Wilk	
	Min	Max	Mean	SD	Skew	Kurtosis	Statistic	*p*
Motor RT	150.50	2958.60	823.70	294.39	1.76	5.75	0.917	<.001
ADHD	150.50	2958.60	813.44	290.52	1.76	6.01	0.846	<.001
Control	188.10	2839.70	830.67	299.79	1.73	5.18	0.940	<.001
Prep Interval	0.00	1150.90	58.44	73.99	4.16	33.78	0.669	<.001
ADHD	0.00	1150.90	59.92	80.17	4.41	34.97	0.946	<.001
Control	0.00	427.10	55.32	58.83	2.09	5.52	0.787	<.001
Speech Rate	9.30	1080.60	267.29	135.22	1.82	4.25	0.821	<.001
ADHD	9.30	1080.60	265.44	133.56	1.87	4.46	0.916	<.001
Control	19.10	1070.90	271.14	138.57	1.73	3.87	0.930	<.001

Table 5. Ex-Gaussian processing speed variables predicting working memory performance, with gender as a moderator.

Motor Reaction Time (RT)

	MRT mu						**MRT sigma**						**MRT tau**						**MRT exGaussian CV**					
	Block 1				Block 2		Block 1				Block 2		Block 1				Block 2		Block 1				Block 2	
	MRT mu		Gender		MRT mu x Gender		MRT sigma		Gender		MRT sigma x Gender		MRT tau		Gender		MRT tau x Gender		MRT CV		Gender		MRT CV x Gender	
	β	*p*	β	*p*	β	*p*	β	*p*	β	*p*	β	*p*	β	*p*	β	*p*	β	*p*	β	*p*	β	*p*	β	*p*
RSpan	0.44	0.94	-0.94	0.60	12.50	0.30	-9.36	0.54	-0.89	0.62	19.74	0.52	-15.68	0.09**	-0.31	0.87	-14.65	0.42	-18.15	0.35	-1.04	0.57	-1.52	0.97
SSpan	7.00	0.49	-4.80	0.10	-15.14	0.48	-3.36	0.91	-4.68	0.11	-49.57	0.40	-29.95	.032*	-3.53	0.22	19.95	0.48	-26.28	0.39	-4.86	0.09	-13.38	0.83
DSB	-0.58	0.65	0.04	0.93	-2.41	0.38	-3.53	0.29	0.03	0.94	-4.16	0.54	1.17	0.57	-0.02	0.96	-0.68	0.87	-6.44	0.13	-0.03	0.94	-0.73	0.93

Preparatory Interval (PI)

	PI mu						**PI sigma**						**PI tau**						**PI exGaussian CV**					
	Block 1				Block 2		Block 1				Block 2		Block 1				Block 2		Block 1				Block 2	
	PI mu		Gender		PI mu x Gender		PI sigma		Gender		PI sigma x Gender		PI tau		Gender		PI tau x Gender		PI CV		Gender		PI CV x Gender	
	β	*p*	β	*p*	β	*p*	β	*p*	β	*p*	β	*p*	β	*p*	β	*p*	β	*p*	β	*p*	β	*p*	β	*p*
RSpan	-0.10	0.12	-0.04	0.98	0.10	0.48	0.05	0.62	-1.01	0.55	-0.08	0.72	-0.07	.010**	-0.29	0.86	0.02	0.75	2.13	0.42	-1.04	0.54	-3.69	0.49
SSpan	-0.09	0.37	-3.46	0.24	-0.04	0.84	0.07	0.68	-4.46	0.11	-0.16	0.63	-0.15	.001**	-3.60	0.18	0.02	0.83	0.75	0.87	-4.34	0.12	-8.37	0.37
DSB	-0.02	0.30	0.10	0.78	0.06	0.06	-0.04	0.14	0.03	0.93	0.05	0.27	-0.01	0.15	0.04	0.91	-0.01	0.56	-1.23	.032*	0.04	0.91	0.47	0.68

Speech Rate (SR)

	SR mu						**SR sigma**						**SR tau**						**SR exGaussian CV**					
	Block 1				Block 2		Block 1				Block 2		Block 1				Block 2		Block 1				Block 2	
	SR mu		Gender		SR mu x Gender		SR sigma		Gender		SR sigma x Gender		SR tau		Gender		SR tau x Gender		SR CV		Gender		PI CV x Gender	
	β	*p*	β	*p*	β	*p*	β	*p*	β	*p*	β	*p*	β	*p*	β	*p*	β	*p*	β	*p*	β	*p*	β	*p*
RSpan	-0.03	.041*	-0.48	0.77	-0.02	0.41	-0.04	.048*	-0.92	0.58	-0.05	0.20	-0.01	0.56	-0.78	0.64	0.04	0.17	-9.59	0.10	-1.10	0.51	-14.70	0.21
SSpan	-0.02	0.29	-4.15	0.14	-0.03	0.47	-0.04	0.17	-4.59	0.10	-0.06	0.37	0.00	0.96	-4.28	0.13	0.05	0.27	-17.02	0.07	-4.99	0.07	-15.18	0.44
DSB	-0.01	0.06	0.05	0.89	-0.01	.049*	0.00	0.35	-0.03	0.92	-0.01	0.33	<.001	0.89	-0.04	0.91	0.01	0.11	-1.16	0.35	-0.06	0.87	-0.24	0.93

Table 6. Post hoc analyses of significant processing speed and working memory relationships, with ADHD as a moderator.

