Abstract

Purpose: Prior research has suggested that people who stutter exhibit differences in some working memory tasks, particularly when more phonologically complex stimuli are used. This study aimed to further specify working memory differences in adults who stutter by not only accounting for linguistic demands of the stimuli but also individual differences in attentional control and experimental influences, such as concomitant processing requirements.

Method: This study included 40 adults who stutter and 42 adults who do not stutter who completed the Attention Network Test (ANT; Fan et al., 2002) and three complex span working memory tasks: the Operation Span (OSPAN), Rotation Span, and Symmetry Span (Draheim et al., 2018; Foster et al., 2015; Unsworth et al., 2005, 2009). All complex span tasks were dual-tasks and varied in linguistic content in task stimuli.

Results: Working memory capacities demonstrated by adults who stutter paralleled the hierarchy of linguistic content across the three complex span tasks, with statistically significant between-group differences in working memory capacity apparent in the task with the highest linguistic demand (i.e., OSPAN). Individual differences in attentional control in adults who stutter also significantly predicted working memory capacity on the OSPAN.

Discussion: Findings from this study extend existing working memory research in stuttering by showing that: (1) significant working memory differences are present between adults who stutter and adults who do not stutter even using relatively simple linguistic stimuli in dual-task working memory conditions; (2) adults who stutter with stronger executive control of attention demonstrate working memory capacity more comparable to adults who do not stutter on the OSPAN compared to adults who stutter with lower executive control of attention.

Working memory is used to temporarily store and act upon information in short term memory (Huettig et al., 2011). In this paper, we use the term *working memory* to reflect both the storage and processing components of temporary memory. Various models of working memory have been proposed (see for review Baddeley, 2012; Barrouillet et al., 2004; Constantinidis & Klingberg, 2016; Engle, 2002). Among the most widely cited models of working memory is the multi-component model (see Baddeley, 2003, 2007; Baddeley & Hitch, 1974), which posits the existence of two distinct, domain-specific sub-systems of working memory: the phonological loop and the visuospatial sketchpad. Using this framework, researchers have hypothesized that phonological information must be stored and manipulated in working memory in order to be assembled for speech production (Gathercole & Baddeley, 1993). Thus, working memory has been of particular interest to the field of communication science and disorders for its hypothesized role in speech and language production. Specifically in the field of stuttering, researchers have discussed phonological encoding, which is one step in word-form encoding (language formulation) (Dell, 1988; Levelt et al., 1999), and manipulating phonological information in working memory as largely overlapping processes (see Bajaj, 2007).

Although a variety of tasks have been used to explore phonological working memory in people who stutter, the most commonly used have been nonword repetition and digit span tasks (see Bowers et al., 2018, for review). Both nonword repetition and digit span tasks are measures of short-term memory because they do not require concomitant attentional processing (Unsworth & Engle, 2007). Counting the number of correctly remembered, ordered, and uttered phonemes (or numbers, in the case of simple digit span) gives a measure of a person's phonological working memory capacity. Prior research has revealed no significant differences in digit span tasks between groups of people who stutter and groups of people who do not stutter (Oyoun et al., 2010; Pelczarski & Yaruss, 2016; Sasisekaran & Byrd, 2013; Smith et al., 2012; C. Spencer & Weber-Fox, 2014). Yet, some studies have shown significant differences in nonword repetition accuracy between children who stutter and those who do not (Anderson et al., 2006; Anderson & Wagovich, 2010; Hakim & Bernstein Ratner, 2004; Pelczarski & Yaruss, 2016; C. Spencer & Weber-Fox, 2014) and between adults who stutter and those who do not (Byrd et al., 2012; Coalson & Byrd, 2017; Sasisekaran & Weisberg, 2014). Although this difference has not been consistently found for either children or adults (see Sasisekaran, 2013; Smith et al., 2010, 2012, as notable examples), people who stutter often (but not always) exhibit subtle working memory capacity differences when they are required to process more linguistically complex nonword stimuli (i.e., longer nonwords with varying phonological information, see Byrd et al., 2012; Pelczarski & Yaruss, 2016) compared to simpler stimuli with shorter and less phonologically complex nonwords or numbers.

Prior research outside the field of stuttering has shown that individual differences in attentional control significantly influence working memory capacity (Cowan, 1999; Cowan et al., 2014; Engle, 2018; Engle et al., 1999; Kane & Engle, 2002; Redick & Engle, 2006). Additional work has shown that working memory capacity can be affected by concomitant processing requirements (Baddeley, 2012; Cowan et al., 2014). Neither of these areas have been systematically examined in stuttering, especially in relation to working memory capacity. The current study aims to fill this gap in knowledge by specifying potential working memory differences in people who stutter through a careful consideration of (a) individual differences in attentional control, (b) the linguistic content of to-be-remembered stimuli, and (c) concomitant processing requirements in the experimental paradigm used to assess working memory.

Attentional Control

Attention has been conceptualized as a neurologically based skill that reflects efficiency at signal detection, orienting to salient stimuli, or vigilance toward a particular task or state (Posner, 1980; Posner et al., 1980; Posner & Petersen, 1990). These processes are represented by large, functionally distinct brain networks (Bressler & Tognoli, 2006; Corbetta et al., 2008; Petersen & Posner, 2012; Posner & Petersen, 1990; Sonuga-Barke & Castellanos, 2007). Most notably, Posner and Peterson (1990) proposed that attention can be characterized as involving three distinct but related systems: alerting (i.e., the ability to maintain vigilance for signal detection), orienting (i.e., the ability to prioritize sensory input), and executive control (i.e., the ability to resolve conflict). Executive control, also commonly referred to as *attentional control* in working memory research (see Engle, 2018; Engle et al., 1999; Engle & Kane, 2003), is of particular relevance when considering individual differences in working memory capacity. Redick and Engle (2006) evaluated individual differences in attentional control in adults using the Attention Network Test (ANT; Fan et al., 2002). These individuals also completed the Operation Span Task (OSPAN; Turner & Engle, 1989). Individuals with very high working memory capacities, indicated by higher OSPAN scores, demonstrated higher attentional control abilities (lower Executive Control network scores) while individuals with very low working memory capacities (i.e., lower OSPAN scores) had significantly lower attentional control. The authors concluded that individual differences in attentional control are the primary driving force behind working memory skills.

The finding that individual differences in attentional control can predict working memory capacity has significant implications for the study of stuttering. First, it is likely that accounting for individual differences in attentional control can help to specify potential working memory capacity differences more accurately in people who stutter compared to people who do not stutter, which have been inconsistently reported. Second, further specifying the nature of working memory differences has the potential to expand on the existing theories into the origins of moments of stuttering. Much research over the past few decades has further specified group differences in linguistic, temperamental/emotional, and motoric processes between people who stutter and people who do not stutter (see Conture et al., 2013; Maxfield et al., 2016; Namasivayam & Van Lieshout, 2011). For example, adults who stutter have been shown to demonstrate less stable and more variable speech-related motor movements (Denny & Smith, 1992; Kelly et al., 1995; Kleinow & Smith, 2000; Olander et al., 2010; Smith et al., 1993, 2010, 2012), supporting the idea that adults who stutter do not develop the well-learned and robust internal models necessary for fluent speech production typical of the general population (Max et al., 2004). Research has also found evidence that adults who stutter have subtle differences in language formulation skills compared to adults who do not stutter in lexical access and retrieval (Lescht et al., 2022; Newman, 2007), syntax (Kleinow & Smith, 2000; E. Spencer et al., 2009), and phonological processing (Byrd et al., 2012, 2015; Coalson & Byrd, 2015, 2017, 2018). The pattern of results showing group differences in multiple areas supports the notion that moments of stuttering arise due to interactions between linguistic, temperamental/emotional, and motoric factors rather than due to any single process (Adams, 1990; Neilson & Neilson, 1987; Perkins et al., 1976; Smith & Kelly, 1997; Smith & Weber, 2017; Starkweather & Gottwald, 1990).

Though current theories hypothesize that interactions in multiple domains influence the occurrence of moments of stuttering, such theories only generally state that moments of stuttering occur when “demands are higher” (e.g., Smith & Weber, 2017, p. 16). As yet, it is unclear how or why these demands arise and interact. Research outside of the field of stuttering has shown that attentional control is critical (a) for supporting the language formulation process

(Levelt et al., 1999; Roelofs, 2008; Roelofs & Piai, 2011), and (b) for establishing the well-learned movements necessary for fluent speech production (Maxwell et al., 2003; Posner, 1967; Schmidt, 1975). Moreover, attentional control is also a foundational component of a person's temperament profile (Posner & Rothbart, 2007; Rothbart, 2007; Rothbart & Posner, 2015). Therefore, to better understand potential interactions between linguistic, temperamental/emotional factors, and motoric factors it is necessary to determine whether individual differences in attentional control can further specify group differences in stuttering research. Such knowledge would also enhance the field's understanding of how, why, and when moments of stuttering occur by highlighting the availability of resources as demands change during ongoing language formulation and speech production. As a first step in this direction, and to further specify working memory research in adults who stutter, it is necessary to account for individual differences in attentional control to predict working memory capacity in adults who stutter.

Concomitant Processing: Central and Peripheral Components of Working Memory

To understand the possible influence of concomitant processing in working memory task performance, it is necessary to differentiate central and peripheral components of working memory. In Baddeley's original multi-component model, all processing, or attentional allocation, was *central* (the central executive), and all storage was *peripheral* (i.e., in the phonological loop or visuospatial sketchpad, Baddeley & Hitch, 1974). Based on ongoing research and clinical evidence (see Baddeley, 2012, for discussion), Baddeley (2000) later proposed an additional component of the model: the episodic buffer*,* whose primary function was to interface between the other sub-systems and the central executive (Baddeley, 2007). The episodic buffer adds the aspects of more-central storage and more-peripheral processing to the multi-component model.