	Block 1		**Block 2**		**Block 3**	
	MRT tau		ADHD		MRT Tau x ADHD	
	β	p	β	p	β	p
Sspan	-0.033	.016*	-9.616	.004**	-5.687	0.724

	PI CV		ADHD		PI CV x ADHD	
	β	p	β	p	β	p
DSB	-1.221	.031*	-7.160	0.074	-0.824	0.524

	PI tau		ADHD		PI Tau x ADHD	
	β	p	β	p	β	p
Rspan	-0.070	.009**	-4.790	.011*	0.002	0.980
Sspan	-0.149	.001**	-8.639	.009**	0.255	0.175

	SR mu		ADHD		SRmu x ADHD	
	β	p	β	p	β	p
RSpan	-0.028	0.036*	-4.929	.009**	0.025	0.553

	SR sigma		ADHD		SR sigma x ADHD	
	β	p	β	p	β	p
RSpan	-0.040	.048*	-4.910	.010**	0.037	0.546

	Factor 4		ADHD		Factor 4 x ADHD	
	β	p	β	p	β	p
Rspan	-2.586	.003**	-4.354	.030*	0.144	0.947
Sspan	-5.452	<.001**	-8.213	.013*	2.081	0.621

Table 7. Component matrix for factor analysis of ex-Gaussian processing speed parameters

	Factors			
	1	2	3	4
1. MRT mu	-0.499	0.680	0.462	0.071
2. MRT sigma	-0.526	0.582	0.488	0.148
3. MRT tau	0.219	-0.413	-0.055	0.456
4. PI mu	0.443	-0.332	0.707	0.179
5. PI sigma	0.322	-0.413	0.77	-0.117
5. PI tau	0.136	0.199	-0.198	0.852
7. SR mu	0.744	0.510	0.060	0.153
8. SR sigma	0.749	0.566	-0.052	0.028
9. SR tau	-0.511	-0.363	0.081	0.546

Extraction Method: Principal Component Analysis.

Table 8. Processing speed factors predicting working memory performance, with gender as a moderator.

	Block 1				Block 2	
	Factor		Sex		FactorxSex	
	unstd β	*p*	unstd β	*p*	unstd β	*p*
Reading Span (Rspan)						
Factor 1 (mRT Mu & Sigma)	-1.514	0.092	-0.586	0.745	-2.126	0.239
Factor 2 (PI Mu & Sigma)	-0.901	0.316	-1.027	0.569	-0.642	0.734
Factor 3 (SR Mu & Sigma)	-0.135	0.881	-0.87	0.639	0.866	0.634
Factor 4 (all measure Taus)	-2.641	.004**	0.436	0.811	0.552	0.761
Symmetry Span (Sspan)						
Factor 1 (mRT Mu & Sigma)	-2.148	0.147	-4.31	0.132	-0.393	0.895
Factor 2 (PI Mu & Sigma)	-0.229	0.875	-4.736	0.102	-3.023	0.329
Factor 3 (SR Mu & Sigma)	0.377	0.79	-4.873	0.1	-2.98	0.297
Factor 4 (all measure Taus)	-5.168	.001**	-2.661	0.339	-2.135	0.487
Digit Span Backward (DSB)						
Factor 1 (mRT Mu & Sigma)	-0.239	0.234	0.09	825	-0.142	0.727
Factor 2 (PI Mu & Sigma)	-0.227	0.254	0.002	0.997	-0.894	.031*
Factor 3 (SR Mu & Sigma)	-0.313	0.124	0.161	0.696	0.376	0.354
Factor 4 (all measure Taus)	-0.182	0.377	0.122	0.772	0.122	0.77

Table 9. Alternative component matrices for factor analysis of processing speed parameters

a. CV and tau for MRT, PI, and SR.

	Factors		
	1	2	3
1. MRT cv	0.365	-0.009	0.693
2. MRT tau	0.315	0.271	0.628
3. PI cv	-0.267	-0.674	0.190
4. PI tau	0.358	0.734	-0.240
5. SR cv	-0.680	0.560	0.185
6. SR tau	0.861	-0.167	-0.218

Extraction Method: Principal Component Analysis.

b. Sigma and tau for MRT, PI, and SR, excluding mu.

	Factors		
	1	2	3
1. MRT sigma	0.230	0.101	-0.652
2. MRT tau	0.184	0.155	0.765
3. PI sigma	0.032	-0.655	0.380
4. PI tau	0.111	0.867	0.186
5. SR sigma	-0.815	0.309	0.088
6. SR tau	0.876	0.142	0.054

Extraction Method: Principal Component Analysis.

c. Mu, Sigma, and Tau for MRT and SR, excluding SR.

	Factors		
	1	2	3
1. MRT mu	0.841	0.457	0.128
2. MRT sigma	0.783	0.48	0.224
3. MRT tau	-0.458	-0.081	0.553
4. PI mu	-0.543	0.699	0.251
5. PI sigma	-0.523	0.773	-0.113
6. PI tau	0.056	-0.247	0.843

Extraction Method: Principal Component Analysis.

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