However, the distinction between central and peripheral components of working memory is not merely semantic; the interpretation of fundamental findings in working memory research hinges on this demarcation (Logie & Cowan, 2015).

If the central executive has enough attentional control capabilities to drive both the phonological loop and visuospatial sketchpad, the amount of stored phonological and visual information should not be influenced by each other (Cowan et al., 2014). Cowan et al. (2014) challenged assumptions of the multi-component model by examining how and under what conditions limitations in shared central resources would influence working memory capacity. Cowan and colleagues conducted a series of dual-task experiments in which participants were asked to encode both verbal and visual information to determine how capacity changed as a function of overlapping content (e.g., verbal, visual, or some combination of both). The amount of information in each domain, commonly called a chunk, was assessed. (A chunk is "a group of elements that are strongly associated with one another and together form a member of a conceptual category," see Cowan et al., 2014, p. 1807; Miller, 1956). Participants were able to encode 3 chunks at one time in each domain alone (total of 6 simultaneous chunks), but only 5 chunks at one time when asked to perform across multiple domains concurrently (Cowan et al., 2014). This finding indicates that there is a decrease in capacity *across* peripheral domains in a dual-task paradigm. When a specific working memory sub-system exceeds its capacity (storage) or processing capability (attentional control) during a given task, central working memory resources (storage and attentional control) are recruited. This recruitment can occur to the possible detriment of concomitant processing in other peripheral areas (Cowan et al., 2014).

Exploring working memory capacity by limiting the contribution of central working memory resources through concomitant processing has the potential to further specify the understanding of working memory research in stuttering. Given the research reviewed above, a nonword repetition or digit span task may not sufficiently limit the contribution of central working memory resources when task demands increase. As task difficulty increases, participants are able to devote more central working memory resources to support maintaining accuracy and precision in that specific working memory task. A working memory dual-task limits recruitment of central working memory resources through the addition of the concomitant processing task. Thus, in adults who stutter, working memory differences for phonological information may be revealed with less phonologically complex and shorter linguistic stimuli if central working memory resources cannot be used to supplement task performance. If working memory capacity differences are found with less phonologically complex and shorter stimuli during dual-task designs, such a finding would constrain past theories into the origin of moments of stuttering which implicate language formulation as at least partially responsible (see Brocklehurst, 2008; Kolk, 1990; Postma & Kolk, 1993; Vasic & Wijnen, 2005).

Purpose and Aims of the Study

Previous group studies in stuttering research investigating working memory have not accounted for individual differences in attentional control or the possibility that central attentional resources may compensate for difficulties in peripheral processing. Accounting for individual differences in both attentional control and concomitant processing may help to further specify working memory capacity differences between people who stutter and people who do not stutter. Past research has found that individuals with very high working memory spans and very low working memory spans differ significantly in their attentional control abilities (Redick & Engle, 2006). It is expected that a similar relationship between attentional control and working memory capacity will be found in adults who do not stutter in this study. Likewise, it is hypothesized that working memory capacities in adults who stutter will be predicted by participant's attentional control abilities. Yet, this relationship between attentional control and working memory capacity in adults who stutter is hypothesized to be stronger and more apparent when more linguistically-demanding stimuli are present in working memory dual-tasks. This hypothesis is supported by prior working memory research in stuttering and theories suggesting the existence of subtle language formulation differences in adults who stutter (see Brocklehurst, 2008; Kolk, 1990; Postma & Kolk, 1993; Vasic & Wijnen, 2005). Such methodological considerations may simultaneously reveal working memory capacity differences using less phonologically complex stimuli as compared to more complex nonwords. Such a finding would shed additional light on the question of whether linguistic/phonological stimuli need to be sufficiently complex and of sufficient length in order for between-group differences to be detected. Therefore, the aims of the current study were to determine whether adults who stutter demonstrate working memory capacity differences compared to adults who do not stutter via (a) an array of complex span tasks (dual-tasks) that varied in the amount of linguistic information present in the task stimuli while (b) accounting for individual differences in attentional control.

Methods

Participants

The study was deemed to be exempt from institutional review by the Michigan State University Human Research Protection Office of Regulatory Affairs, under Category 98 of the Federal Policy for the Protection of Human Subjects. Category 98 allows data collection through exempted protocols when disclosure of participant data would not place participants at risk for criminal or civil liability or be damaging to subject's financial standing, employability, educational advancement, or reputation. Participants were 40 adults who stutter (*Mean age* =

27.05, *SD* = 11.20) and 42 adults who do not stutter (*Mean age* = 24.07, *SD* = 5.86), between the ages of 18 and 69. All participants provided informed consent before participation. Demographic information for both participant groups is presented in Table 1. Insert Table 1 here Both groups were recruited to ensure an approximately equal sex ratio and average age: there were approximately twice as many males as females in each group (consistent with the well-known sex ratio in adults who stutter), and there was no significant between-group difference in age $t(58.5) = -1.50$, $p = .14$. Participants were assigned to the group of adults who stutter if they self-reported to be a person who stutters at the time of the study and reported childhood-onset stuttering (*Mean age of onset* = 6.16, *SD* = 4.19). That is, these participants were confirmed to experience Childhood Onset Fluency Disorder (ICD Code F80.81), rather than another type of stuttering condition with onset associated with psychogenic or neurogenic causes. Inclusion in the stuttering group was affirmed based on discussion with participants and clinical impression by the first author, a practicing speech-language pathologist with 10 years of clinical practice and research experience in stuttering. Adults who self-reported to not be people who stutter were used as a comparison group. No adult who reported not to stutter gave the clinical impression of being a person who stutters during the experiment. Four people responded to the study recruitment and indicated a positive history of stuttering but denied currently identifying as people who stutter. These individuals were excluded from participating in the study. Measures of observable stuttering behavior severity (e.g., percent stuttered syllables) were not collected in this study because such data come from just a single point in time and do not necessarily reflect a person's experience of stuttering (Constantino et al., 2016). Given that stuttering behavior is highly variable (Constantino et al., 2016; Tichenor & Yaruss, 2020b; Yaruss, 1997), this was considered an appropriate way to limit spurious inferences relating to how findings from this study relate to overt stuttered speech. The *Overall Assessment of the Speaker's Experience of Stuttering* (OASES; Yaruss & Quesal, 2016) was given to quantify the range of adverse impact experienced in the sample of adults who stutter; results indicated that we were successful in recruiting adults who stutter with a range of stuttering experiences, suggesting that our findings are representative of the broader population of individuals who stutter (*Mean OASES Total Score* = 2.6, *SD* = .76, range = 1 - 4.2). In an attempt to account for individual differences in cognitive ability, each subject also completed the Test of Nonverbal Intelligence—4th edition (TONI-4, Brown et al., 2010). The TONI has been used in stuttering research as a test of nonverbal intelligence (see Gkalitsiou, 2018). It has been shown to be a reliable and stable measure of nonverbal intelligence (Brown et al., 2010).

Self-help/support history and speech therapy history data were collected to account for possible sources of individual differences in participants' experiences of stuttering. Education level was collected by written self-report using the following categories: (a) some high school, (b) high school graduate, (c) some college, (d) graduated college, (e) advanced degree. Other questions screened for concomitant attention deficits (e.g., ADHD diagnosis), hearing deficits, and other speech-language disorders. Individuals with concomitant attention-related conditions such as ADHD were not excluded from participating given evidence that people who stutter frequently exhibit characteristics of ADHD (Druker et al., 2019; Tichenor et al., 2021). By incorporating these characteristics as possible random effects as described below, the sample of adults who stutter in this study was both more representative of the population and any systematic effect of these characteristics were accounted for in the analyses.

Complex Working Memory Span Tasks

Complex span tasks commonly used in psychology to assess working memory capacity were used to determine whether the group of adults who stutter exhibited working memory capacity differences compared to the group of adults who do not stutter (Unsworth & Engle, 2006, 2007). Complex span tasks are dual-tasks that are completely silent (i.e., they do not involve overt speech) and require a participant to remember selected stimuli while performing a distractor task (Unsworth & Engle, 2006). Participants interacted directly with the computer program via button press (mouse clicks); no speaking was required in these tasks. These tasks were selected because the inclusion of the dual-task limits the possibility that central attentional resources can be used to support task performance as task demands increase. The dual nature of complex span tasks requires that participants focus their attention on the processing component of the second task (the distractor) and not solely on reinforcing storage of the to-be-remembered stimuli, thus limiting the contribution of central attentional resources to the primary task (Cowan et al., 2014).

The following automated computer-based dual-tasks were chosen: the Operation Span task (OSPAN), the Rotation Span task, and the Symmetry Span task (Foster et al., 2015; Unsworth et al., 2005). The OSPAN, Rotation, and Symmetry Span tasks all differ in the type of stimuli to be remembered and in the type of concomitant distractor task. The OSPAN task requires that participants remember strings of orthographic English letters (relatively simple linguistic stimuli compared to more phonologically complex nonwords) while also processing simple math problems (addition, subtraction, multiplication, division). Participants alternate between remembering a letter, performing a math problem, remembering a letter, performing a math problem, etc. before being asked to recall all the letters in that string (e.g., string of 3, 4, 5, 6, 7, 8, or 9 letters). The Rotation Span task requires participants to remember the direction and magnitude of large or small arrows facing in one of 8 possible directions. Participants alternate between remembering the direction/magnitude of arrows and making judgements about whether a rotated English letter can be rotated further to become a correct, forward-facing English letter. The Symmetry Span task requires participants to remember strings of locations of red squares in a 4 x 4 grid. Participants alternate between remembering the locations of red squares and making judgments about whether a displayed shape is symmetrical along its vertical axis (see Draheim et al., 2018, for visualization of all three tasks). For each task, string length increased as participants responded correctly.

The OSPAN task is more linguistically demanding than the Rotation and Symmetry Span tasks because it contains linguistic information in both the to-be-remembered task (letter recall) and the distractor task (math problems). The Rotation Span task contains linguistic information in the stimuli of the distractor task (judgements about rotated letters) but not in the distractor task (judgements about arrow direction and magnitude). The task with the least amount of linguistic information is the Symmetry Span task, which is purely visual. At the start of each task, participants complete a training session that includes both the memory and the distractor tasks in isolation. A time limit for each Span task is calculated by multiplying the average training response time by 2.5 standard deviations. This ensures that participants did not compensate for apparent reductions in working memory performance by taking increased time on the task (Conway et al., 2005). Overall difficulty of the span tasks is accounted for by incorporating the individual time limits. All tasks yield a partial-credit score (also commonly called a partial-span score), which is automatically calculated by task software. Partial-span scores are psychometrically preferable to absolute span scores (i.e., correct or incorrect responses) because partial-span scores contain more variance than absolute scores. This allows for better differentiation between individuals (see Conway et al., 2005, for discussion).

For all complex span tasks, an accuracy of 85% on the concomitant task indicates the cut-off point that is typically used to determine whether participants faithfully engaged in the complex span task (i.e., that participants attended to and completed the concomitant task, see Conway et al., 2005; Draheim et al., 2018). Data from participants who fail to meet this accuracy criterion on the concomitant task are usually discarded (Draheim et al., 2018; Unsworth et al., 2005). Because it was anticipated, based on prior research, that adults who stutter might have more difficulty on complex span task(s) that contained more linguistic information (i.e., OSPAN task), such data were not removed in this study. This allowed investigation of differences in group performance across tasks. The raw accuracy measures on distractor tasks are presented in Figure 1. Insert Figure 1 here Despite the rationale for including a broader number of subjects beyond the typical 85% accuracy criterion, a small number of subjects were excluded from all data analyses. The rotation span score from one participant who does not stutter (Participant 83) was removed for one task due to an accuracy of .60 and a partial-span score greater than five z-scores, indicating that the participant may have sacrificed accuracy on the concomitant task to aid retention. Also, complete data from two participants who stutter (Participant 6 and 21) were excluded because they failed to meet the criterion levels on *any* of the three complex span tasks. Observation during data collection further revealed that they also failed to participate faithfully in the tasks (e.g., they were checking their cell phones during the experiment). No other data were removed for participants who failed to meet accuracy criterion because their partial-span scores were within 2.5 z-scores from zero.

Numerous studies have found that complex span tasks are reliable across time (minutes, days, weeks, months), with typical test-retest correlations of .70 to .80 (Klein & Fiss, 1999; Redick et al., 2012; Turley-Ames & Whitfield, 2003; Unsworth et al., 2005, 2009). Overall, complex span tasks are considered to have relatively limited measurement error (Conway et al., 2005). Moreover, test-retest scores from various studies show only small re-test differences of two to three partial-span scores (Unsworth et al., 2005, 2009). The specific form of the tasks used in this study were developed by Draheim et al. (2018), who revised the original complex span tasks to include increased set sizes to better differentiate people at the higher and lower ends of working memory abilities, while also allowing optional numbers of blocks (i.e., 1, 2, or 3) to be selected by the researcher. These complex span tasks were used in order to better differentiate participants. In keeping with established best practices for these tasks, the number of blocks completed in this study was limited to two blocks per complex span task to reduce the likelihood of fatigue and to minimize learning effects (see Draheim et al., 2018, for discussion).

The Attention Network Test (ANT)

The Attention Network Test (ANT; Fan et al., 2002) assesses the neurophysiological attentional networks proposed by Posner and colleagues (Orienting, Alerting, and Executive Control; see Petersen & Posner, 2012; Posner & Petersen, 1990). The ANT combines a flanker task (i.e., a task that requires participants to inhibit inappropriate responses to non-target stimuli and respond to appropriate target stimuli; Eriksen & Eriksen, 1974) with the addition of reaction time measures (Fan et al., 2002; Posner, 1980). Participants attend to a fixation point and are required to attend to neutral, congruent, or incongruent arrow stimuli arrays in conditions of no cue, center cue, double cue, and spatial cue (Fan et al., 2002). The ANT task, which has been used in hundreds of studies (MacLeod et al., 2010), has been successfully used to measure attentional network functioning in various populations (e.g., Johnson et al., 2008; Urbanek et al., 2009). Higher scores on Orienting and Alerting indicate higher network efficiencies, while lower scores on the Executive Control indicate higher network efficiency (Eggers et al., 2012; Fan et al., 2002). There is evidence that individual differences in working memory span are primarily a function of attentional control processes that determine how effectively capacity is used rather than the size of a peripheral memory store (Redick & Engle, 2006).

Instrumentation, Procedures, and Data Analysis

All data were collected in a quiet environment free of distractions. Data collection occurred automatically via the complex span tasks provided by the Engle Lab at Georgia Institute of Technology (Draheim et al., 2018; Unsworth & Engle, 2006). All tasks were run in E-prime version 2.0 on a 2.0 GHz Dell Latitude 3460 (8gb Ram, Windows 7), with a built-in 14-inch monitor. The majority of data collection occurred in the Spartan Stuttering Lab in the Oyer Speech and Hearing Building on the campus of Michigan State University. However, several participant sessions were completed at nearby facilities with comparable testing environments, including the University of Michigan and two private speech clinics. When data collection occurred at a remote site, all experimental protocols were the same as in the Spartan Stuttering Lab.

The order of the complex span tasks was randomized across participants. Task order was coded as a variable and included among possible random effects in the linear mixed effects model, described below. Given that the complex span tasks in this study were fully automated and have well-documented, high reliability (Conway et al., 2005; Klein & Fiss, 1999; Redick et al., 2012; Turley-Ames & Whitfield, 2003; Unsworth et al., 2005, 2009), no inter- or intra-rater agreement check was conducted for this study.

Linear mixed effects models were run using lme4 (Bates et al., 2014), a package developed for the statistical computing package R (R Core Team, 2020). Because each participant completed two blocks of each complex span task, the two partial-span scores were transformed into z-scores for comparison across complex span tasks. These z-scores were calculated from responses across all participants in the study to allow comparisons across groups. This yielded six complex span partial z-scores (2 blocks each for 3 complex span tasks) per participant. These partial-span z-scores were the primary outcome variables of interest. Each partial-span z-score was predicted from group (adults who stutter or adults who do not stutter) and complex span task (OSPAN, Rotation Span, Symmetry Span). The fixed effects were group (categorical variable with 2 levels) and span task (categorical variable with 3 levels).

Multiple linear regression was used to evaluate whether Executive Control network score, group, or their interaction could predict working memory capacity. The outcome variable of the model was mean partial-span score. These mean scores were calculated from averaging the two partial-span scores attained from each block of each complex span task. The predictor variables were Executive Control network score (continuous variable), group (categorical with two levels), and their interaction. Assumptions of linearity, normality of residuals, and homoscedasticity were met for the multiple linear regression model. An alpha level of .05 was selected as a threshold to determine significant effects.

Results

Group Differences on Non-Verbal Intelligence

Non-verbal intelligence (TONI-4 scores) did not significantly differ between adults who stutter (*Mean* = 102.95, *SD* = 8.41) and adults who do not stutter (*Mean* = 104.12, *SD* = 8.62),

$t(75.77) = .56$, $p = .58$, indicating that the groups did not significantly differ in nonverbal intelligence.

Group Differences on ANT Measures

Attention Network Test scores did not differ between groups: Alerting $t(77.12) = -.24$, $p = .80$; Orienting $t(77.20) = .98$, $p = .33$; and Executive Control $t(77.81) = -.15$, $p = .88$. Figure 2 depicts the mean score for each network plotted for each group. Insert Figure 2 here

Group Differences on Complex Span Tasks

A Chi-Square test was completed to determine whether accuracy on the concomitant task was independent of participant group status. Results indicated that the relationship between accuracy and group was significant, X^2 (30) = 87.75, $p < .001$, $V = .43$, meaning that the group of adults who stutter in this study were less likely to meet the accuracy criterion across all complex span tasks than the group of adults who do not stutter. This effect size was medium to large (Cohen, 1988). Adults who stutter demonstrated difficulty achieving accuracy criterion across all three span tasks: five adults who stutter did not meet the accuracy criterion in the OSPAN and Symmetry Span tasks, and seven adults who stutter did not meet the accuracy criterion in the Rotation Span task. In contrast, only two adults who do not stutter failed to meet criterion in the OSPAN task, and one failed to meet criterion in the Symmetry Span.

Linear Mixed Effect Models Predicting Working Memory Capacity

In order to evaluate whether working memory capacity differed between groups across the three complex span tasks, it was necessary to determine whether partial-span z-scores were significantly predicted by group status (Stuttering or Non-Stuttering), complex span task (OSPAN, Rotation, or Symmetry Span), or their interactions. An initial model (Model 1) comprised a fixed effect of group, complex span task, and their interaction, with a random intercept of participant. A second model (Model 2) added a random slope of complex span task. This random slope allowed for participant performance to vary across the tasks (i.e., the possibility that individuals may perform higher or lower on some tasks versus others). Model 2 significantly improved fit compared to Model 1 (X^2 (5) = 59.30, $p < .001$), indicating that Model 2 better explained the relationship between the predictors and partial-span score than Model 1. To maximize the random effects structure (Barr et al., 2013), other models were constructed using possible random intercepts of Order (participants completed the three complex span tasks in different orders), Block, Age, Sex, history of therapy, self-report of ADHD/Depression, nonverbal intelligence, accuracy on the concomitant task, average time to complete the complex span task, etc.). These models did not significantly improve fit compared to Model 2; Model 2 was the most maximal model. Results for Model 2 are presented in Table 2 and discussed below. Insert Table 2 here

Figure 3 depicts the predicted changes in the fixed effects (Group and Complex Span Task) in Model 2. Insert Figure 3 here The left side of Figure 3 illustrates the fixed effects for Group and the right side of Figure 3 illustrates the fixed effects for Task. Visual inspection of Figure 3 supports the formal interpretation of Model 2 below, indicating that the most robust (and significant) difference between groups in complex span task occurred on the OSPAN task (the task with the most linguistically demanding information in the stimuli). The partial-span scores were most closely matched between groups on the Symmetry Span task, with the group of adults who stutter performing slightly lower on the Rotation Span task compared to the group adults who do not stutter.

When participants who stutter completed the OSPAN task (the intercept in Model 2), the OSPAN partial-span z-score was estimated to be -.22. The first predictor in the model (Group N:

OSPAN) was the predicted difference in mean partial-span z-score on the OSPAN task between groups. Not being an adult who stutters increased partial-span z-scores by .41, giving an estimated mean of .19 partial-span z-scores (-.22 + .41). This effect was significant $t(79.57) = -2.02$, $p = .046$, $d = .28$, and the effect size of this difference was small to medium (see, Westfall et al., 2014). In people who stutter, partial-span z-scores were predicted to increase by .06 (-.22 + .06), yielding an estimated -.16 partial-span z-scores on the Rotation Span Task. Similarly, partial-span z-scores were predicted to increase by .11 (-.22 +.11), yielding an estimated mean of -.11 partial-span z-scores on the Symmetry span task. These increases in partial-span z-scores in the group of adults who stutter were not statistically significant from their OSPAN task predicted performance. The data for adults who do not stutter indicated an opposite pattern of results – highest performance on OSPAN task, slightly lower performance on Rotation Span task, and lowest performance on Symmetry Span task. Details are not reiterated here to limit redundancy.

These data indicate that the group of adults who stutter demonstrated significantly lower working memory capacities in the OSPAN task—the task that had the most linguistic information of the three tasks. The overall pattern of results (lowest predicted performance on OSPAN, higher performance on the Rotation Span task, highest performance on the Symmetry Span task) parallels the hierarchy of the amount of linguistic information present in the task stimuli. Moreover, the result cannot be explained by greater difficulty for the OSPAN task in general given that adults who do not stutter had higher performance on this task than the other two tasks. Instead, lower performance on the OSPAN task by adults who stutter is likely a function of its higher linguistic content in stimuli.

ANT Score Predicting Working Memory Capacity

One multiple linear regression model was built to explore the effects of Executive Control network score from the ANT task on mean OSPAN partial-span score. To reduce the likelihood of spurious findings, models focused only on OSPAN scores given the significant group effects observed for this task. Executive Control, group, and their interaction explained a significant amount of the variance on mean OSPAN partial-span score $F(3,75) = 2.894$, $p < .041$, $R^2 = .10$, $R^2_{Adjusted} = .07$, $f^2 = .12$, with a small to medium effect size (Cohen, 1988). The interaction was significant, meaning that Executive Control moderated the relationship between group and mean partial-span z-score in the OSPAN task. Adults who stutter with lower attentional control (higher Executive Control network scores) demonstrated significantly lower mean partial-span z-scores in the OSPAN task compared to the mean partial-span z-scores of adults who do not stutter. Additional details on specific regression variables are presented in Table 3. Insert Table 3 here The relationships between Executive Control network score and OSPAN partial-span z-score for each participant, highlighted by group, are illustrated in Figure 4. Insert Figure 4 here

Discussion

The first purpose of this study was to provide greater insight into working memory capacity differences in adults who stutter by using complex span tasks (dual-tasks) that varied in the amount of linguistic information present. Analyses revealed that predicted working memory capacities of adults who stutter (as indicated by partial-span z-scores) were significantly lower than those of adults who do not stutter on the OSPAN task, the task with the highest relative linguistic content of the three complex span tasks used in this study. This suggests that working memory capacity differences between adults who stutter and adults who do not stutter are more robust for working memory tasks that incorporate greater linguistic demands. Because this study involved dual-tasks that limited the contribution of central working memory resources (i.e., storage and attentional control, see Cowan et al., 2014), these results extend previous findings in stuttering research by demonstrating significant working memory capacity differences even when stimuli have relatively simple linguistic content as opposed to more linguistically complex nonwords. This suggests that working memory capacity differences do not exist *only* as a function of phonological complexity, a finding that constrains previous research in stuttering (see Anderson et al., 2006; Anderson & Wagovich, 2010; Byrd et al., 2012; Coalson & Byrd, 2017; Hakim & Bernstein Ratner, 2004; Pelczarski & Yaruss, 2016; Sasisekaran & Weisberg, 2014; C. Spencer & Weber-Fox, 2014). Instead, differences in working memory capacity may be found in tasks with less complex linguistic content when the possible contribution of central working memory resources are limited, as in dual-task paradigms.

A second purpose of this study was to ascertain whether individual differences in attentional control predicted working memory span differences. Results indicated that attentional control in the stuttering group significantly predicted working memory capacity on the OSPAN task. Lower attentional control (higher Executive Control network scores) was significantly associated with lower partial-span z-scores on the OSPAN task; individuals who stutter with lower attentional control were predicted to demonstrate significantly lower mean partial-span z-scores in the OSPAN task compared to the mean partial-span z-scores of adults who do not stutter. As can be seen in Figure 4, the raw data from adults who do not stutter did not show the predicted relationship between attentional control and OSPAN performance that has been found with very high and very low span individuals in the general population (see Redick & Engle, 2006). This likely occurred for two reasons. First, there were fewer adults who do not stutter in this study who demonstrated lower partial-span z-scores on the OSPAN. That is, adults who do not stutter performed higher on the OSPAN than on the other two complex span tasks (see Figure 3). Second, other research has shown that of the three complex span tasks used in this study, the OSPAN task is the least able to differentiate high- vs low-span individuals in the general population (see Draheim et al., 2018, for discussion).

The different pattern of results between the group of adults who stutter and the group of adults who do not stutter suggests that the nature of the working memory task itself (i.e., linguistic demands) influenced the pattern of results in adults who stutter. This finding suggests that (a) activating the relatively simple linguistic stimuli may be inherently more difficult for adults who stutter as a group and (b) individuals who stutter who have higher executive control of attention may be less susceptible to dual-task effects. These individuals may be able to supplement their performance in activating the to-be-remembered stimuli in the OSPAN to a greater degree than individuals who stutter with lower executive control of attention.

Implications for Theories of How Stuttering Occurs

The finding that individual differences in attentional control in adults who stutter predict working memory differences on the OSPAN task has implications for better understanding related areas of research in stuttering. Specifically, the study of word-form encoding or language formulation has long been of interest in stuttering research (see Brocklehurst, 2008, for review). In the Covert Repair Hypothesis, Postma and Kolk (1993) proposed that the linguistic plans of people who stutter are ill-formed as they prepare speech in an ongoing fashion. Speakers' attempts to repair these errors before they are overtly produced directly result in stuttered speech behavior (Postma & Kolk, 1993). Similarly, due to a disruption in translating a well-formed linguistic plan to the speech motor system for execution, the ExPlan hypothesis similarly implicates word-form encoding as being at least partially responsible for stuttering behaviors (Howell & Au-Yeung, 2002).

The OSPAN task used in this study required participants to activate simple word forms, the exact type of word form activation seen in more naturalistic language formulation (see Roelofs, 2008; Roelofs & Piai, 2011, for discussion of *enhancement*). Thus, reduced working memory capacity in adults who stutter for activating and silently rehearsing relatively simple linguistic stimuli adds to a growing body of evidence indicating that adults who stutter have subtle differences in word-form encoding abilities. Specifically, past research has shown that children and adults who stutter demonstrate slower or reduced responses to priming (Hampton Wray & Spray, 2020; Wijnen & Boers, 1994) and that children who stutter are later in making the transition into more adult-like phonological encoding (see Byrd et al., 2007, for discussion of holistic vs. incremental encoding). Research has also shown that children and adults who stutter demonstrate slower phoneme monitoring than children and adults who do not stutter (Coalson & Byrd, 2015, 2018; Sasisekaran et al., 2006, 2013; Sasisekaran & Byrd, 2013). Ferreira and Pashler (2002) evaluated picture naming in college-aged adults with semantic, phonological, and unrelated distractors while subjects also monitored a series of pure tones. The authors found that earlier stages of language formulation (e.g., semantics) but not later stages (e.g., phonological encoding) were susceptible to decreased efficiency under dual-task conditions in college-aged adults. Maxfield et al. (2016) extended this work to show that phonological encoding, a later stage of word-form encoding processes, was also susceptible to dual-task effects in adults who stutter. Thus, growing evidence combined with the current findings indicate that people who stutter have inefficiencies in their word-form encoding abilities and these inefficiencies appear to be most evident in conditions when word-form encoding processes cannot be supplemented by more central processes, such as attentional control. This may occur when linguistic demands are great (e.g., during phonologically complex nonword repetition tasks), when supplemental attentional resources are limited (e.g., due to concomitant processing as induced by the dual-tasks in this study), or when a speaker natively has less efficient executive control of attention (the case for many of the adults who stutter in this study, as indicated by the significant interaction of Executive Control network score and stuttering group status).

Individual differences in the experience of stuttering may also predispose a person to situations in which attentional control may be unable to support peripheral processing. Speakers who have a lower tolerance for disfluencies or for errors in the language formulation and speech production processes may set unrealistic or unattainable thresholds for accuracy or fluency in speech (Brocklehurst et al., 2013). If higher thresholds are required for mapping a word form to the motor system for execution in such individuals, then the word-form encoding system would require greater allocation of attention toward the intended-to-speak word form in order for it to be translated to the motor system (Roelofs, 2008; Roelofs & Piai, 2011). Such requirements may predispose some people who stutter to experience more breakdowns, delays, or inefficiencies in language formulation, especially when central attentional resources are insufficient. Thus, findings from this study further constrain theories describing the origin of moments of stuttering that suggest that the occurrence of stuttering is due to increased motoric, linguistic, cognitive, or emotional demands (see Adams, 1990; Smith & Weber, 2017). Present findings suggest that increased demands should not be viewed mainly in terms of increased complexity. Rather, increased demands may be more accurately described as the summative effect of group predispositions for breakdowns, delays, or inefficiencies in impaired peripheral processes (such as linguistic formulation), combined with individual differences in experiential or environmental factors. Devoting attention to these experiential or environmental factors may exacerbate instances when central attentional resources cannot supplement peripheral processes.

Directions for Future Research

The word-form encoding process, in which linguistic information serves as an input to the motor system, is a critical and necessary step in speech production (Guenther & Hickok, 2016; Levelt et al., 1999). Efficient translation of linguistic information to the motor system leads to efficient motor learning and the establishment of well-formed feedforward internal models of speech movements that are automatic and relatively effortless (Posner, 1967; Schmidt, 1975; Tourville & Guenther, 2011). Researchers have theorized that children who stutter may not develop sufficient feedforward internal models of speech movements, which are necessary for supporting automatic and relatively effortless speech. Ineffective feedforward internal models could negatively impact fluent speech production (Max et al., 2004). The result of inefficient input to a motor system may result in internal models that are less well-formed, and this might thereby lead to greater reliance on feedback control (Civier et al., 2010). Data from the current study suggest that word-form encoding differences might be one factor contributing to an inability to develop well-formed internal models of speech motor movements. Specifically, a word-form encoding system that is less efficient might directly result in linguistic output that is more slowly translated to the motor system for execution, thereby increasing the need for greater reliance on feedback control. Future research is needed to explore this possibility, though the present findings highlight the value of considering individual differences when developing models about the possible underlying nature of stuttering.

The notion that attentional control may be unable to support peripheral processes in a specific speaker or at a specific timepoint has both clinical and theoretical implications that should be investigated in future studies. Adults who stutter on the lower end of attentional control abilities may be less able to supplement domain peripheral processing to the same degree as adults who stutter on the higher end of attentional control abilities. Thus, if word-form encoding in people who stutter is prone to inefficiency and requires more attentional control to supplement processing (see Maxfield et al., 2016), individuals with lower attentional control may be unable to supplement word-form encoding with more central attentional resources when needed. Moreover, the ways in which a specific person is experiencing stuttering may directly influence attentional allocation. Research has shown that individuals who are experiencing depression also demonstrate decreased working memory capacities (Hubbard et al., 2015, 2016). Given that many people who stutter experience negative affective and cognitive reactions to stuttering (Tichenor & Yaruss, 2019, 2020a), such individuals may be adding concomitant processing requirements through more negative stuttering experiences that could lead to even more frequent breakdowns or episodes of inefficiencies in language formulation. Future research should explore these hypotheses by building on present findings to determine whether individual differences in affective or cognitive reactions to stuttering often experienced by people who stutter can predict working memory capacity or attentional control more broadly.

The adults who stutter in this study only demonstrated significantly decreased working memory capacities compared to the adults who do not stutter on the OSPAN task (the task with the most linguistic content in to-be-remembered stimuli of the three tasks). At the same time, participants who stutter also exhibited significantly more difficulty than participants who do not stutter in meeting the typical accuracy criterion (85%) in each of the concomitant tasks. This apparent discrepancy suggests that future research should continue to explore the possibility that adults who stutter may be more affected by concomitant attentional processing than adults who do not stutter both during speech and other attention-demanding tasks (see Bosshardt, 2006, for discussion). Other factors that may be considered in future research include the potential impact of subclinical ADHD characteristics on the processing skills of adults who stutter on working memory. Such investigations are warranted given growing research highlighting the commonality of attentional differences in adults who stutter related to inattention (Alm & Risberg, 2007; Tichenor et al., 2021). Future research in this area may also consider exploring working memory skills in adults who stutter with respect to observable stuttering severity to further expand these findings.

Limitations

There are a number of potential limitations that warrant consideration in interpreting the results of this study and point toward additional opportunities for future research to further clarify these findings. Linear models were used for the primary analysis in this study for the maximum likelihood of detecting group effects (Bates et al., 2014). It was not possible to simulate models to predict sample size and power *a priori* because no published research existed using complex span tasks with people who stutter. Also, prior research using complex span tasks has reported means and standard deviations only, so there was no guidance in the literature upon which to base parameter estimates for simulated data in adults who stutter. Significant differences in this study were found on predicted OSPAN scores between 42 adults who stutter and 40 adults who do not stutter, and the effect size was small-to-medium. Data in this study serve as a foundation for future studies to replicate or expand these findings.

A number of self-reported diagnoses of ADHD were reported in the group of adults who stutter (n=5) compared to fewer self-reports in the group of adults who do not stutter (n =2). Though we incorporated the presence or absence of ADHD self-reported diagnoses as a possible random effect in model comparisons, future research should explore working memory capacity differences and ADHD diagnoses directly in group comparisons with larger numbers of participants who report ADHD diagnoses or characteristics. Relatedly, we did not attempt to measure or account for the presence of concomitant language disorders or language abilities in either group in this study. We therefore cannot rule out the possibility that lower working memory task performance was explained by language abilities. Additionally, given our *a priori* decision to include individuals who did not meet the 85% accuracy criterion typical in complex span task research, it is possible that the effects found in this study may be at least partially indicative of unaccounted variance in participants' ability to understand and follow task instructions, which may have influenced concomitant task accuracy and working memory capacity measures. Future research should account for the possibility that such differences may influence findings.

As we did not control nor attempt to evaluate how participants were encoding information during the tasks, future research should also consider expanding these findings in a mixed method study to account for the possibility that different people may have had different strategies for retaining information in the working memory tasks. Lastly, care should be taken in applying these working memory capacity differences to different tasks or dual-task conditions that may limit attentional processing in different ways. Finally, data in this study are from adults, so care should be taken in applying the findings to younger speakers. Future research should explore the relationships between working memory capacity and attentional control in children who stutter.

Summary

Results from this study further specify previously observed working memory differences in adults who stutter. Working memory capacities in adults who stutter paralleled differences in the amount of linguistic content across a set of complex span tasks, suggesting that working memory capacity in adults who stutter may be associated with linguistic demands in task stimuli. Furthermore, individual differences in executive control of attention predicted working memory capacity on the OSPAN task, the task with the most linguistic demands. Working memory capacity differences observed with relatively simple word-forms (i.e., single orthographic letters) indicate that working memory differences in adults who stutter do not exist *only* as a function of linguistic complexity. Instead, working memory capacity for linguistic content in adults who stutter appears to be associated with task complexity more broadly as moderated by individual differences in attentional control.

References

Adams, M. R. (1990). The demands and capacities model I: Theoretical elaborations. *Journal of Fluency Disorders*, *15*(3), 135–141.
Alm, P. A., & Risberg, J. (2007). Stuttering in adults: The acoustic startle response, temperamental traits, and biological factors. *Journal of Communication Disorders*, *40*(1), 1–41. https://doi.org/10.1016/j.jcomdis.2006.04.001
Anderson, J. D., & Wagovich, S. A. (2010). Relationships among linguistic processing speed, phonological working memory, and attention in children who stutter. *Journal of Fluency Disorders*, *35*(3), 216–234.
Anderson, J. D., Wagovich, S. A., & Hall, N. E. (2006). Nonword repetition skills in young children who do and do not stutter. *Journal of Fluency Disorders*, *31*(3), 177–199.
Baddeley, A. (2000). The episodic buffer: A new component of working memory? *Trends in Cognitive Sciences*, *4*(11), 417–423. https://doi.org/10.1016/S1364-6613(00)01538-2
Baddeley, A. (2003). Working memory: looking back and looking forward. *Nature Reviews Neuroscience*, *4*(10), 829–839. https://doi.org/10.1038/nrn1201
Baddeley, A. (2007). *Working Memory, Thought, and Action*. Oxford University Press.
Baddeley, A. (2012). Working Memory: Theories, Models, and Controversies. *Annual Review of Psychology*, *63*(1), 1–29. https://doi.org/10.1146/annurev-psych-120710-100422
Baddeley, A., & Hitch, G. (1974). Working memory. *Psychology of Learning and Motivation*, *8*, 47–89. https://doi.org/10.1016/j.cub.2009.12.014
Bajaj, A. (2007). Working memory involvement in stuttering: Exploring the evidence and research implications. *Journal of Fluency Disorders*, *32*(3), 218–238.
Barr, D. J., Levy, R., Scheepers, C., & Tily, H. J. (2013). Random effects structure for confirmatory hypothesis testing: Keep it maximal. *Journal of Memory and Language*, *68*(3), 255–278. https://doi.org/10.1016/j.jml.2012.11.001
Barrouillet, P., Bernardin, S., & Camos, V. (2004). Time Constraints and Resource Sharing in Adults' Working Memory Spans. *Journal of Experimental Psychology: General*, *133*(1), 83–100. https://doi.org/10.1037/0096-3445.133.1.83
Bates, D., Maechler, M., Bolker, B., & Walker, S. (2014). lme4: Linear mixed-effects models using Eigen and S4. *R Package Version*, *1*(7).
Bosshardt, H. G. (2006). Cognitive processing load as a determinant of stuttering: Summary of a research programme. *Clinical Linguistics and Phonetics*, *20*(5), 371–385. https://doi.org/10.1080/02699200500074321
Bowers, A., Bowers, L. M., Hudock, D., & Ramsdell-hudock, H. L. (2018). Phonological working memory in developmental stuttering : Potential insights from the neurobiology of language and cognition. *Journal of Fluency Disorders*, *58*(August), 94–117. https://doi.org/10.1016/j.jfludis.2018.08.006
Bressler, S. L., & Tognoli, E. (2006). Operational principles of neurocognitive networks. *International Journal of Psychophysiology*, *60*(2), 139–148. https://doi.org/10.1016/j.ijpsycho.2005.12.008
Brocklehurst, P. H. (2008). A review of evidence for the covert repair hypothesis of stuttering. *Contemporary Issues in Communication Science & Disorders*, *35*, 25–43. http://www.asha.org/uploadedFiles/asha/publications/cicsd/2008SAReviewofEvidence.pdf
Brocklehurst, P. H., Lickley, R. J., & Corley, M. (2013). Revisiting Bloodstein's Anticipatory Struggle Hypothesis from a psycholinguistic perspective: A Variable Release Threshold

hypothesis of stuttering. *Journal of Communication Disorders*, *46*(3), 217–237.

Brown, L., Shernenou, R., & Johnsen, S. (2010). *Test of Nonverbal Intelligence* (4th ed.). Pro-ed.

Byrd, C. T., Conture, E. G., & Ohde, R. N. (2007). Phonological priming in young children who stutter: Holistic versus incremental processing. *American Journal of Speech-Language Pathology*, *16*(1), 43–53. https://doi.org/10.1044/1058-0360(2007/006)

Byrd, C. T., McGill, M., & Usler, E. (2015). Nonword repetition and phoneme elision in adults who do and do not stutter: Vocal versus nonvocal performance differences. *Journal of Fluency Disorders*, *44*, 17–31. https://doi.org/10.1016/j.jfludis.2015.01.004

Byrd, C. T., Vallely, M., Anderson, J. D., & Sussman, H. (2012). Nonword repetition and phoneme elision in adults who do and do not stutter. *Journal of Fluency Disorders*, *37*(3), 188–201.

Civier, O., Tasko, S. M., & Guenther, F. H. (2010). Overreliance on auditory feedback may lead to sound/syllable repetitions: simulations of stuttering and fluency-inducing conditions with a neural model of speech production. *J Fluency Disord*, *35*(3), 246–279. https://doi.org/10.1016/j.jfludis.2010.05.002

Coalson, G. A., & Byrd, C. T. (2015). Metrical Encoding in Adults Who Do and Do Not Stutter. *Journal of Speech Language Hearing and Research*, *58*, 601–621.

Coalson, G. A., & Byrd, C. T. (2017). Nonword repetition in adults who stutter: The effects of stimuli stress and auditory-orthographic cues. *PLoS ONE*, *12*(11), 1–21. https://doi.org/10.1371/journal.pone.0188111

Coalson, G. A., & Byrd, C. T. (2018). Delayed silent phoneme monitoring in adults who do and do not stutter. *Speech, Language and Hearing*, *0*(0), 1–18. https://doi.org/10.1080/2050571X.2018.1458067

Cohen, J. (1988). *Statistical Power Analysis for The Behavioral Sciences*. Lawrence Erlbaum Associates, Inc.

Constantinidis, C., & Klingberg, T. (2016). The neuroscience of working memory capacity and training. *Nature Reviews Neuroscience*, *17*(7), 438–449. https://doi.org/10.1038/nrn.2016.43

Constantino, C. D., Leslie, P., Quesal, R., & Yaruss, J. S. (2016). A preliminary investigation of daily variability of stuttering in adults. *Journal of Communication Disorders*, *60*, 39–50. https://doi.org/http://dx.doi.org/10.1016.02.001

Conture, E. G., Kelly, E. M., & Walden, T. A. (2013). Temperament, speech and language: An overview. *Journal of Communication Disorders*, *46*(2), 125–142. https://doi.org/10.1016/j.jcomdis.2012.11.002

Conway, A. R. a, Kane, M. J., & Al, C. E. T. (2005). Working memory span tasks : A methodological review and user ' s guide. *Psychonomic Bulletin & Review*, *12*(5), 769–786. https://doi.org/10.3758/BF03196772

Corbetta, M., Patel, G., & Shulman, G. L. (2008). The Reorienting System of the Human Brain: From Environment to Theory of Mind. *Neuron*, *58*(3), 306–324. https://doi.org/10.1016/j.neuron.2008.04.017

Cowan, N. (1999). An Embedded-Processes Model of Working Memory. In A. Miyake & P. Shah (Eds.), *Models of Working Memory: Mechanisms of Active Maintenance and Executive Control*. Cambridge University Press.

Cowan, N., Saults, J. S., & Blume, C. L. (2014). Central and peripheral components of working memory storage. *Journal of Experimental Psychology: General*, *143*(5), 1806–1836. https://doi.org/10.1037/a0036814

Dell, G. S. (1988). The retrieval of phonological forms in production: Tests of predictions from a connectionist model. *Journal of Memory and Language*, *27*(2), 124–142. https://doi.org/10.1016/0749-596X(88)90070-8

Denny, M., & Smith, A. (1992). Gradations in a pattern of neuromuscular activity associated with stuttering. *J Speech Hear Res*, *35*(6), 1216–1229. http://www.ncbi.nlm.nih.gov/pubmed/1494267

Draheim, C., Harrison, T. L., Embretson, S. E., & Engle, R. W. (2018). What item response theory can tell Us about the complex span tasks. *Psychological Assessment*, *30*(1), 116–129. https://doi.org/10.1037/pas0000444

Druker, K., Hennessey, N., Mazzucchelli, T., & Beilby, J. (2019). Elevated attention deficit hyperactivity disorder symptoms in children who stutter. *Journal of Fluency Disorders*, *59*(August 2018), 80–90. https://doi.org/10.1016/j.jfludis.2018.11.002

Eggers, K., De Nil, L. F., & Van den Bergh, B. R. H. (2012). The Efficiency of Attentional Networks in Children Who Stutter. *Journal of Speech, Language, and Hearing Research*, *55*(3), 946–959. https://doi.org/10.1044/1092-4388(2011/10-0208)

Engle, R. W. (2002). Working memory capacity as executive attention. *Current Directions in Psychological Science*, *11*(1), 19–23. https://doi.org/10.1111/1467-8721.00160

Engle, R. W. (2018). Working Memory and Executive Attention: A Revisit. *Perspectives on Psychological Science*, *13*(2), 190–193. https://doi.org/10.1177/1745691617720478

Engle, R. W., & Kane, M. J. (2003). Executive Attention, Working Memory Capacity, and a Two-Factor Theory of Cognitive Control. *Psychology of Learning and Motivation - Advances in Research and Theory*, *44*, 145–199. https://doi.org/10.1016/S0079-7421(03)44005-X

Engle, R. W., Kane, M. J., & Tuholski, S. W. (1999). Individual differences in working memory capacity and what they tell us about controlled attention, general fluid intelligence, and functions of the prefrontal cortex. In A. Miyake & P. Shah (Eds.), *Models of working memory: Mechanisms of active maintenance and executive control* (pp. 102–134). Cambridge University Press.

Eriksen, B., & Eriksen, C. W. (1974). Performance variability, impulsivity errors and the impact of incentives as gender-independent endophenotypes for ADHD. *Perception & Psycholinguistics*, *16*(1), 143–149.

Fan, J., McCandliss, B. D., Sommer, T., Raz, A., & Posner, M. I. (2002). Testing the efficiency and independence of attentional networks. *Journal of Cognitive Neuroscience*, *14*(3), 340–347.

Ferreira, V. S., & Pashler, H. (2002). Central Bottleneck Influences on the Processing Stages of Word Production. *Journal of Experimental Psychology: Learning Memory and Cognition*, *28*(6), 1187–1199. https://doi.org/10.1037/0278-7393.28.6.1187

Foster, J. L., Shipstead, Z., Harrison, T. L., Hicks, K. L., Redick, T. S., & Engle, R. W. (2015). Shortened complex span tasks can reliably measure working memory capacity. *Memory and Cognition*, *43*(2), 226–236. https://doi.org/10.3758/s13421-014-0461-7

Gathercole, S. E., & Baddeley, A. D. (1993). *Working Memory and Language*. Lawrence Erlbaum Associates, Inc.

Gkalitsiou, Z. (2018). *Phonological Working Memory in Adults who Stutter*. University of Texas at Austin.

Guenther, F. H., & Hickok, G. (2016). Neural Models of Motor Speech Control. In *Neurobiology of Language*. Elsevier Inc. https://doi.org/10.1016/B978-0-12-407794-2.00058-4

Hakim, H. B., & Bernstein Ratner, N. (2004). Nonword repetition abilities of children who stutter: An exploratory study. *Journal of Fluency Disorders*, *29*(3), 179–199.

Hampton Wray, A., & Spray, G. (2020). Neural processes underlying nonword rhyme differentiate eventual stuttering persistence and recovery. *Journal of Speech, Language, and Hearing Research*, *63*(8), 2535–2554. https://doi.org/10.1044/2020_JSLHR-19-00320

Howell, P., & Au-Yeung, J. (2002). The EXPLAN theory of fluency control applied to the diagnosis of stuttering. *AMSTERDAM STUDIES IN THE THEORY AND HISTORY OF LINGUISTIC SCIENCE SERIES 4*, 75–94.

Hubbard, N. A., Hutchison, J. L., Hambrick, D. Z., & Rypma, B. (2016). The enduring effects of depressive thoughts on working memory. *Journal of Affective Disorders*, *190*, 208–213. https://doi.org/10.1016/j.jad.2015.06.056

Hubbard, N. A., Hutchison, J. L., Turner, M., Montroy, J., Bowles, R. P., & Rypma, B. (2015). Depressive thoughts limit working memory capacity in dysphoria. *Cognition and Emotion*, *30*(2), 193–209. https://doi.org/10.1080/02699931.2014.991694

Huettig, F., Olivers, C. N. L., & Hartsuiker, R. J. (2011). Looking, language, and memory: Bridging research from the visual world and visual search paradigms. *Acta Psychologica*, *137*(2), 138–150. https://doi.org/10.1016/j.actpsy.2010.07.013

Johnson, K. A., Robertson, I. H., Barry, E., Mulligan, A., Dáibhis, A., Daly, M., Watchorn, A., Gill, M., & Bellgrove, M. A. (2008). Impaired conflict resolution and alerting in children with ADHD: evidence from the Attention Network Task (ANT). *Journal of Child Psychology and Psychiatry, and Allied Disciplines*, *49*(12), 1339–1347. https://doi.org/10.1111/j.1469-7610.2008.01936.x

Kane, M. J., & Engle, R. W. (2002). The role of prefrontal cortex in working-memory capacity, executive attention, and general fluid intelligence: An individual-differences perspective. *Psychonomic Bulletin & Review*, *9*(4), 637–671. https://doi.org/10.3758/BF03196323

Kelly, E., Smith, A., & Goffman, L. (1995). Orofacial muscle activity of children who stutter: a preliminary study. *J Speech Hear Res*, *38*(5), 1025–1036. http://www.ncbi.nlm.nih.gov/pubmed/8558872

Klein, K., & Fiss, W. H. (1999). The reliability and stability of the Turner and Engle working memory. *Behavior Research Methods, Instruments, and Computers*, *31*(3), 429–432. https://doi.org/10.3758/BF03200722

Kleinow, J., & Smith, A. (2000). Influences of length and syntactic complexity on the speech motor stability of the fluent speech of adults who stutter. *Journal of Speech, Language, and Hearing Research*, *43*(2), 548–559.

Kolk, H. H. J. (1990). *Stuttering as Corrective Adaptation: Technical Report 90-06*. The Nijmegen Institute for Cognition Research and Information Technology.

Lescht, E., Dickey, M. W., Stockbridge, M. D., & Ratner, N. B. (2022). Adults Who Stutter Show Diminished Word Fluency, Regardless of Mode. *Journal of Speech, Language, and Hearing Research*, *65*(3), 906–922. https://doi.org/10.1044/2021_JSLHR-21-00344

Levelt, W. J. M., Roelofs, A., & Meyer, A. S. (1999). A theory of lexical access in speech production. *Behavioral and Brain Sciences*, *22*(01), 1–38.

Logie, R. H., & Cowan, N. (2015). Perspectives on working memory: introduction to the special issue. *Memory & Cognition*, *43*(3), 315–324. https://doi.org/10.3758/s13421-015-0510-x

MacLeod, J. W., Lawrence, M. A., McConnell, M. M., Eskes, G. A., Klein, R. M., & Shore, D. I. (2010). Appraising the ANT: Psychometric and Theoretical Considerations of the Attention Network Test. *Neuropsychology*, *24*(5), 637–651. https://doi.org/10.1037/a0019803

Max, L., Guenther, F. H., Gracco, V. L., Ghosh, S. S., & Wallace, M. E. (2004). Unstable or insufficiently activated internal models and feedback-biased motor control as sources of dysfluency: A theoretical model of stuttering. *Contemporary Issues in Communication Science and Disorders*, *31*(Spring), 105–122.

Maxfield, N. D., Olsen, W. L., Kleinman, D., Frisch, S. A., Ferreira, V. S., & Lister, J. J. (2016). Attention demands of language production in adults who stutter. *Clinical Neurophysiology*, *127*(4), 1942–1960. https://doi.org/10.1016/j.clinph.2016.01.016

Maxwell, J. P., Masters, R. S. W., & Eves, F. F. (2003). The role of working memory in motor learning and performance. *Consciousness and Cognition*, *12*(3), 376–402. https://doi.org/10.1016/S1053-8100(03)00005-9

Miller, G. A. (1956). The magical number seven, plus or minus two: Some limits on our capacity for processing information. *The Psychological Review*, *63*(2), 81–97. http://www.edwardtufte.com/bboard/q-and-a-fetch-msg?msg_id=0000U6&topic_id=1

Namasivayam, A. K., & Van Lieshout, P. (2011). Speech motor skill and stuttering. *Journal of Motor Behavior*, *43*(6), 477–489.

Neilson, M. D., & Neilson, P. D. (1987). Speech motor control and stuttering: A computational model of adaptive sensory-motor processing. *Speech Communication*, *6*(4), 325–333. https://doi.org/10.1016/0167-6393(87)90007-0

Newman, R. S. (2007). The Role of Selected Lexical Factors on Confrontation Naming Accuracy, Speed, and Fluency in Adults Who Do and Do Not Stutter. *Journal of Speech, Language, and Hearing Research*, *50*, 196–213. https://doi.org/https://doi.org/10.1044/1092-4388(2007/016)

Olander, L., Smith, A., & Zelaznik, H. (2010). Evidence That a Motor Timing Deficity is a Factor in the Development of Stuttering. *Journal of Speech, Language, and Hearing Research*, *53*, 876–886.

Oyoun, H. A., El Dessouky, H., Shohdi, S., & Fawzy, A. (2010). Assessment of Working Memory in Normal Children and Children Who Stutter. *Journal of American Science*, *6*(11), 562–569.

Pelczarski, K., & Yaruss, J. S. (2016). Phonological memory in young children who stutter. *Journal of Communication Disorders*, *62*, 54–66.

Perkins, W. H., Rudas, J., Johnson, L., & Bell, J. (1976). Stuttering : Discoordination of Phonation with Articulation and Respiration. *Journal of Speech Language Hearing and Research*, *19*, 509–522.

Petersen, S. E., & Posner, M. I. (2012). The Attention System of the Human Brain: 20 Years After. *Annual Review of Neuroscience*, *35*(1), 73–89. https://doi.org/10.1146/annurev-neuro-062111-150525

Posner, M. I. (1967). Characteristics of Visual and Kinesthetic Memory Codes. *Journal of Experimental Psychology*, *75*(1), 103–107.

Posner, M. I. (1980). Orienting of Attention. *Quarterly Journal of Experimental Psychology*, *32*(1), 3–25.

Posner, M. I., & Petersen, S. E. (1990). The Attention System of the Human Brain. *Annual Review of Neuroscience1*, *13*, 25–42.

Posner, M. I., & Rothbart, M. (2007). Research on Attention Networks as a Model for the Integration of Psychological Science. *Annual Review of Psychology*, *58*(1), 1–23. https://doi.org/10.1146/annurev.psych.58.110405.085516

Posner, M. I., Snyder, C. R., & Davidson, B. J. (1980). Attention and the detection of signals.

Journal of Experimental Psychology: General, *109*(2), 160–174. https://doi.org/10.1037/0096-3445.109.2.160

Postma, A., & Kolk, H. (1993). The Covert Repair HypothesisPrearticulatory Repair Processes in Normal and Stuttered Disfluencies. *Journal of Speech, Language, and Hearing Research*, *36*(3), 472–487.

R Core Team. (2020). *R: A language and environment for statistical computing.* (3.6.2 (2019-12-12)). The R Foundation for Statistical Computing.

Redick, T. S., Broadway, J. M., Meier, M. E., Kuriakose, P. S., Unsworth, N., Kane, M. J., & Engle, R. W. (2012). Measuring working memory capacity with automated complex span tasks. *European Journal of Psychological Assessment*, *28*(3), 164–171. https://doi.org/10.1027/1015-5759/a000123

Redick, T. S., & Engle, R. W. (2006). Working memory capacity and attention network test performance. *Applied Cognitive Psychology*, *20*(5), 713–721. https://doi.org/10.1002/acp.1224

Roelofs, A. (2008). Tracing attention and the activation flow of spoken word planning using eye movements. *J Exp Psychol Learn Mem Cogn*, *34*(2), 353–368. https://doi.org/10.1037/0278-7393.34.2.353

Roelofs, A., & Piai, V. (2011). Attention demands of spoken word planning: A review. *Frontiers in Psychology*, *2*(NOV), 1–14. https://doi.org/10.3389/fpsyg.2011.00307

Rothbart, M. K. (2007). Temperament, Development, and Personality. *Current Dire*, *16*(4), 207–212.

Rothbart, M. K., & Posner, M. I. (2015). Temperament, Attention, and Developmental Psychopathology. In D. Cicchetti & D. Cohen (Eds.), *Developmental Psychopathology* (Vol. 2, pp. 465–501). https://doi.org/10.1002/9780470939390.ch11

Sasisekaran, J. (2013). Nonword repetition and nonword reading abilities in adults who do and do not stutter. *Journal of Fluency Disorders*, *38*(3), 275–289. https://doi.org/10.1016/j.jfludis.2013.06.001

Sasisekaran, J., Brady, A., & Stein, J. (2013). A preliminary investigation of phonological encoding skills in children who stutter. *Journal of Fluency Disorders*, *38*(1), 45–58. https://doi.org/10.1016/j.jfludis.2012.12.003

Sasisekaran, J., & Byrd, C. T. (2013). A preliminary investigation of segmentation and rhyme abilities of children who stutter. *Journal of Fluency Disorders*, *38*(2), 222–234.

Sasisekaran, J., De Nil, L. F., Smyth, R., & Johnson, C. (2006). Phonological encoding in the silent speech of persons who stutter. *Journal of Fluency Disorders*, *31*(1), 1–21. https://doi.org/10.1016/j.jfludis.2005.11.005

Sasisekaran, J., & Weisberg, S. (2014). Practice and retention of nonwords in adults who stutter. *Journal of Fluency Disorders*, *41*, 55–71.

Schmidt, R. (1975). A Schema Theory of Discrete Motor Skill Learning. *Psychological Review*, *82*(4), 225–260. https://doi.org/10.1037/h0076770

Smith, A., Goffman, L., Sasisekaran, J., & Weber-Fox, C. (2012). Language and motor abilities of preschool children who stutter: Evidence from behavioral and kinematic indices of nonword repetition performance. *Journal of Fluency Disorders*, *37*(4), 344–358. https://doi.org/10.1016/j.jfludis.2012.06.001

Smith, A., & Kelly, E. (1997). Stuttering: A dynamic, multifactorial model. *Nature and Treatment of Stuttering: New Directions*, *2*, 204–217.

Smith, A., Luschei, E., Denny, M., Wood, J., Hirano, M., & Badylak, S. (1993). Spectral analyses of activity of laryngeal and orofacial muscles in stutterers. *J Neurol Neurosurg Psychiatry*, *56*(12), 1303–1311. http://www.ncbi.nlm.nih.gov/pubmed/8270932

Smith, A., Sadagopan, N., Walsh, B., & Weber-Fox, C. (2010). Increasing phonological complexity reveals heightened instability in inter-articulatory coordination in adults who stutter. *J Fluency Disord*, *35*(1), 1–18. https://doi.org/10.1016/j.jfludis.2009.12.001

Smith, A., & Weber, C. (2017). How Stuttering Develops: The Multifactorial Dynamic Pathways Theory. *Journal of Speech Language Hearing and Research*, 1–23. https://doi.org/10.1044/2017_JSLHR-S-16-0343

Sonuga-Barke, E. J. S., & Castellanos, F. X. (2007). Spontaneous attentional fluctuations in impaired states and pathological conditions: A neurobiological hypothesis. *Neuroscience and Biobehavioral Reviews*, *31*(7), 977–986. https://doi.org/10.1016/j.neubiorev.2007.02.005

Spencer, C., & Weber-Fox, C. (2014). Preschool speech articulation and nonword repetition abilities may help predict eventual recovery or persistence of stuttering. *Journal of Fluency Disorders*, *41*, 32–46.

Spencer, E., Packman, A., Onslow, M., & Ferguson, A. (2009). The effect of stuttering on communication: A preliminary investigation. *Clinical Linguistics and Phonetics*, *23*(7), 473–488. https://doi.org/10.1080/02699200902833373

Starkweather, C. W., & Gottwald, S. R. (1990). The demands and capacities model II: Clinical Applications. *Journal of Fluency Disorders*, *15*, 143–157. https://doi.org/10.1016/S0094-730X(00)00086-3

Tichenor, S. E., Johnson, C. A., & Scott Yaruss, J. (2021). A preliminary investigation of attention-deficit/hyperactivity disorder characteristics in adults who stutter. *Journal of Speech, Language, and Hearing Research*, *64*(3), 839–853. https://doi.org/10.1044/2020_JSLHR-20-00237

Tichenor, S. E., & Yaruss, J. S. (2019). Group Experiences and Individual Differences in Stuttering. *Journal of Speech, Language & Hearing Research*, *62*, 4335–4350. https://doi.org/https://doi.org/10.1044/2019_JSLHR-19-00138

Tichenor, S. E., & Yaruss, J. S. (2020a). Repetitive negative thinking, temperament, and adverse impact in adults who stutter. *American Journal of Speech-Language Pathology*, *29*(1), 201–215. https://doi.org/10.1044/2019_AJSLP-19-00077

Tichenor, S. E., & Yaruss, J. S. (2020b). Variability of stuttering: Behavior and impact. *American Journal of Speech-Language Pathology*, *30*(1), 75–88. https://doi.org/10.1044/2020_AJSLP-20-00112

Tourville, J. A., & Guenther, F. H. (2011). The DIVA model: A neural theory of speech acquisition and production. *Language and Cognitive Processes*, *26*(7), 952–981.

Turley-Ames, K. J., & Whitfield, M. M. (2003). Strategy training and working memory task performance. *Journal of Memory and Language*, *49*(4), 446–468. https://doi.org/10.1016/S0749-596X(03)00095-0

Turner, M., & Engle, R. W. (1989). Is Working Memory Capacity Task Dependent. *Journal of Memory and Language*, *28*, 127–154.

Unsworth, N., & Engle, R. W. (2006). Simple and complex memory spans and their relation to fluid abilities: Evidence from list-length effects. *Journal of Memory and Language*, *54*(1), 68–80. https://doi.org/10.1016/j.jml.2005.06.003

Unsworth, N., & Engle, R. W. (2007). On the Division of Short-Term and Working Memory: An Examination of Simple and Complex Span and Their Relation to Higher Order Abilities.

Psychological Bulletin, *133*(6), 1038–1066. https://doi.org/10.1037/0033-2909.133.6.1038

Unsworth, N., Heitz, R. P., Schrock, J. C., & Engle, R. W. (2005). An automated version of the operation span task. *Behavior Research Methods*, *37*(3), 498–505. https://doi.org/10.3758/BF03192720

Unsworth, N., Redick, T. S., Heitz, R. P., Broadway, J. M., & Engle, R. W. (2009). Complex working memory span tasks and higher-order cognition: A latent-variable analysis of the relationship between processing and storage. *Memory*, *17*(6), 635–654. https://doi.org/10.1080/09658210902998047

Urbanek, C., Neuhaus, A. H. M., Opgen-Rhein, C., Strathmann, S., Wieseke, N., Schaub, R., Hahn, E., & Dettling, M. (2009). Attention network test (ANT) reveals gender-specific alterations of executive function in schizophrenia. *Psychiatry Research*, *168*(2), 102–109. https://doi.org/10.1016/j.psychres.2008.04.006

Vasic, N., & Wijnen, F. (2005). Stuttering as a monitoring deficit. In R. J. Hartsuiker, A. Bastiaanse, A. Postma, & F. Wijnen (Eds.), *Phonological encoding and monitoring in normal and pathological speech* (pp. 226–247). Psychology Press.

Westfall, J., Kenny, D. A., & Judd, C. M. (2014). Statistical Power and Optimal Design in Experiments in Which Samples of Participants Respond to Samples of Stimuli. *Journal of Experimental Psychology: General*, *143*(5), 2020–2045. http://dx.doi.org/10.1037/xge0000014

Wijnen, F., & Boers, I. (1994). Phonological priming effects in stutterers. *Journal of Fluency Disorders*, *19*(1), 1–20. https://doi.org/10.1016/0094-730X(94)90011-6

Yaruss, J. S. (1997). Clinical implications of situational variability in preschool children who stutter. *Journal of Fluency Disorders*, *22*(3), 187–203. https://doi.org/10.1016/S0094-730X(97)00009-0

Yaruss, J. S., & Quesal, R. (2016). *Overall Assessment of the Speaker's Experience of Stuttering (OASES).* Stuttering Therapy Resources, Inc.

Figure Captions

Figure 1.
Caption: The accuracy on the concomitant task in each complex span task by group is illustrated. In all three complex span tasks, the group of adults who stutter in this study were less likely to meet the accuracy criterion across all complex span tasks than were the group of adults who do not stutter.

Figure 2.
Caption: The mean Alerting, Orienting, and Executive Control network scores are plotted for each group. The top and bottom lines of each box represent the 25th ands 75th percentile, respectively. The line within the box is the median and the diamond indicates the mean.

Figure 3.
Caption: The predicted changes in the fixed effects (Group and Complex Span Task) in the best fitting model are plotted. The left side of the figure illustrates the predicted effects of group (participants who stutter or do not stutter). The right side of the figure visualizes the predicted effects of task.

Figure 4.
Caption: Attentional control (Executive Control) moderated the relationship between group and mean partial-span z-score, indicating that adults who stutter with lower attentional control (higher Executive Control network scores) demonstrated significantly lower mean partial-span z-scores in the OSPAN task compared to the mean partial-span z-scores of adults who do not stutter.